An Invitation to Mathematical Physics

and Its History

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Abstract

Science has evolved over thousands of years. It began out of curiosity of how the world around us works and a need to know how to make thing work better. From water management to space travel, science is essential for success.

The evolution of science is layered: The early science depended mostly on critical observation, thus the early scientist was considered a philosopher, who created a theory. Soon experiments were designed to test these theories. This process was successful when a correct was established, leading to a new agreed upon understanding. This process typically took years. Thus he key component is the making and testing of models, that are designed to quantitatively pit the results of experiment in a mathematical framework. Good science is observation and experimentation. Great science is the art of making a model that explains the experimental results. Great science always results in a deeper question, suggesting new experiments. Each generation had its geniuses. One of these was Galileo, who was both a philosopher, experimentalist and the ultimate mathematician.

An understanding of physics requires knowledge of mathematics. The converse is not true. By definition, pure mathematics contains no physics. Yet historically, mathematics has a rich history filled with physical applications. Mathematics was developed by individuals with the intent of making things work. As an engineer, I see these creators of early mathematics as budding engineers. This book is an attempt to tell their story, of the development of mathematical physics, as viewed by an engineer.

There are two distinct ways to learn mathematics: by learning definitions and relationships or by associating each mathematical concept with its physical counterpart. Students of physicists and engineers learn mathematics on the path to learning physics. Students of pure mathematics are taught via a system of definitions of abstract structures. These students do not learn based the origins of the mathematics, which lie largely in physics. These two teaching methods result in very different understandings of the material.

There is a deep common thread between physics and mathematics, which is the chronological development, i.e., the history of mathematics. This is because much of mathematics was developed to solve physical problems. Most early mathematics evolved from attempts to understand the world, with the goal of navigating it. Pure mathematics followed as generalizations of the physical concepts.

For example, around 1638\footnote{https://en.wikipedia.org/wiki/Galileo_Galilei#Falling_bodies} Galileo stated that based on experiments with balls rolling down inclined planes and pendulums, the height of a falling object is given by

\[ h(t) = \frac{1}{2} G t^2, \]

where \( t \) is time and \( G \) is a constant. This formula leads to a constant acceleration \( a(t) \) of the object since

\[ a(t) = \frac{d^2}{dt^2} h(t) = G \]

is independent of time. It follows that the force on a body is proportional to its acceleration \( a \), defined as \( G \), namely \( F = a \equiv G \). It also follows that if the object has a constant forward velocity, the object will have a parabolic trajectory.

Following up on the observations of Galileo’s study of pendulums and falling objects, Newton showed that differential equations were necessary to explain gravity and that the force of gravity is proportional to the masses of the two objects over the square of the reciprocal of the distance between them, namely

\[ \frac{d^2}{dt^2} r(t) = G \frac{mM}{r^2(t)}. \]
To find \( r(t) \) one must integrate this equation. For the case of an object at height \( h(t) \) above the surface of the earth, \( r(t) = R_e + h(t) \approx R_e \), where \( R_e \) is the radius of earth. In this case the force is effectively constant since \( h \ll R_e \). Newton’s equation says the acceleration is constant,

\[
\frac{d^2 h(t)}{dt^2} = \frac{GmM}{R_e^2},
\]

but different from Galileo’s. Yet it seems clear that the physics behind Newton’s formula for the acceleration \( a(t) \) of two large masses (sun and earth, or earth and moon) and Galileo’s physics for balls rolling down inclined planes, is the same. The difference is that Newton’s proportionality constant is a significant generalization of Galileo’s. But other than the constant, which defines the acceleration, the two formulae are the same.

This book is not a typical mathematics book; rather, it is about the relation of math to physics, presented roughly in chronological order, via their history. To teach mathematical physics in an orderly way, our treatment requires a step backwards in terms of the mathematics, but a step forward in terms of the physics. Historically speaking, mathematics was created by individuals such as Galileo who, by modern standards, may be viewed as engineers. This book contains the basic information that a well-informed engineer needs to know.

I feel that while there are similarities between this book and that of Graham et al. (1994), the differences are notable. First, Concrete Mathematics presents an impossible standard to be measured against. Second, Graham et al. is clearly a math book, brilliantly written and targeted at computer science students. The present volume is not strictly a math book, but a mathematical-physic s text. I would like to believe there are similarities in 1) the broad range of topics, 2) the in-depth discussion and 3) the use of historical context.

The presentation is broken down around three streams, presented as five chapters: 1) Introduction, 2) Number Systems, 3) Algebra Equations, 4) Scalar Calculus, and 5) Vector Calculus. The material is delivered as 42 “Lectures,” spread out over a semester of 15 weeks, 3 lectures per week, with a three-lecture time-out for administrative duties. Eleven problem sets are provided for weekly assignments. Once the assignments are turned in, each student is given the solution.

Many students have rated these assignments as the most important part of the course. There is a built-in interplay between these assignments and the lectures. On many occasions I solved the problems in class, as motivation to come to every class.

There are four exams, one at the end of each of the three sections, plus the final. The first exam is in class, two others and the final are evening exams. Each exam and assignment is a \( \LaTeX \) file, with solutions encoded with a one-line software switch. When the exam is returned by the student, the full solution is provided, while the exam is fresh in the students mind, providing a teaching moment. The exams are entirely based on the assignments. It is my philosophy that, in principle, the students can see the exam in advance of taking it. In a real sense they do, since each exam is based on the assignments.

**Author’s Personal Statement**

An expert is someone who has made all possible mistakes in a small field. I don’t know if I would be called an expert, but I certainly have made my share of mistakes. I openly state that I love making mistakes, because I learn so much from them. One might call that the “expert’s corollary.”

This book has been written out of both my love for the topic of mathematical physics, and a desire to share many key concepts, and many new ideas about these basic concepts. Over the years I have developed a certain physical sense of math, along with a related mathematical sense of physics. While doing my research,\(^2\) I have come across what I feel are certain conceptual holes that need filling, and sense many deep relationships between math and physics that remain unidentified. While what we presently teach is not wrong, it is missing these relationships. What is lacking is an intuition for how

\(^2\) https://auditorymodels.org/index.php/Main/Publications
Figure 1: There is a natural symbiotic relationship between Mathematics, Engineering, and Physics (MEP), depicted in the Venn diagram. Mathematics provides the method and rigor. Engineering transforms the method into technology. Physics explores the boundaries. While these three disciplines work well together, there is poor communication, in part due to the different vocabulary. But style may be more at issue. For example, mathematics rarely uses a system of units, whereas physics and engineering depend critically on them. Mathematics strives to abstract the ideas into proofs. Physics rarely uses a proof. When they attempt rigor, physicists and engineers typically get into difficulty. An important observation by Felix Klein about pure mathematicians, regarding the unavoidable inaccuracies in physics: “It may be said that the idea [of inaccuracy] is usually so repulsive to them [mathematicians] that its recognition sooner or later spoils their interest in natural science.” (Condon and Morse, 1929, p. 19)

math “works.” Good scientists “listen” to their data. In the same way we need to start listening to the language of mathematics. We need to let mathematics guide us toward our engineering goals.

As summarized in Fig. 1, this marriage of math, engineering and physics (MEP) will help us make progress in understanding the physical world. We must turn to mathematics and physics when trying to understand the universe. My views follow from a lifelong attempt to understand human communication, i.e., the perception and decoding of human speech sounds. This research arose from my 32 years at Bell Labs in the Acoustics Research Department. There such lifelong pursuits were not only possible, they were openly encouraged. The idea was that if you are successful at something, take it as far as you can, but on the other hand you should not do something well that’s not worth doing. People got fired for the latter. I should have left for a university after a mere 20 years, but the job was just too cushy.

In this text it is my goal to clarify conceptual errors while telling the story of physics and mathematics. My views have been inspired by classic works, as documented in the bibliography. This book was inspired by my reading of Stillwell (2002), through Chapter 21 (Fig. 2, p. 12). Somewhere in Chapter 22 I switched to the third edition (Stillwell, 2010), at which point I realized I had much more to master. It became clear that by teaching this material to first year engineers, I could absorb the advanced material at a reasonable pace. This book soon followed.

Summary

This is foremost a math book, but not the typical math book. First, this book is for the engineering minded, for those who need to understand math to do engineering, to learn how things work. In that sense the book is more about physics and engineering than mathematics. Math skills are essential for making progress in building things, be it pyramids or computers, as clearly shown by the many great civilizations of the Chinese, Egyptians, Mesopotamians, Greeks and Romans.

Second, this is a book about the math that developed to explain physics, to allow people to engineer complex things. To sail around the world one needs to know how to navigate. This requires a model of the planets and stars. You can only know where you are, on earth, once you understand where earth is, relative to the sun, planets, Milky Way and the distant stars. The answer to such a cosmic question depends strongly on who you ask. Who is qualified to answer such a question? It is best answered by those who study mathematics applied to the physical world. The utility and accuracy of that answer depends critically on the depth of understanding of the physics of the cosmic clock.

The English astronomer Edmond Halley (1656–1742) asked Newton (1643–1727) for the equation that describes the orbit of the planets. Halley was obviously interested in comets. Newton immediately

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3 MEP is a focused alternative to STEM.
4 I started around December 1970, fresh out of graduate school, and retired on December 5, 2002.
answered “an ellipse.” It is said that Halley was stunned by the response (Stillwell, 2010, p. 176), as this was what had been experimentally observed by Kepler (c1619), and thus he knew Newton must have some deeper insight. Both were eventually knighted.

When Halley asked Newton to explain how he knew, Newton responded “I calculated it.” But when challenged to show the calculation, Newton was unable to reproduce it. This open challenge eventually led to Newton’s grand treatise, Philosophiae Naturalis Principia Mathematica (July 5, 1687). It had a humble beginning, as a letter to Halley, explaining how to calculate the orbits of the planets. To do this Newton needed mathematics, a tool he had mastered. It is widely accepted that Isaac Newton and Gottfried Leibniz invented calculus. But the early record shows that perhaps Bhāskara II (1114–1185 CE) had mastered the art well before Newton.5

Third, the main goal of this book is to teach motivated engineers mathematics, in a way that it can be understood, mastered and remembered. How can this impossible goal be achieved? The answer is to fill in the gaps with Who did what, and when? Compared with the math, the historical record is easily mastered.

To be an expert in a field, one must know its history. This includes who the people were, what they did, and the credibility of their story. Do you believe the Pope or Galileo on the roles of the sun and the earth? The observables provided by science are clearly on Galileo’s side. Who were those first engineers? They are names we all know: Archimedes, Pythagoras, Leonardo da Vinci, Galileo, Newton, etc. All of these individuals had mastered mathematics. This book presents the tools taught to every engineer. Rather than memorizing complex formulas, make the relations “obvious” by mastering each simple underlying concept.

Fourth, when most educators look at this book, their immediate reactions are: Each lecture is a topic we spend a week on (in our math/physics/engineering class). And: You have too much material crammed into one semester. The first sentence is correct, the second is not. Tracking the students who have taken the course, looking at their grades, and interviewing them personally, demonstrate that the material presented here is appropriate for one semester.6

To write this book I had to master the language of mathematics. I had already mastered the language of engineering, and a good part of physics. One of my secondary goals is to build this scientific Tower of Babel, by unifying the terminology and removing the jargon.

Acknowledgments

Besides thanking my parents, I would like to credit John Stillwell for his constructive, historical summary of mathematics. My close friend and colleague Steve Levinson somehow drew me into this project, without my even knowing it. My brilliant graduate student Sarah Robinson was constantly at my side, grading homeworks and exams, and tutoring the students. Without her, I would never have survived the first semester the material was taught. Her proofreading skills are amazing. Thank you Sarah for your infinite help. Finally I would like to thank John D’Angelo for putting up with my many silly questions. When it comes to the heavy hitting, John was always there to provide a brilliant explanation that I could easily translate into Engineerese (Matheering?) (i.e., engineer language). I also had many valuable comments (good vibrations) from Michael Stone (Physics).

My delightful friend Robert Fossum, emeritus professor of mathematics from the University of Illinois, kindly pointed out flawed mathematical terminology. James (Jamie) Hutchinson’s precise use of the English language dramatically raised the bar on my more than occasionally casual writing style. To each of you, thank you!

Finally I would like to thank my wife Sheau Feng Jeng, aka Patricia Allen, for her unbelievable support and love. She delivered constant peace of mind, without which this project could never have been started, much less finished. Many others played important roles, but they must remain anonymous.5

–Jont Allen, Mahomet IL, Dec. 24, 2015 (Updated Jan 1, 2018)

5http://www-history.mcs.st-and.ac.uk/Projects/Pearce/Chapters/Ch8_5.html
6http://www.istem.illinois.edu/news/jont.allen.html
A contract has been signed with Springer in Dec, 2018. Hopefully this book will see the light of day some time in 2019.

–Jont Allen, Mahomet IL, Dec. 20, 2018
Mathematics and its History (Stillwell, 2002)

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Figure 2: Table of contents of Stillwell (2002)
Preface

It is widely acknowledged that interdisciplinary science is the backbone of modern scientific inquiry as embodied in the STEM (Science, Technology, Engineering, and Mathematics) programs. Cross-disciplinary research is about connecting different areas of knowledge. However, while STEM is being taught, interdisciplinary science is not, due to its inherent complexity and breadth. There are few people to teach it. As diagrammed in Fig. 1 (p. 9), Mathematics, Engineering and Physics (MEP) define the core of these studies.

STEM vs. MEP

Mathematics is about rigor. Mathematicians specifically attend to the definitions of increasingly general concepts. Thus mathematics advances slowly, as these complex definitions must be collectively agreed upon. Since it embraces rigor, mathematics shuns controversy. Engineering addresses the advancement of technology. Engineers, much like mathematicians, are uncomfortable with uncertainty, but are trained to deal with it. Physics explores the fringes of uncertainty, since physicists love controversy. Richard Hamming expressed this thought succinctly:

Great scientists tolerate ambiguity very well. They believe the theory enough to go ahead; they doubt it enough to notice the errors and faults so they can step forward and create the new replacement theory. (Hamming, 1986)

To create an interdisciplinary STEM program, the MEP core is critical. In my view, this core should be based on mathematics, from the historical perspective, starting with Euclid or before (i.e., Chinese mathematics), up to modern information theory and logic. As a bare minimum, the fundamental theorems of mathematics (arithmetic, algebra (real, complex and matrix), calculus (real, complex and matrix) etc.) should be taught to every MEP student. The core of this curriculum is outlined in Fig. 1.1 (p. 26). Again quoting Hamming:

Well, that book I’m trying to write [on Mathematics, Calculus, Probability and Statistics] says clearly . . . we can no longer tell you what mathematics you need, we must teach you how to find it for yourself. . . . We must give up the results, and teach the methods. You are only shown finished theorems and proofs. That is just plain wrong for teaching.

If first year students are taught a common MEP methodology and vocabulary, presented in terms of the history of mathematics, they will be equipped to

1. Exercise interdisciplinary science (STEM), and
2. Communicate with other MEP trained (STEM) students and professors.

The goal should be a comprehensive understanding of the fundamental concepts of mathematics, defined in terms of the needs of the student. The goal should not be drilling on surface integrals, at least not in the first year. As suggested by Hamming, these details must be self-taught, at the time they are needed. Furthermore, start with the students who place out of early math courses: they love math and are highly motivated to learn as much as possible. I contend that if first or second year students are given a comprehensive early conceptual understanding, they will end up at the top of their field.
There is a second insightful view into this problem, that relates to STEM teaching to young women. Barbra Oakley points out that test results suggest that women are more equipped than men to deal with basics such as reading and writing.

A large body of research has revealed that boys and girls have, on average, similar abilities in math. But girls have a consistent advantage in reading and writing and are often relatively better at these than they are at math, even though their math skills are as good as the boys.

The argument goes that rather than compete with the boys the girls move into their easier alternative, away from STEM. As a result, we are losing a large talented population of young women (girls) in the STEM area. This is not in the best interest of the sciences, or the girls.

As identified by Hamming, a key problem is the traditional university approach, a five to eight semester sequence of: Calc I, II, III, Linear Algebra IV, DiffEq V, Real analysis VI, Complex analysis VII and given near-infinite stamina, Number theory VIII, over a time frame of three or more years (six semesters). This was the way I learned math. The process simply took too long, and the concepts spread too thin. After following this regime, I felt I had not fully mastered the material, so I started over. I consider myself to be largely self-taught.

We need a more effective teaching method. I am not suggesting we replace the standard six semester math curriculum of Calc I, II, III, etc. Rather, I am suggesting a broad unified introduction to all these topics, based on an historical approach. The present approach is driving the talent away from science and mathematics by focusing too much on the details (as clearly articulated by Hamming). One needs more than a high school education to succeed in college engineering courses. The key missing element in our present education system is teaching critical thought. Drilling facts does not do that.

By learning mathematics in the context of history, the student will fully and easily appreciate the underlying concepts. The history provides a uniform terminology for understanding the fundamentals of MEP. The present teaching method, using abstract proofs, with no (or few) figures or physical principles and units, by design, removes the intuition and motivation that were available to the creators of these fundamentals. The present six-semester regime serves many students poorly, leaving them with little insight (i.e., intuition) and an aversion to mathematics.

Postscript Dec 5, 2017 How to cram five semesters of math into one semester, and leave the students with something they can remember? Here are some examples:

Maxwell’s equations (MEs) are a fundamental challenging topic, presented in one lecture (Section 5.6, p. 225). Here is how it works:

1. The development starts with Sections 4.2-4.5.3 (pp. 146-176), which develop complex integration (p. 147) and the Laplace transform (pp. 165-175).

2. Kennelly’s 1893 complex impedance, a key extension of Ohm’s law, is the ratio of the force over the flow, the key elements being 1) capacitance (e.g., compliance) per unit area ($\epsilon_o$ [F/dm$^2$]), and 2) inductance (e.g., mass) per unit area ($\mu_o$ [H/m$^2$]).

3. Section 5.1 (p. 183) develops analytic field theory, while Sect. 5.1.1 (p. 185) introduces Grad $\nabla \cdot (\cdot)$, Div $\nabla \cdot (\cdot)$, and Curl $\nabla \times (\cdot)$, starting from the scalar $A \cdot B$ and vector product $A \times B$ of two vectors.

4. On p. 222, second-order operators are introduced and given physical meanings (based on the physics of fluids), but most important they are given memorable names (DoC, CoG, Dog, God, and CoC: p. 185). Thanks to this somewhat quaint and gamy innovation, the students can both understand and easily remember the relationships between these confusing second-order vector calculus operations.

5. Exercises and examples are interspersed throughout the lectures.

The foregoing carefully sets the stage for ME (p. 225), introduced using proper names and units of the electrical and magnetic field intensity (strengths, and forces seen by charge) \( E, H \), and electric and magnetic flux (flow) \( \mathbf{D}, \mathbf{B} \), as summarized on page 225. The meanings of ME equations are next explored in integral form (p. 218). After Sect. 5.1.1-5.6, the students are fully conversant with MEs. The confirmation of this is in the final exam grade distributions.

Postscript Dec 15, 2017

As this book comes to completion, I’m reading and appreciating the Feynman lectures. We all know (I hope you know) that Feynman had a special lecture style that was both entertaining and informative. His communication skill was a result of his depth of understanding, and he was not afraid to question the present understanding of physics. He was always on a quest. He died in 1988 at the age of 70. Let us all be on his quest. Any belief that we have figured out the ways of the universe is absurd. We have a lot to learn. Major errors in our understanding must be corrected. We cannot understand the world around us until we understand its creation. That is, we cannot understand where we are going until we understand where we came from.

– Jont Allen
Chapter 1

Introduction

Much of early mathematics dating before 1600 BCE centered around the love of art and music, due to the sensations of light and sound. Our psychological senses of color and pitch are determined by the frequencies (i.e., wavelengths) of light and sound. The Chinese and later the Pythagoreans are well known for their early contributions to music theory. We are largely ignorant of exactly what the Chinese scholars knew. The best record comes from Euclid, who lived in the 3rd century, after Pythagoras. Thus we can only trace the early mathematics back to the Pythagoreans in the 6th century (580-500 BCE), which is centered around the Pythagorean theorem and early music theory.

Pythagoras strongly believed that “all is number,” meaning that every number, and every mathematical and physical concept, could be explained by integral (integer) relationships, mostly based on either ratios, or the Pythagorean theorem. It is likely that his belief was based on Chinese mathematics from thousands of years earlier. It is also believed that his ideas about the importance of integers followed from the theory of music. The musical notes (pitches) obey natural integral ratio relationships, based on the octave (a factor of two in frequency). The western 12-tone scale breaks the octave into 12 ratios. Today this has been rationalized to be the 12 root of 2, which is approximately equal to 18/17. This innate sense of frequency ratios comes from the physiology of the auditory organ (the cochlea) which represents a fix distance along the Organ of Corti, the sensory organ of the inner ear.

As acknowledged by Stillwell (2010, p. 16), the Pythagorean view is relevant today:

> With the digital computer, digital audio, and digital video coding everything, at least approximately, into sequences of whole numbers, we are closer than ever to a world in which “all is number.”

1.1 Early Science and Mathematics

While early Asian mathematics has been lost, it clearly defined the course for math for at least several thousand years. The first recorded mathematics were those of the Chinese (5000-1200 BCE) and the Egyptians (3,300 BCE). Some of the best early records were left by the people of Mesopotamia (Iraq, 1800 BCE). While the first 5,000 years of math are not well documented, but the basic record is clear, as outlined in Fig. 1.1 (p. 19).

Thanks to Euclid, and later Diophantus (c250 CE), we have some basic (but vague) understanding of Chinese mathematics. For example, Euclid’s formula (Eq. 2.11, p. 59) provides a method for computing Pythagorean triplets, a formula believed to be due to the Chinese (Stillwell, 2010, pp. 4-9). Chinese bells and stringed musical instruments were exquisitely developed with tonal quality, as documented by ancient physical artifacts (Fletcher and Rossing, 2008). In fact this development was so rich that one must ask why the Chinese failed to initiate the industrial revolution. Specifically, why

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1See Fig. 2.8, p. 60.
2One might reasonably view Euclid’s role as that of a mathematical messenger.
did Europe eventually dominate with its innovation when it was the Chinese who did the extensive early invention?

It could have been for the wrong reasons, but perhaps our best insight into the scientific history from China may have come from an American chemist and scholar from Yale, Joseph Needham, who learned to speak Chinese after falling in love with a Chinese woman, and ended up researching early Chinese science and technology for the US government.

According to Lin (1995) this is known as the Needham question:

“Why did modern science, the mathematization of hypotheses about Nature, with all its implications for advanced technology, take its meteoric rise only in the West at the time of Galileo[; but] had not developed in Chinese civilization or Indian civilization?”

Needham cites the many developments in China:

“Gunpowder, the magnetic compass, and paper and printing, which Francis Bacon considered as the three most important inventions facilitating the West’s transformation from the Dark Ages to the modern world, were invented in China.” (Lin, 1995)

“Needham’s works attribute significant weight to the impact of Confucianism and Taoism on the pace of Chinese scientific discovery, and emphasize what it describes as the ‘diffusionist’ approach of Chinese science as opposed to a perceived independent inventiveness in the western world. Needham held that the notion that the Chinese script had inhibited scientific thought was ‘grossly overrated’” (Grosswiler, 2004).

Lin was focused on military applications, missing the importance of non-military contributions. A large fraction of mathematics was developed to better understand the solar system, acoustics, musical instruments and the theory of sound and light. Eventually the universe became a popular topic, as it still is today.

Regarding the “Needham question,” I suspect the resolution is now clear. In the end, China withdrew itself from its several earlier expansions, based on internal politics (Menzies, 2004, 2008).

**Chronological history pre 16th century**

<table>
<thead>
<tr>
<th>Period</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>20th BCE</td>
<td>Chinese (Primes; quadratic equation; Euclidean algorithm (GCD))</td>
</tr>
<tr>
<td>18th BCE</td>
<td>Babylonia (Mesopotamia/Iraq) (quadratic equation)</td>
</tr>
<tr>
<td>6th BCE</td>
<td>Pythagoras (Thales) and the Pythagorean “tribe”</td>
</tr>
<tr>
<td>4th BCE</td>
<td>Euclid (quadratic equation); Archimedes</td>
</tr>
<tr>
<td>3rd BCE</td>
<td>Eratosthenes 276-194BCE</td>
</tr>
<tr>
<td>3rd CE</td>
<td>Diophantus c250CE</td>
</tr>
<tr>
<td>4th</td>
<td>Alexandria Library destroyed 391CE</td>
</tr>
<tr>
<td>6th</td>
<td>Brahmagupta (negative numbers; quadratic equation) 598-670CE</td>
</tr>
<tr>
<td>10th</td>
<td>al-Khwārizmī (algebra) 830CE Hasan Ibn al-Haytham (Alhazen) 965-1040CE</td>
</tr>
<tr>
<td>12th</td>
<td>Bhaskara (calculus) 1114-1183 Marco Polo 1254-1324</td>
</tr>
<tr>
<td>15th</td>
<td>Leonardo da Vinci 1452-1519; Michelangelo 1475-1564 Copernicus 1473-1543</td>
</tr>
<tr>
<td>16th</td>
<td>Tartaglia (cubic eqs); Bombelli 1526-1572 Galileo Galilei 1564-1642</td>
</tr>
</tbody>
</table>

### 1.1.1 Lec 1: The Pythagorean theorem

Thanks to Euclid’s *Elements* (c323 BCE) we have an historical record, tracing the progress in geometry, as established by the Pythagorean theorem, which states that *for any right triangle* having sides of

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1.1. EARLY SCIENCE AND MATHEMATICS

Figure 1.1: Mathematical timeline between 1500 BCE and 1650 CE. The western renaissance is considered to have occurred between the 15th and 17th centuries. However, the Asian “renaissance” was likely well before the 1st century (i.e., 1500 BCE). There is significant evidence that a Chinese ‘treasure ship’ visited Italy in 1434, initiating the Italian renaissance (Menzies, 2008). This was not the first encounter between the Italians and the Chinese, as documented in ‘The travels of Marco Polo’ (c1300 CE).

lengths \((a, b, c) \in \mathbb{R}\) that are either positive real numbers, or more interesting, integers \(c > [a, b] \in \mathbb{N}\) such that \(a + b > c\),

\[c^2 = a^2 + b^2.\] (1.1)

Early integer solutions were likely found by trial and error rather than by an algorithm.

If \(a, b, c\) are lengths, then \(a^2, b^2, c^2\) are each the area of a square. Equation 1.1 says that the area \(a^2\) plus the area \(b^2\) equals the area \(c^2\). Today a simple way to prove this is to compute the magnitude of the complex number \(c = a + bj\), which forces the right angle

\[|c|^2 = (a + bj)(a - bj) = a^2 + b^2.\] (1.2)

However, complex arithmetic was not an option for the Greek mathematicians, since complex numbers and algebra had yet to be discovered.

Almost 700 years after Euclid’s Elements, the Library of Alexandria was destroyed by fire (391 CE), taking with it much of the accumulated Greek knowledge. As a result, one of the best technical records remaining is Euclid’s Elements, along with some sparse mathematics due to Archimedes (c300 BCE) on geometrical series, computing the volume of a sphere, the area of the parabola, and elementary hydrostatics. In c1572 a copy Diophantus’s Arithmetic was discovered by Bombelli in the Vatican library (Stillwell, 2010, p. 51). This book became an inspiration for Galileo, Descartes, Fermat and Newton.

**Early number theory:** Well before Pythagoras, the Babylonians (c1,800 BCE) had tables of triplets of integers \([a, b, c]\) that obey Eq. 1.1, such as \([3, 4, 5]\). However, the triplets from the Babylonians were larger numbers, the largest being \(a = 12709, c = 18541\). A stone tablet (Plimpton-322) dating back to 1800 BCE (Fig. 2.8, p. 60) was found with integers for \([a, c]\). Given such sets of two numbers, which determined a third positive integer \(b = 13500\) such that \(b = \sqrt{c^2 - a^2}\), this table is more than convincing that the Babylonians were well aware of *Pythagorean triplets* (PTs), but less convincing that they had access to Euclid’s formula, a formula for PTs. (Eq. 2.11 p. 59).

It seems likely that Euclid’s Elements was largely the source of the fruitful era due to the Greek mathematician Diophantus (215-285) (Fig. 1.1), who developed the field of *discrete mathematics* now known as *Diophantine analysis*. The term means that the solution, not the equation, is integer. The work of Diophantus was followed by fundamental change in mathematics, possibly leading to the development of algebra, but at least including the discovery of

1. negative numbers,
2. quadratic equation (Brahmagupta, 7th CE),
3. algebra (al-Khwārizmī, 9th CE), and
4. complex arithmetic (Bombelli, 15th CE).
CHAPTER 1. INTRODUCTION

These discoveries overlapped with the European middle (aka, dark) ages. While Europe went “dark,” presumably European intellectuals did not stop working during these many centuries.

1.1.2 What is mathematics?

It seems strange when people complain they “can’t learn math,” but then claim to be good at languages. Pre-high-school students tend to confuse arithmetic with math. One does not need to be good at arithmetic to be good at math (but it doesn’t hurt).

Math is a language, with the symbols taken from various languages, not so different from other languages. Today’s mathematics is a written language with an emphasis on symbols and glyphs, biased toward Greek letters, obviously due to the popularity of Euclid’s Elements. The specific evolution of these symbols is interesting (Mazur, 2014). Each symbol is dynamically assigned a meaning, appropriate for the problem being described. These symbols are then assembled to make sentences. It is similar to Chinese in that the spoken and written versions are different across dialects. Like Chinese, the sentences may be read out loud in any language (dialect), while the mathematical sentence (like Chinese characters) is universal.

Learning languages is an advanced social skill. However, the social outcomes of learning a language and math are very different. First learning a new language is fun because it opens doors to other cultures. Second math is different due to the rigor of the rules of the language, along with the way it is taught (e.g., not as a language). A third difference between math and language is that math evolved from physics, with important technical applications.

Like any language, the more mathematics you learn, the easier it is to understand, because mathematics is built from the bottom up. It’s a continuous set of concepts, much like the construction of a house. If you try to learn calculus and differential equations, while skipping simple number theory, the lessons will be more difficult to understand. You will end up memorizing instead of understanding, and as a result you will likely forget it. When you truly understand something, it can never be forgotten. A nice example is the solution to a quadratic equation: If you learn how to complete the square (p. 75), you will never forget the quadratic formula.

The topics need to be learned in order, just as in the case of building the house. You can’t build a house if you don’t know about screws or cement (plaster). Likewise in mathematics, you will not learn to integrate if you have failed to understand the difference between integers, complex numbers, polynomials, and their roots.

A short list of topics for mathematics is numbers (\( \mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{I}, \mathbb{C} \)), algebra, derivatives, anti-derivatives (i.e., integration), differential equations, vectors and the spaces they define, matrices, matrix algebra, eigenvalues and vectors, solutions of systems of equations, matrix differential equations and their eigen-solution. Learning is about understanding, not memorizing.

The rules of mathematics are formally defined by algebra. For example, the sentence \( a = b \) means that the number \( a \) has the same value as the number \( b \). The sentence is spoken as “a equals b.” The numbers are nouns and the equal sign says they are equivalent, playing the role of a verb, or action symbol. Following the rules of algebra, this sentence may be rewritten as \( a - b = 0 \). Here the symbols for minus and equal indicate two types of actions (verbs).

Sentences can become arbitrarily complex, such as the definition of the integral of a function, or a differential equation. But in each case, the mathematical sentence is written down, may be read out loud, has a well-defined meaning, and may be manipulated into equivalent forms following the rules of algebra and calculus. This language of mathematics is powerful, with deep consequences, first known as algorithms, but eventually as theorems.

The writer of an equation should always translate (explicitly summarize the meaning of the expression), so the reader will not miss the main point, as a simple matter of clear writing.

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4It would be interesting to search the archives of the monasteries, where the records were kept, to determine exactly what happened during this religious blackout.

5“it looks like Greek to me.”
1.1. EARLY SCIENCE AND MATHEMATICS

Just as math is a language, so language may be thought of as mathematics. To properly write correct English it is necessary to understand the construction of the sentence. It is important to identify the subject, verb, object, and various types of modifying phrases. Look up the interesting distinction between *that* and *which*.\(^5\) Thus, like math, language has rules. Most individuals use what “sounds right,” but if you’re learning English as a second language, it is necessary to understand the rules, which are arguably easier to master than the foreign speech sounds.

Context is everything, and the most important context is physics. Without a physical problem to solve, there can be no mathematics. People wanted to navigate the earth, and weigh things. This required an understand of gravity. Many questions about gravity were deep, such as “Where is the center of the universe?” Actually this answer is simple: Ask the Pope and he will tell you. But church dogma only goes so far. Mathematics, along with a heavy dose of physics, finally answered this huge question. Someone needed to perfect the telescope, and put satellites into space, and view the cosmos. Without mathematics none of this would have happened.

1.1.3 Early physics as mathematics: Back to Pythagoras

There is a second answer to the question What is mathematics? The answer comes from studying its history, which starts with the earliest record. This chronological view starts, of course, with the study of numbers. First there is the taxonomy of numbers. It took thousands of years to realize that numbers are more than the counting numbers \(\mathbb{N}\), and to create a symbol for nothing (i.e., zero), and to invent negative numbers. With the invention of the abacus, a memory aid for the manipulation of complex sets of real integers, one could do very detailed calculations. But this required the discovery of *algorithms* (procedures) to add, subtract, multiply (many adds of the same number) and divide (many subtracts of the same number), such as the *Euclidean algorithm*. Eventually it became clear to the experts (early mathematicians) that there were natural rules to be discovered, thus books (e.g., Euclid’s *Elements*) were written to summarize this knowledge.

The role of mathematics is to summarize algorithms (i.e., sets of rules), and formalize the idea as a theorem. Pythagoras and his followers, the Pythagoreans, believed that there was a fundamental relationship between mathematics and the physical world. The Pythagoreans may have been the first to capitalize on the relationship between science and mathematics, to use mathematics to design things for profit.\(^7\) This may have been the beginning of capitalizing technology (i.e., engineering), based on the relationship between physics and math. This impacted commerce in many ways, such as map making, tools, implements of war (the wheel, gunpowder), art (music), water transport, sanitation, secure communication, food, etc. Of course the Chinese were the first to master many of these technologies.

Why is Eq. 1.1 called a *theorem*? Theorems require a proof. What exactly needs to be proved? We do not need to prove that \((a, b, c)\) obey this relationship, since this is a condition that is observed. We do not need to prove that \(a^2\) is the area of a square, as this is the definition of an area. What needs to be proved is that the relation \(c^2 = a^2 + b^2\) holds if, and only if, the angle between the two shorter sides is 90°. The Pythagorean theorem (Eq. 1.1) did not begin with Euclid or Pythagoras, rather they appreciated its importance, and documented its proof.

In the end the Pythagoreans, who instilled fear in the neighborhood, were burned out, and murdered, likely the fate of mixing technology with politics:

> “Whether the complete rule of number (integers) is wise remains to be seen. It is said that when the Pythagoreans tried to extend their influence into politics they met with popular resistance. Pythagoras fled, but he was murdered in nearby Mesopotamia in 497 BCE.”

—Stillwell (2010, p. 16)

\(^{5}\)https://en.oxforddictionaries.com/usage/that-or-which

\(^{7}\)It seems likely that the Chinese and Egyptians also did this, but it is more difficult to document.
1.2 Modern mathematics is born

Modern mathematics (what we practice today) was born in the 15-16th centuries, in the minds of Leonardo da Vinci, Bombelli, Galileo, Descartes, Fermat, and many others (Stillwell, 2010). Many of these early masters were, like the Pythagoreans, secretive to the extreme about how they solved problems. This soon changed due to Galileo, Mersenne, Descartes and Newton, causing mathematics to blossom. The developments during this time may seemed hectic and disconnected. But this is a wrong impression, as the development was dependent on new technologies such as the telescope (optics) and more accurate time and frequency measurements, due to Galileo’s studies of the pendulum, and a better understanding of the relation $f \lambda = c_0$ between frequency $f$, wavelength $\lambda$ and the wave speed $c_0$.

Chronological history: 16th to 19th centuries

<table>
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<th>1750</th>
<th>1800</th>
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<tbody>
<tr>
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<td>Newton</td>
<td>Gauss</td>
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<tr>
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<td>1667</td>
<td>1856</td>
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<tr>
<td>Galileo</td>
<td>Jacob Bernoulli</td>
<td>Mozart</td>
<td></td>
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<tr>
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<td>1655</td>
<td>1756</td>
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</tr>
<tr>
<td>Fermat</td>
<td>Johann Bernoulli</td>
<td>Beethoven</td>
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<td>1667</td>
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<tr>
<td>Descartes</td>
<td>Daniel Bernoulli</td>
<td>d’Alembert</td>
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<tr>
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</tbody>
</table>

Figure 1.2: Timeline for the development of the theory of calculus, between 16th and 19th CE. Given the timeline, it seems likely that Bombelli’s discovery of Diophantus’s book “Arithmetic” in the Vatican library triggered many of the ideas presented by Galileo, Descartes and Fermat, followed by others (i.e., Newton). Bombelli’s discovery might be considered as a magic moment in mathematics. The vertical red lines indicate mentor-student relationships. Mozart and Beethoven are shown as landmarks. Related timelines include (see index): Fig. 1.1 (p. 19) which gives the timeline from 1500 BCE to 1650 CE; Fig. 3.1 (p. 71) presents the 17-20 CE (Newton–Einstein) view from 1640–1950; Fig. 3.2 (p. 110) presents the period from Descartes to Gauss and Cauchy; Fig. 4.1 (p. 144) presents the period from Bombelli to Einstein (1525-1925).

1.2.1 Science meets mathematics

Galileo: In 1589 Galileo famously conceptualized an experiment where he suggested dropping two different weights from the Leaning Tower of Pisa, and he suggested that they must take the same time to hit the ground.

Conceptually this is a mathematically sophisticated experiment, driven by a mathematical argument in which he considered the two weights to be connected by an elastic cord (a spring). His studies resulted in the concept of conservation of energy, one of the cornerstones of physical theory since that time.

Being joined with an elastic cord, the masses become one. If the velocity were proportional to the mass, as believed by Archimedes, the sum of the two weights would necessarily fall even faster. This results in a logical fallacy: How can two masses fall faster than either? This also violates the concept of conservation of energy, as the total energy of two masses would be greater than that of the parts. In fact Galileo’s argument may have been the first time that the principle of conservation of energy was clearly stated.

It seems likely that Galileo was attracted to this model of two masses connected by a spring because he was also interested in planetary motion, which consist of masses (sun, earth, moon), also mutually attracted by gravity (i.e., the spring).

Galileo also performed related experiments on pendulums, where he varied the length $l$, mass $m$, and angle $\theta$ of the swing. By measuring the period (periods/unit time) he was able to formulate precise rules between the variables. This experiment also measured the force exerted by gravity, so the experiments were related, but in very different ways. The pendulum served as the ideal clock, as it needed very little energy to keep it going, due to its very low friction (energy loss).  

8http://muse.tau.ac.il/museum/galileo/pendulum.html
1.2. MODERN MATHEMATICS IS BORN

In a related experiment, Galileo measured the duration of a day by counting the number of swings of the pendulum in 24 hours, measured precisely by the daily period of a star as it crossed the tip of a church steeple. The number of seconds in a day is $24 \times 60 \times 60 = 86400 = 2^73^35^2 \text{[s/day]}$. Since 86,400 is the product of the first three primes, it is highly composite, and thus may be reduced in many equivalent ways. For example, the day can be divided evenly into 3, 5 or 6 parts, and remain exact in terms of the number of seconds that transpire. Factoring the number of days in a year ($365=5*73$) is not useful, since it may not be decomposed into many small primes. Galileo also extended work on the relationship of wavelength and frequency of a sound wave in musical instruments. On top of these impressive accomplishments, Galileo greatly improved the telescope, which he needed for his observations of the planets.

Many of Galileo’s contributions resulted in new mathematics, leading to Newton’s discovery of the wave equation (c1687), followed 60 years later by its one-dimensional general solution by d’Alembert (c1747).

Mersenne: Marin Mersenne (1588–1648) also contributed to our understanding of the relationship between the wavelength and the dimensions of musical instruments, and is said to be the first to measure the speed of sound. At first Mersenne strongly rejected Galileo’s views, partially due to errors in Galileo’s reports of his results. But once Mersenne saw the significance of Galileo’s conclusion, he became Galileo’s strongest advocate, helping to spread the word (Palmerino, 1999).

This incident invokes an important theorem of nature: Is data more like bread or wine? The answer is, it depends on the data. Galileo’s original experiments on pendulums and ball falling down slopes, were flawed by inaccurate data. This is likely because he didn’t have good clocks. But he soon solved that problem and the data became more accurate. We don’t know if Mersenne repeated Galileo’s experiments, and then appreciated his theory, or if he communicated with Galileo. But resolution was that the early data were like bread (it rots), but when the experimental method was improved, with a better clock, the corrected data was like wine (which gets better with age). Galileo claimed that the time for the mass to drop a fixed distance was exactly proportional to the square of the time. This expression lead to $F = ma$. One follows from the other. If the mass varies then you get Newton’s second law of motion (Eq. 3.2, p. 72).

He was also a decent mathematician, inventing (1644) the Mersenne primes (MP) $\pi_m$ of the form

$$\pi_m = 2^{\pi_k} - 1,$$

where $\pi_k (k < m)$ denotes the $k$th prime (p. 34). As of Dec 2018 51 MPs are known. The first MP is $3 = \pi_2 = 2^{\pi_1} - 1$, and the largest known prime is a MP. Note that $127 = \pi_{31} = 2^{77} - 1$ is the MP of the MP $\pi_7$.

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9For example, if the year were $364 = 2^2 \cdot 7 \cdot 13$ days, it would would make for shorter years (by 1 day), 13 months per year (e.g., $28 = 2 \cdot 2 \cdot 7$ day vacation per year?), perfect quarters, and exactly 52 week. Every holiday would always fall on the same day, every year.

10http://mathworld.wolfram.com/MersennePrime.html
**CHAPTER 1. INTRODUCTION**

**Newton:** With the closure of Cambridge University due to the plague of 1665, Newton returned home to Woolsthorpe-by-Colsterworth (95 [mi] north of London), to work by himself for over a year. It was during this solitary time that he did his most creative work.

While Newton (1642–1726) may be best known for his studies on light, he was the first to predict the speed of sound. However, his theory was in error\(^{11}\) by \(\sqrt{c_p/c_v} = \sqrt{\frac{1}{1.4}} = 1.183\). This famous error would not be resolved for 140 years, awaiting the formulation of thermodynamics and the equi-partition theorem by Laplace in 1816.\(^{12}\)

Just 11 years prior to Newton’s 1687 *Principia*, there was a basic understanding that sound and light traveled at very different speeds, due to the experiments of Ole Rømer.\(^{13,14}\)

Ole Rømer first demonstrated in 1676 that light travels at a finite speed (as opposed to instantaneously) by studying the apparent motion of Jupiter’s moon Io. In 1865, James Clerk Maxwell proposed that light was an electromagnetic wave, and therefore traveled at the speed \(c_o\), appearing in his theory of electromagnetism.\(^{15}\)

The idea behind Rømer’s discovery was that due to the large distance between Earth and Io, there was a difference between the period of the moon when Jupiter was closest to Earth vs. when it was farthest from Earth. This difference in distance caused a delay or advance in the observed eclipse of Io as it went behind Jupiter, delayed by the difference in time due to the difference in distance. It is like watching a video of a clock, delayed or sped up. When the video is slowed down, the time will be inaccurate (it will indicate an earlier time).

**Studies of vision and hearing:** Since light and sound (music) played such a key role in the development of the early science, it was important to fully understand the mechanism of our perception of light and sound. There are many outstanding examples where physiology impacted mathematics. Leonardo da Vinci (1452–1519) is well known for his early studies of the human body. Exploring our physiological senses requires a scientific understanding of the physical processes of vision and hearing, first considered by Newton (1687) (1643–1727), but first properly researched much later by Helmholtz (Stillwell, 2010, p. 261). Helmholtz’s (1821–1894) studies and theories of music and the perception of sound are fundamental scientific contributions (Helmholtz, 1863a). His best known mathematical contribution is today known as the *fundamental theorem of vector calculus*, or simply *Helmholtz theorem*.

**The amazing Bernoulli family:** The first individual who seems to have openly recognized the importance of mathematics, enough to actually teach it, was Jacob Bernoulli (1654–1705) (Fig. 1.4). Jacob worked on what is now viewed as the standard package of analytic “circular” (i.e., periodic) functions: \(\sin(x)\), \(\cos(x)\), \(\exp(x)\), \(\log(x)\).\(^{16}\) Eventually the full details were developed (for real variables) by Euler (Sections 3.1 p. 92 and ??, p. ??).

From Fig. 1.2 we see that Jacob was contemporary with Descartes, Fermat, and Newton. Thus it seems likely that he was strongly influenced by Newton, who in turn was influenced by Descartes,\(^{17}\) Vié and Wallis (Stillwell, 2010, p. 175).

Jacob Bernoulli, like all successful mathematicians of the day, was largely self-taught. Yet Jacob was in a new category of mathematicians because he was an effective teacher. Jacob taught his sibling Johann (1667–1748), who then taught his sibling Daniel (1700–1782). But most importantly, Johann taught Leonhard Euler (1707–1783) (Figs. 1.2 and 1.4), the most prolific (thus influential) of all mathematicians. This teaching resulted in an explosion of new ideas and understanding. It is most significant

\(^{11}\) The square root of the ratio of the *specific heat capacity* at constant pressure \(c_p\) to that at constant volume \(c_v\).  
\(^{13}\) [https://www.youtube.com/watch?v=b9F8Whn4vf5Y](https://www.youtube.com/watch?v=b9F8Whn4vf5Y)  
\(^{14}\) [https://www.youtube.com/watch?v=rZ0wx3uB2w0](https://www.youtube.com/watch?v=rZ0wx3uB2w0)  
\(^{16}\) The log and tan functions are related by Eq. 4.2 p. 144.  
1.2. MODERN MATHEMATICS IS BORN

Figure 1.4: Above: Jakob Bernoulli (1655–1705) and Johann (1667–1748) Bernoulli. Below: Leonhard Euler (1707–1783) and Jean le Rond d’Alembert (1717–1783). Euler was blind in his right eye, hence the left portrait view. The figure numbers are from Stillwell (2010).
CHAPTER 1. INTRODUCTION

that all four mathematicians published their methods and findings. Much later, Jacob studied with students of Descartes18 (Stillwell, 2010, p. 268-9).

**Euler:** Euler went far beyond all the Bernoulli family (Stillwell, 2010, p. 315). A special strength of Euler was the degree to which he published. First he would master a topic, and then he would publish. His papers continued to appear long after his death (Calinger, 2015). It is also interesting that Leonhard Euler was a contemporary of Mozart (and James Clerk Maxwell of Abraham Lincoln).

**Bach’s mathematics:** It turns out which I need to further document that JS Bach did a mathematical analysis of music. This seems to be about the same time that Euler was writing a book on music theory. Someone please help to fill in these details.19

d’Alembert: Another individual of that time of special note, who also published extensively, was d’Alembert (Fig. 1.4). Some of the most creative ideas were first proposed by d’Alembert. Unfortunately, and perhaps somewhat unfairly, his rigor was criticized by Euler, and later by Gauss (Stillwell, 2010). But once the tools of mathematics were finally openly published, largely by Euler, mathematics grew exponentially.20

Gauss: Figure 4.1 (p. 144) shows the timeline of the most famous mathematicians. It was one of the most creative times in mathematics. Gauss was born at the end of Euler’s long and productive life. I suspect that Gauss owed a great debt to Euler: surely he must have been a scholar of Euler. One of Gauss’s most important achievements may have been his contribution to solving the open question about the density of prime numbers.21

Table 1.1: Three streams followed from Pythagorean theorem: number systems (Stream 1), geometry (stream 2) and infinity (stream 3).

- The Pythagorean theorem is the mathematical spring which bore the three streams.
- Several centuries per stream:

  1) **Numbers:**
  6th BCE $\mathbb{N}$ counting numbers, $\mathbb{Q}$ rationals, $\mathbb{P}$ primes
  5th BCE $\mathbb{Z}$ common integers, $\mathbb{I}$ irrationals
  7th CE zero $\in \mathbb{Z}$

  2) **Geometry:** (e.g., lines, circles, spheres, toroids, . . .)
  17th CE Composition of polynomials (Descartes, Fermat)
  Euclid’s geometry & algebra $\Rightarrow$ analytic geometry
  18th CE Fundamental theorem of algebra

  3) **Infinity:** ($\infty \to$ Sets)
  17-18th CE Taylor series, functions, calculus (Newton, Leibniz)
  19th CE $\mathbb{R}$ real, $\mathbb{C}$ complex 1851
  20th CE Set theory

---

18It seems clear that Descartes was also a teacher.
19https://www.youtube.com/watch?v=6b5MM4x=3aQ, https://www.uchicago.edu/features/combining_math_and_music/
20There are at least three useful exponential scales: Factors of 2, factors of $e \approx 2.7$, and factors of 10. The decibel uses factors of 2 (6 [dB]) and factors of 10 (20 [dB]). Information theory uses powers of 2 (1 [bit]), 4 (2 [bits]). Circuit theory uses factors of both $e$ and 10.
1.2. MODERN MATHEMATICS IS BORN

1.2.2 Three Streams from the Pythagorean theorem

From the outset of his presentation, Stillwell (2010, p. 1) defines “three great streams of mathematical thought: Numbers, Geometry and Infinity” that flow from the Pythagorean theorem, as summarized in Table 1.1. This is a useful concept, based on reasoning not as obvious as one might think. Many factors are in play here. One of these is the strongly held opinion of Pythagoras that all mathematics should be based on integers. The rest are tied up in the long, necessarily complex history of mathematics, as best summarized by the fundamental theorems (Table 2.1, p. 42), each of which is discussed in detail in a relevant chapter. Stillwell’s concept of three streams, following from the Pythagorean theorem, is the organizing principle behind this book:

1. Introduction Section 1 is intended to be a self-contained survey of basic pre-college mathematics, as a detailed overview of the fundamentals, presented as three main streams:
   
   2. Number systems: Stream 1 (p. 33)
   3. Algebraic equations: Stream 2 (p. 71)
   4. Scalar calculus: Stream 3a (p. 143)
   5. Vector calculus: Stream 3b (p. 183)

If you’re a student, stick to these sections.
Sections 2-5 are disorganized research ideas that have not yet found a home. Students, please stay out of these later chapters.

2. Number Systems (Stream 1, p. 271) Some uncertain ideas of number systems, starting with prime numbers, through complex numbers, vectors and matrices.

3. Algebraic Equations (Stream 2, p. ??) Algebra and its development, as we know it today. The theory of real and complex equations and functions of real and complex variables. Complex impedance \( Z(s) \) of complex frequency \( s = \sigma + \omega j \) is covered with some care, developing the topic which is needed for engineering mathematics.


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22https://www.youtube.com/watch?v=gHSv94aTTnk
1.2.3 Exercises NS-1

**Topic of this homework:** Introduction to MATLAB/OCTAVE (see the Matlab or Octave tutorial for help).

Deliverable: Report with charts and answers to questions. Hint: Use \LaTeX.\textsuperscript{23}

**Plotting complex quantities in Octave/Matlab**

**Problem # 1:** Consider the functions \( f(s) = s^2 + 6s + 25 \) and \( g(s) = s^2 + 6s + 5 \).

-\textbf{Q 1.1:} Find the zeros of functions \( f(s) \) and \( g(s) \) using the command \texttt{roots()}.  
\textbf{Solution:} The roots of \( f(s) \) are \(-3 \pm 4i\) (in Matlab: \texttt{roots([1 6 25])}). The roots of \( g(s) \) are \(-1\) and \(-5\) (in Matlab: \texttt{roots([1 6 5])}). You will find the program that generates all these figures at http://jontalle.web.engr.illinois.edu/uploads/298.17/NS1.m

-\textbf{Q 1.2:} Show the roots of \( f(s) \) as red circles and of \( g(s) \) as blue plus signs.

The x-axis should display the real part of each root, and the y-axis should display the imaginary part. Use \texttt{hold on} and \texttt{grid on} when plotting the roots.  
\textbf{Solution:}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{complex_roots.png}
\caption{Complex Roots of \( f(s) \) and \( g(s) \).}
\end{figure}

-\textbf{Q 1.3} Give your figure the title ‘Complex Roots of \( f(s) \) and \( g(s) \)’ Label the x- and y-axis ‘Real Part’ and ‘Imaginary Part.’

Hint: use \texttt{xlabel} and \texttt{ylabel}. Type \texttt{ylim([-10 10])} and \texttt{xlim([-10 10])}, to expand the axes.

**Problem # 2:** Consider the function \( h(t) = e^{2\pi ft} \) for \( f = 5 \) and \( t = [0:0.01:2] \).

-\textbf{Q 2.1:} Use \texttt{subplot} to show the real and imaginary parts of \( h(t) \)

Make two graphs in one figure. Label the x-axes ‘Time (s)’ and the y-axes ‘Real Part’ and ‘Imaginary Part’.

\textbf{Solution:} Breaking \( h(t) \) into real and imaginary parts gives \( e^{j2\pi 5t} = \cos(10\pi t) + j\sin(10\pi t) \).

\textsuperscript{23}http://www.overleaf.com
1.2. MODERN MATHEMATICS IS BORN

–Q 2.2: Use subplot to plot the magnitude and phase parts of $h(t)$.
Use the command angle or unwrap(angle()) to plot the phase. Label the x-axes ‘Time (s)’ and the y-axes ‘Magnitude’ and ‘Phase (radians)’. Solution:

Prime numbers, infinity, etc. in Octave/Matlab

Problem # 1: Prime numbers, infinity, etc.

–Q 1.1: Use the Matlab function factor to find the prime factors of 123, 248, 1767, and 999,999.
Solution: Factors: 123 (3, 41), 248 (2,2,2,31), 1767 (3,19,31), 999999 (3,3,3,7,11,13,37)

–Q 1.2: Use the Matlab function isprime to check if 2, 3 and 4 are prime numbers.
What does the function isprime return when a number is prime, or not prime? Why?
Solution: isprime(2) returns 1, isprime(3) returns 1, and isprime(4) returns 0. 1 means ‘yes’ and 0 means ‘no’

–Q 1.3: Use the Matlab/Octave function primes.m to generate prime numbers between 1 and $10^6$.
Save them in a vector $x$. Plot this result using the command hist(x). Solution:
–Q 1.4: Now try \([n, \text{bincenters}] = \text{hist}(x)\). Use \text{length}(n)\) to find the number of bins. \textbf{Solution:} \text{length}(n)\) is 10

–Q 1.5: Set the number of bins to 100 by using an extra input argument to the function \text{hist}. Show the resulting figure and give it a title and axes labels. \textbf{Solution:} 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{histogram.png}
\caption{Histogram of numbers between 1 and 10^6.}
\end{figure}

\textbf{Problem # 2: Inf, NaN and logarithms in Matlab}

–Q 2.1: Try \(1/0\) and \(0/0\) in the command window. What are the results? What do these ‘numbers’ mean in Matlab? \textbf{Solution:} \(1/0\) returns Inf (infinity) and \(0/0\) returns NaN (‘not a number’).

–Q 2.2: Try \(\log(0)\) in the command window. In Matlab, the natural logarithm \(\ln(\cdot)\) is computed using the function \(\log\) (\(\log_{10}\) and \(\log_2\) are computed using \(\log_{10}\) and \(\log_2\)). \textbf{Solution:} \(\log(0)\) is -Inf

–Q 2.3: Try \(\log(-1)\) in the command window. Do you get what you expect for \(\ln(-1)\)? Show how Matlab arrives at the answer by considering \(-1 = e^{i\pi}\). \textbf{Solution:} \(\log(-1)\) is \(0 + i\pi\), because \(\ln(-1) = \ln(e^{i\pi}) = i\pi \ln(e) = i\pi\)

–Q 2.4: (not graded) What is a decibel? Look up decibels on the internet. \textbf{Solution:} The decibel is very important in engineering (unused in mathematics). It is defined as the log of a power ratio. If a power ratio is 2, the dB value is 6 [dB]. A ratio of 10 is 20
1.2. MODERN MATHEMATICS IS BORN

[dB]. Thus the formula for the dB-ref is $10 \log_{10} \frac{P}{P_{\text{ref}}}$. Thus the decibel is defined on the log (i.e., ratio) scale. Engineers quickly learn to “think” in dB units, because its so easy (once they learn to think in terms of ratios).

**Problem # 3: Very large primes on Intel computers**

---Q 3.1: Find the largest prime number that can be stored on an Intel 64 bit computer, which we call $\pi_{\text{max}}$.  

Hint: As explained in the Matlab/Octave command `help flintmax`, the largest positive integer is $2^{53}$, however the largest integer that can be factored is $2^{32} = \sqrt{2^{64}}$. Explain the logic of your answer. Hint: help isprime().  

**Solution:** Using Matlab/Octave, start with the largest integer $2^{32}$ and check if its prime. Then work down by subtracting 1, and again check. Stop when you get to the first prime below the largest integer. The answer I get is: $2^{32} - 5 = 4,294,967,291$, is the first prime below $2^{32}$ prime.

**Problem # 4: Suppose you are interested in primes that are greater than $\pi_{\text{max}}$. How can you find them on an Intel computer (i.e., one using IEEE-floating point)?**

---Q 4.1: Thus consider a sieve containing only odd numbers, starting from 3 (not 2).  

Hint: Since every prime number greater than 2 is odd, there is no reason to check the even numbers. $n_{\text{odd}} \in \mathbb{N}/2$ contain all the primes other than 2.  

**Solution:** At this time, I don’t see any way to do this, due to the matlab limitation that it cannot factor numbers larger that $2^{32}$.

**Problem # 5: The following identity is interesting:**

\[
1 = 1^2 \\
1 + 3 = 2^2 \\
1 + 3 + 5 = 3^2 \\
1 + 3 + 5 + 7 = 4^2 \\
1 + 3 + 5 + 7 + 9 = 5^2 \\
\ldots \\
\sum_{n=0}^{N-1} 2n + 1 = N^2.
\]

---Q 5.1: Can you find a proof?  

**Solution:** Subtracting any line from the line following it, gives:

\[
(1 - 1) + 3 = 2^2 - 1^2 \\
5 = 3^2 - 2^2 \\
7 = 4^2 - 3^2 \\
9 = 5^2 - 4^2 \\
\ldots \\
\sum_{n=0}^{N-1} 2n + 1 - \sum_{n=0}^{N-2} 2n + 1 = N^2 - (N - 1)^2 \\
2N - 1 = N^2 - (N^2 - 2N + 1) \\
2N - 1 = 2N - 1.
\]

---

This problem came from an exam problem for Math 213, Fall 2016.
Thus the two sides are equal, as suggested by the above formula.

Can you find a simpler more constructive “proof?” Hint: assuming you know what integration by parts is, can you devise a concept called Summation by parts?
Chapter 2

Stream 1: Number Systems

Number theory (the study of numbers) was a starting point for many key ideas. For example, in Euclid’s geometrical constructions the Pythagorean theorem for real \([a, b, c]\) was accepted as true, but the emphasis in the early analysis was on integer constructions, such as Euclid’s formula for Pythagorean triplets (Eq. 2.11, Fig. 2.7, p. 59).

As we shall see, the derivation of the formula for the Pythagorean triplets is the first of a rich source of mathematical constructions, such as solutions of the Fibonacci recursion formula \(f_{n+1} = f_n + f_{n-1}\) (p. 63), and solutions of Pell’s equation (p. 61). Recursive difference equation solutions predate calculus, going back at least to the Chinese (c2000 BCE). These are early (pre-limit) forms of linear differential equations, best analyzed using an eigenfunction (e.g., eigenmatrix) expansion (a geometrical concept from linear algebra), as an orthogonal set of normalized unit-length vectors (Appendix E, p. 265).

The first use of zero and \(\infty\): It is hard to imagine that one would not appreciate the concept of zero and negative numbers when using an abacus. It does not take much imagination to go from counting numbers \(\mathbb{N}\) to the set of all integers \(\mathbb{Z}\), including zero. On an abacus, subtraction is obviously the inverse of addition. Subtraction, to obtain zero abacus beads, is no different than subtraction from zero, giving negative beads. To assume the Romans, who first developed counting sticks, or the Chinese who then deployed the concept using beads, did not understand negative numbers, is impossible.

However, understanding the concept of zero (and negative numbers) is not the same as having a symbolic notation. The Roman number system has no such symbols. The first recorded use of a symbol for zero is said to be by Brahmagupta\(^2\) in 628 CE.\(^3\) Defining zero (c628 CE) depends on the concept of subtraction, which formally requires the creation of algebra (c830 CE, Fig. 1.1, p. 19). But apparently it takes more than 600 years, i.e., from the time Roman numerals were put into use, without any symbol for zero, to the time when the symbol for zero is first documented. Likely this delay is more about the political situation, such as government rulings, than mathematics.

The concept that caused much more difficulty was \(\infty\), first resolved by Riemann in 1851 with the development of the extended plane, which mapped the plane to a sphere (Fig. 3.10 p. 136). His construction made it clear that the point at \(\infty\) is simply another point on the open complex plane, since rotating the sphere (extended plane) moves the point at \(\infty\) to a finite point on the plane, thereby closing the complex plane.

---

3. The fall of the Roman Empire has been established as Sept. 4, 476 CE.
2.1 **Lec 2: The taxonomy of numbers:** \( \mathbb{N}, \mathbb{P}, \mathbb{Z}, \mathbb{Q}, \mathbb{F}, \mathbb{I}, \mathbb{R}, \mathbb{C} \)

Once symbols for zero and negative numbers were accepted, progress could be made. To fully understand numbers, a transparent notation was required. First one must differentiate between the different classes (genus) of numbers, providing a notation that defines each of these classes, along with their relationships. It is logical to start with the most basic counting numbers, which we indicate with the double-bold symbol \( \mathbb{N} \). For easy access, double-bold symbols and set-theory symbols, i.e., \( \{\}, \cup, \cap, \in, \notin, \perp \) etc., are summarized in Appendix A, p. 241.

**Counting numbers** \( \mathbb{N} \): These are known as the “natural numbers” \( \mathbb{N} = \{1, 2, 3, \ldots\} \), denoted by the double-bold symbol \( \mathbb{N} \). For clarity we shall refer to the natural numbers as counting numbers, since natural, which means integer, is vague. The mathematical sentence “\( 2 \in \mathbb{N} \)” is read as \( 2 \) is a member of the set of counting numbers. The word *set* is defined as the collection of any objects that share a specific property. Typically the set may be defined either as a sentence, or by example.

**Primes** \( \mathbb{P} \): A number is prime (\( \pi_n \in \mathbb{P} \)) if its only factors are 1 and itself. The set of primes \( \mathbb{P} \) is a subset of the counting numbers (\( \mathbb{P} \subset \mathbb{N} \)). A somewhat amazing fact, well known to the earliest mathematicians, is that every integer may be written as a unique product of primes. A second key idea is that the density of primes \( \rho_\pi(N) \sim 1/\log(N) \), that is \( \rho_\pi(N) \) is inversely proportional to the log of \( N \) (Eq. G.1, p. 271), an observation first made by Gauss (Goldstein, 1973). A third is that there is a prime between every integer \( N > 2 \) and \( 2N \).

We shall use the convenient notation \( \pi_n \) for the prime numbers, indexed by \( n \in \mathbb{N} \). The first 12 primes \( \{n|1 \leq n \leq 12\} = \{\pi_n|2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37\} \). Since \( 4 = 2^2 \) and \( 6 = 2 \cdot 3 \) may be factored, \( 4, 6 \notin \mathbb{P} \) (read as: 4 and 6 are not in the set of primes). Given this definition, multiples of a prime, i.e., \([2, 3, 4, 5, \ldots] \cdot \pi_k \) of any prime \( \pi_k \), cannot be prime. It follows that all primes except 2 must be odd and every integer \( N \) is unique in its prime factorization.

**Exercise:** Write out the first 10 to 20 integers in prime-factored form. **Solution:** \( 1, 2, 3, 2^2, 5, 2 \cdot 3, 7, 2^3, 3^2, 2 \cdot 5, 11, 3 \cdot 2^2, 13, 2 \cdot 7, 3 \cdot 5, 2^4, 17, 2 \cdot 3^2, 19, 2^2 \cdot 5 \).

**Exercise:** Write integers 2 to 20 in terms of \( \pi_n \). Here is a table to assist you:

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \pi_n )</th>
<th>( 1 )</th>
<th>( 2 )</th>
<th>( 3 )</th>
<th>( 4 )</th>
<th>( 5 )</th>
<th>( 6 )</th>
<th>( 7 )</th>
<th>( 8 )</th>
<th>( 9 )</th>
<th>( 10 )</th>
<th>( 11 )</th>
<th>( 12 )</th>
<th>( 13 )</th>
<th>( 14 )</th>
<th>( \ldots )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>( \pi_n )</td>
<td>( 2 )</td>
<td>( 3 )</td>
<td>( 4 )</td>
<td>( 5 )</td>
<td>( 6 )</td>
<td>( 7 )</td>
<td>( 8 )</td>
<td>( 9 )</td>
<td>( 10 )</td>
<td>( 11 )</td>
<td>( 12 )</td>
<td>( 13 )</td>
<td>( 14 )</td>
<td>( \ldots )</td>
<td></td>
</tr>
</tbody>
</table>

**Solution:**

Coprimes, or relatively prime, are two numbers with no common (i.e., prime) factors. For example, \( 21 = 3 \cdot 7 \) and \( 10 = 2 \cdot 5 \) are coprime whereas \( 4 = 2 \cdot 2 \) and \( 6 = 2 \cdot 3 \), which have 2 as a common factor, are not. By definition all unique pairs of primes are coprime. We shall use the notation \( m \perp n \) to indicate that \( m, n \) are coprime. The ratio of two coprimes is reduced, as it has no factors to cancel. The ratio of two numbers that are not coprime may always be reduced by canceling the common factors. This is called the reduced form, or an irreducible fraction. When doing numerical work, for computational accuracy it is always beneficial to work with coprimes. Generalizing this idea we could define tri-primes as three primes with no common factor, such as \( \{\pi_3, \pi_9, \pi_2\} \).

The fundamental theorem of arithmetic states that each integer may be uniquely expressed as a product of primes. The Prime Number Theorem estimates the mean density of primes over \( \mathbb{N} \).

**Integers** \( \mathbb{Z} \): These include positive and negative counting numbers and zero. Notionally we might indicate this using set notation as \( \mathbb{Z} = -\mathbb{N} \cup \{0\} \cup \mathbb{N} \). Read this as The integers are in the set composed of the negative natural numbers \( -\mathbb{N} \), zero, and \( \mathbb{N} \).
2.1. LECTURE 2: THE TAXONOMY OF NUMBERS: \( \mathbb{P}, \mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{F}, \mathbb{I}, \mathbb{R}, \mathbb{C} \)

**Rational numbers** \( \mathbb{Q} \): These are defined as numbers formed from the ratio of two integers. Given two numbers \( n, d \in \mathbb{N} \), then \( n/d \in \mathbb{Q} \). Since \( d \) may be 1, it follows that the rations include the counting numbers as a subset. For example, the rational number \( 3/1 \in \mathbb{N} \).

The main utility of rational numbers is that they can efficiently approximate any number on the real line, to any precision. For example, the rational approximation \( \pi \approx 22/7 \) has a relative error of \( \approx 0.04\% \).

**Fractional number** \( \mathbb{F} \): A fractional number \( \mathbb{F} \) is defined as the ratio of signed coprimes. If \( n, d \in \pm\mathbb{P} \), then \( n/d \in \mathbb{F} \). Given this definition, \( \mathbb{F} \subset \mathbb{Q} = \mathbb{Z} \cup \mathbb{F} \). Because of the powerful approximating power of rational numbers, the fractional set \( \mathbb{F} \) has special utility. For example, \( \pi \approx 22/7, 1/\pi \approx 7/22 \) (to 0.04\%), \( e \approx 19/7 \) to 0.15\%, and \( \sqrt{2} \approx 7/5 \) to 1\%.

**Irrational numbers** \( \mathbb{I} \): Every real number that is not rational is **irrational** (\( \mathbb{Q} \perp \mathbb{I} \)). Irrational numbers include \( \pi, e \) and the square roots of primes. These are decimal numbers that never repeat, thus requiring infinite precision in their representation. Such numbers cannot be represented on a computer, as they would require an infinite number of bits (precision).

The rations \( \mathbb{Q} \) and irrational \( \mathbb{I} \) split the reals (\( \mathbb{R} = \mathbb{Q} \cup \mathbb{I} \)), thus each is a subset of the reals (\( \mathbb{Q} \subset \mathbb{R}, \mathbb{I} \subset \mathbb{R} \)). This relation is analogous to that of the integers \( \mathbb{Z} \) and fractionals \( \mathbb{F} \), which split the rationals (\( \mathbb{Q} = \mathbb{Z} \cup \mathbb{F} \), \( \mathbb{Z} \perp \mathbb{F} \)) (thus each is a subset of the rationals (\( \mathbb{Z} \subset \mathbb{Q}, \mathbb{F} \subset \mathbb{Q} \)).

Irrational numbers \( \mathbb{I} \) were famously problematic for the Pythagoreans, who incorrectly theorized that all numbers were rational. Like \( \infty \), irrational numbers required mastering a new and difficult concept before they could even be defined: It was essential to understand the factorization of counting numbers into primes (i.e., the fundamental theorem of arithmetic) before the concept of irrationals could be sorted out. Irrational numbers could only be understood once limits were mastered.

As discussed in Sect. 2.3.2 (p. 55), fractionals can approximate any irrational number with arbitrary accuracy. Integers are also important, but for a very different reason. All numerical computing today is done with \( \mathbb{Q} = \mathbb{F} \cup \mathbb{Z} \). Indexing uses integers \( \mathbb{Z} \), while the rest of computing (flow dynamics, differential equations, etc.) is done with fractionals \( \mathbb{F} \) (i.e., IEEE-754). Computer scientists are trained on these topics, and computer engineers need to be at least conversant with them.

**Real numbers** \( \mathbb{R} \): Reals are the union of rational and irrational numbers, namely \( \mathbb{R} = \mathbb{Q} \cup \mathbb{I} = \mathbb{Z} \cup \mathbb{F} \cup \mathbb{I} \). Lengths in Euclidean geometry are reals. Many people assume that IEEE 754 **floating point numbers** (c1985) are real (i.e., \( \in \mathbb{R} \)). In fact they are rational (\( \mathbb{Q} = \{\mathbb{F} \cup \mathbb{Z}\} \)) approximations to real numbers, designed to have a very large dynamic range. The hallmark of fractional numbers (\( \mathbb{F} \)) is their power in making highly accurate approximations of any real number.

Using Euclid’s compass and ruler methods, one can make line length proportionally shorter or longer, or (approximately) the same. A line may be made be twice as long, an angle bisected. However, the concept of an integer length in Euclid’s geometry was not defined.\(^5\) Nor can one construct an imaginary or complex line, as all lines are assumed to be real lengths.

Real numbers were first fully accepted only after set theory was developed by Cantor (1874) (Stillwell, 2010, pp. 461). At first blush, this seems amazing, given how widely accepted real numbers are today. In some sense they were accepted by the Greeks, as lengths of real lines.

**Complex numbers** \( \mathbb{C} \): Complex numbers are best defined as **ordered pairs** of real numbers.\(^6\) For example, if \( a, b \in \mathbb{R} \) and \( j = -i = \pm\sqrt{-1} \), then \( c = a + bj \in \mathbb{C} \). The word “complex,” as used here, does not mean that the numbers are complicated or difficult. They are also known as “imaginary” numbers, but this does not mean the numbers disappear. Complex numbers are quite special in engineering...

---

\(^5\)As best I know.

\(^6\)A polynomial \( a + bx \) and a 2-vector \( [a, b]^T = \begin{bmatrix} a \\ b \end{bmatrix} \) are also examples of ordered pairs.
mathematics, as roots of polynomials. The most obvious example is the quadratic formula, for the roots of polynomials of degree 2, having coefficients $\in C$. All real numbers have a natural order on the real line. Complex numbers do not have a natural order. For example, $j > 1$ makes no sense.

Today the common way to write a complex number is using the notation $z = a + bj \in C$, where $a, b \in \mathbb{R}$. Here $1j = \sqrt{-1}$. We also define $1j = -1j$ to account for the two possible signs of the square root. Accordingly $1j^2 = 1^2 = -1$.

Cartesian multiplication of complex numbers follows the basic rules of real algebra, for example, the rules of multiplying two monomials and polynomials. Multiplication of two first-degree polynomials (i.e., monomials) gives

$$(a + bx)(c + dx) = ac + (ad + bc)x + bdx^2.$$ If we substitute $1j$ for $x$, and use the definition $1j^2 = -1$, we obtain the Cartesian product of the two complex numbers

$$(a + bj)(c + dj) = ac - bd + (ad + bc)j.$$ Thus multiplication and division of complex numbers obey the usual rules of algebra.

However, there is a critical extension: Cartesian multiplication only holds when the angles sum to less than $\pm \pi$, namely the range of the complex plane. When the angles add to more than $\pm \pi$, one must use polar coordinates, where the angles add for angles beyond $\pm \pi$ (Boas, 1987, p. 8). This is particularly striking for the Laplace transform of a delay (Table B.2, p. 250).

Complex numbers can be challenging, providing unexpected results. For example, it is not obvious that $\sqrt{3 + 4j} = \pm (2 + j)$.

**Exercise:** Verify that $\sqrt{3 + 4j} = \pm (2 + j)$. **Solution:** Square the left side gives $\sqrt{3 + 4j}^2 = 3 + 4j$. Squaring the right side gives $(2 + j)^2 = 4 - j^2 + 4j = 3 + 4j$. Thus the two are equal.

**Exercise:** What is special about this example? **Solution:** Note this is a $\{3, 4, 5\}$ triangle. Can you find another example like this one? Namely how does one find integers that obey Eq. 1.1 (p. 19)?

An alternative to Cartesian multiplication of complex numbers is to work in polar coordinates. The polar form of complex number $z = a + bj$ is written in terms of its magnitude $\rho = \sqrt{a^2 + b^2}$ and angle $\theta = \angle z = \tan^{-1} z = \arctan z$, as

$$z = \rho e^{i\theta} = \rho (\cos \theta + j\sin \theta).$$ From the definition of the complex natural log function

$$\ln z = \ln \rho e^{i\theta} = \ln \rho + i\theta,$$ which is important, even critical, in engineering calculations. When the angles of two complex numbers are greater than $\pm \pi$, one must use polar coordinates. It follows that when computing the phase, this is much different than the single- and double-argument $\angle \theta = \arctan(z)$ function.

The polar representation makes clear the utility of a complex number: Its magnitude scales while its angle $\Theta$ rotates. The property of scaling and rotating is what makes complex numbers useful in engineering calculations. This is especially obvious when dealing with impedances, which have complex roots with very special properties, as discussed in Sect. ?? (p. ??).

**Matrix representation:** An alternative way to represent complex numbers is in terms of 2x2 matrices. This relationship is defined by the mapping from a complex number to a 2x2 matrix

$$a + bj \leftrightarrow \begin{bmatrix} a & -b \\ b & a \end{bmatrix}, \quad 1 \leftrightarrow \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad 1j \leftrightarrow \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, \quad e^{i\theta} \leftrightarrow \begin{bmatrix} \sin(\theta) & -\cos(\theta) \\ \cos(\theta) & \sin(\theta) \end{bmatrix}. \quad (2.1)$$
The conjugate of $a + bj$ is then defined as $a - bj \leftrightarrow \begin{bmatrix} a \\ -b \end{bmatrix}$. By taking the inverse of the $2 \times 2$ matrix (assuming $|a + bj| \neq 0$), one can define the ratio of one complex number by another. Until you try out this representation, it may not seem obvious, or even that it could work.

This representation proves that $1j$ is not necessary when defining a complex number. What $1j$ can do is to conceptually simplify the algebra. It is worth your time to become familiar with the matrix representation, to clarify any possible confusions you might have about multiplication and division of complex numbers. This matrix representation can save you time, heartache and messy algebra. Once you have learned how to multiply two matrices, it’s a lot simpler than doing the complex algebra. In many cases we will leave the results of our analysis in matrix form, to avoid the algebra altogether. Thus both representations are important. More on this topic may be found in Section G (p. 271).

**Exercise:** Using Matlab/Octave, verify that

$$\frac{a + bj}{c + dj} = \frac{ab + bd + (bc - ad)j}{c^2 + d^2} \leftrightarrow \begin{bmatrix} a -b \\ b a \end{bmatrix} \begin{bmatrix} c & -d \\ d & c \end{bmatrix}^{-1} = \begin{bmatrix} a & -b \\ b & a \end{bmatrix} \begin{bmatrix} c & d \\ -d & c \end{bmatrix} \frac{1}{c^2 + d^2}. \quad (2.2)$$

**Solution:** The best way may be using numbers. The better solution is to use a symbolic code:

```Matlab
sym a b c d A B
A=[a -b; b a]
B=[c -d; d c];
C=A*inv(B)
```

2.1.1 Numerical taxonomy:

A simplified taxonomy of numbers is given by the mathematical sentence

$$\pi_k \in \mathbb{P} \subset \mathbb{N} \subset \mathbb{Z} \subset \mathbb{Q} \subset \mathbb{R} \subset \mathbb{C}.$$  

This sentence says:

1. Every prime number $\pi_k$ is in the set of primes $\mathbb{P}$,
2. which is a subset of the set of counting numbers $\mathbb{N}$,
3. which is a subset of the set of integers $\mathbb{Z} = -\mathbb{N}, \{0\}, \mathbb{N}$,
4. which is a subset of the set of rationals $\mathbb{Q}$ (ratios of signed counting numbers $\pm \mathbb{N}$),
5. which is a subset of the set of reals $\mathbb{R}$,
6. which is a subset of the set of complex numbers $\mathbb{C}$.

---

Sometimes we let the computer do the final algebra, numerically, as $2 \times 2$ matrix multiplications.
The rationals $\mathbb{Q}$ may be further decomposed into the fractionals $F$ and the integers $\mathbb{Z}$ ($\mathbb{Q} = F \cup \mathbb{Z}$), and the reals $\mathbb{R}$ into the rationals $\mathbb{Q}$ and the irrationals $I$ ($\mathbb{R} = I \cup \mathbb{Q}$). This classification nicely defines all the numbers (scalars) used in engineering and physics.

The taxonomy structure may be summarize with the single compact sentence, starting with the prime numbers $\pi_k$ and ending with complex numbers $\mathbb{C}$:

$$\pi_k \in P \subset N \subset Z \subset (Z \cup F = Q) \subset (Q \cup I = R) \subset \mathbb{C}.$$  

As discussed in Appendix A (p. 241), all numbers may be viewed as complex. Namely, every real number is complex if we take the imaginary part to be zero (Boas, 1987). For example, $2 \in P \subset \mathbb{C}$. Likewise every purely imaginary number (e.g., $0 + 1j$) is complex with zero real part.

Finally, note that complex numbers $\mathbb{C}$, much like vectors, do not have “rank-order,” meaning one complex number cannot be larger or smaller than another. It makes no sense to say that $j > 1$ or $j = 1$ (Boas, 1987). The real and imaginary parts, and the magnitude and phase, have order. Order seems restricted to $\mathbb{R}$. If time $t$ were complex, there could be no yesterday and tomorrow.\footnote{One can usefully define $\xi = x + 1j \text{ct}$ to be complex ($x, t \in \mathbb{R}$), with $x$ in meters [m], $t$ in seconds [s], and the speed of light $c_0$, [m/s].}

### 2.1.2 Applications of integers

The most relevant question at this point is “Why are integers important?” First, we count with them, so we can keep track of “how much.” But there is much more to numbers than counting: We use integers for any application where absolute accuracy is essential, such as banking transactions (making change), the precise computing of dates (Stillwell, 2010, p. 70) and locations (“I’ll meet you at 34th and Vine at noon on Jan. 1, 2034.”), or building roads or buildings out of bricks (objects built from a unit size).

To navigate we need to know how to predict the tides, the location of the moon and sun, etc. Integers are important, precisely because they are precise: Once a month there is a full moon, easily recognizable. The next day it’s slightly less than full. If one could represent our position as integers in time and space, we would know exactly where we are at all times. But such an integral representation of our position or time is not possible.

The Pythagoreans claimed that all was integer. From a practical point of view, it seems they were right. Today all computers compute floating point numbers as fractionals. However, in theory they were wrong. The error (difference) is a matter of precision.

#### Numerical Representations of $\mathbb{I}, \mathbb{R}, \mathbb{C}$

When doing numerical work, one must consider how we may compute within the set of reals (i.e., which contain irrationals). There can be no irrational number representation on a computer. The international standard of computation, IEEE floating point numbers,\footnote{IEEE 754: http://www.h-schmidt.net/FloatConverter/IEEE754.html.} is based on rational approximation. The mantissa and the exponent are both integers, having sign and magnitude. The size of each integer depends on the precision of the number being represented. An IEEE floating-point number is rational because it has a binary (integer) mantissa, multiplied by 2 raised to the power of a binary (integer) exponent. For example, $\pi \approx \pm a2^{\pm b}$ with $a, b \in \mathbb{Z}$. In summary, IEEE floating-point rational numbers cannot be irrational, because irrational representations would require an infinite number of bits.

True floating point numbers contain irrational numbers, which must be approximated by fractional numbers. This leads to the concept of fractional representation, which requires the definition of the mantissa, base and exponent, where both the mantissa and the exponent are signed. Numerical results must not depend on the base. One could dramatically improve the resolution of the numerical representation by the use of the fundamental theorem of arithmetic (Section 2.2.2, page 43). For example, one could factor the exponent into its primes and then represent the number as $2^a3^b5^c7^e$ ($a, b, c, d, e \in \mathbb{Z}$),

---

This concludes the introduction to number systems.
2.1. LECTURE 2: THE TAXONOMY OF NUMBERS: \( \mathbb{P}, \mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{F}, \mathbb{I}, \mathbb{R}, \mathbb{C} \)

etc. Such a representation would improve the resolution of the representation. But even so, the irrational numbers would be approximate. For example, base ten\(^{10}\) is natural using this representation since \(10^n = 2^n 5^n\). Thus

\[
\pi \cdot 10^5 \approx 314159.2652 \ldots = 3 \cdot 2^5 5^5 + 1 \cdot 2^4 5^4 + 4 \cdot 2^3 5^3 + \ldots + 9 \cdot 2^0 5^0 + 2 \cdot 2^{-1} 5^{-1} \ldots .
\]

**Exercise:** If we work in base 2, and use the approximation \( \pi \approx 22/7 \), then according to the Matlab/Octave `dec2bin()` routine, show that the binary representation of \( \hat{\pi} \cdot 2^{17} \) is

\[
\pi \cdot 2^{17} \approx 411,940_{10} = 64,924_{16} = 1100100100100100100_{2}.
\]

**Solution:** First we note that this must be an approximation since \( \pi \in \mathbb{I} \), which cannot have an exact representation \( \in \mathbb{F} \). Thus above, we have asked for a large integer approximation to \( \pi \), with

\[
\hat{\pi} = 22/7 = 3 + 1/7 = [3; 7], \tag{2.3}
\]

where \( \text{int64}(\text{fix}(2^{17} \times 22/7)) = 411,940 \) and \( \text{dec2hex}(\text{int64}(\text{fix}(2^{17} \times 22/7))) = 64,924 \), where 1 and 0 are multipliers of powers of 2, which are then added together as follows:

\[
411,940_{10} = 2^{18} + 2^{17} + 2^{14} + 2^{11} + 2^8 + 2^5 + 2^2.
\]

Computers keep track of the decimal point using the exponent, which in this case is the factor \( 2^{17} = 131072_{10} \). The concept of the decimal point is replaced by an integer, having the desired precision, and a scale factor of any base (radix). This scale factor may be thought of as moving the decimal point to the right (larger number) or left (smaller number). The mantissa “fine-tunes” the value about a scale factor (the exponent). In all cases the number actually used is a positive integer. Negative numbers are represented by an extra sign bit.

**Exercise:** Using Matlab/Octave, use base 16 (i.e., hexadecimal) numbers, with \( \pi \approx 22/7 \), find

1. \( \pi \times 10^5 \)

   **Solution:** Using the command \( \text{dec2hex}(\text{fix}(22/8 \times 1e5)) \) we get \( 4\text{c}b\text{ad}_{16} \), since \( 22/7 \times 10^5 = 314285.7 \ldots \) and \( \text{hex2dec('4cbad')} = 314285 \).

2. \( 2^{17} \cdot 22/7 \)

   **Solution:** \( 2^{18} \cdot 11_{16}/7_{16} \).

**Exercise:** Write out the first 11 primes, base 16. **Solution:** The Octave/Matlab command \( \text{dec2hex()} \) provides the answer:

\[
\begin{array}{c|ccccccccc}
  n & \text{dec} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & \ldots \\
  \pi_n & \text{dec} & 2 & 3 & 5 & 7 & 11 & 13 & 17 & 19 & 23 & 29 & 31 & \ldots \\
  \pi_n & \text{hex} & 2 & 3 & 5 & 7 & 0\text{B} & 0\text{D} & 11 & 13 & 17 & 1\text{D} & 1\text{F} & \ldots \\
\end{array}
\]

**Example:** \( x = 2^{17} \times 22/7 \), using IEEE-754 double precision.\(^{11}\)

\[
x = 411,940.5625_{10} \\
= 2^{54} \times 1198372 \\
= 0, 10010, 00, 110010, 010010, 010010, 010010, 010010_2 \\
= 0x48c92492_{16}.
\]

\(^{10}\)Base 10 is the natural world wide standard simply because we have 10 fingers, that we count with.

\(^{11}\)http://www.h-schmidt.net/FloatConverter/IEEE754.html
The exponent is $2^{18}$ and the mantissa is $4,793,490_{10}$. Here the commas in the binary $(0,1)$ string are to help visualize the quasi-periodic nature of the bit-stream. The numbers are stored in a 32 bit format, with 1 bit for sign, 8 bits for the exponent and 23 bits for the mantissa. Perhaps a more instructive number is $x = 4,793,490.0$

$$= 0,100,1010,100,100,100,100,100,100,100,100,100_2$$

$$= 0x4a924924_{16},$$

which has a repeating binary bit pattern of $((100))_3$, broken by the scale factor $0x4a$. Even more symmetrical is

$$x = 0x24,924,924_{16}$$

$$= 00,100,100,100,100,100,100,100,100,100,100_2$$

$$= 6.344,131,191,146,900 \times 10^{-17}.$$ In this example the repeating pattern is clear in the hex representation as a repeating $((942))_3$, as represented by the double brackets, with the subscript indicating the period, in this case, three digits. As before, the commas are to help with readability and have no other meaning.

The representation of numbers is not unique. For example, irrational complex numbers have approximate rational representations (i.e., $\pi \approx 22/7$). A better example is complex numbers $z \in \mathbb{C}$, which have many representations, as a pair of reals (i.e., $z = (x,y)$), or by Euler’s formula, and matrices ($\theta \in \mathbb{R}$)

$$e^{j\theta} = \cos \theta + j \sin \theta \leftrightarrow \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}.$$ At a higher level, differentiable functions, aka, analytic functions, may be represented by a single-valued Taylor series expansion (Sect. 3.2.2, p. 87), limited by its region of convergence (RoC).

**Pythagoreans and Integers:** The integer is the cornerstone of the Pythagorean doctrine, so much so that it caused a fracture within the Pythagoreans when it was discovered that not all numbers are rational. One famous proof of such irrational numbers comes from the spiral of Theodorus, as shown in Fig. 2.1, where the short radius of each triangle has length $b_n = \sqrt{n}$ with $n \in \mathbb{N}$, and the long radius (the hypotenuses) is $c_n = \sqrt{1 + b_n^2} = \sqrt{1 + n}$. This figure may be constructed using a compass and ruler by maintain right triangles.

![Figure 2.1: This construction is called the spiral of Theodorus, made from contiguous triangles having lengths $a = 1$, $b_n = \sqrt{n}$, with $n \in \mathbb{N}$, and $c_n = \sqrt{n+1}$. In this way, each value of $c_n^2 = b_n^2 + 1 \in \mathbb{N}$ (Adapted from https://en.wikipedia.org/wiki/spiral_of_Theodorus). The first side that is not a perfect square is $c_1 = \sqrt{2}$, as are most values of $c_n$.](https://en.wikipedia.org/wiki/spiral_of_Theodorus) The first side that is not a perfect square is $c_1 = \sqrt{2}$, as are most values of $c_n$.

**Public-key security:** An important application of prime numbers is public-key encryption, essential for internet security applications (e.g., online banking). Most people assume encryption is done by a
personal login and passwords. Passwords are fundamentally insecure, for many reasons. Decryption depends on factoring large integers, formed from products of primes having thousands of bits.\textsuperscript{12} The security is based on the relative ease of multiplying large primes, along with the virtual impossibility of factoring their products.

When a computation is easy in one direction, but its inverse is impossible, it is called a \textit{trap-door function}. We shall explore trapdoor functions in Appendix G. If everyone were to switch from passwords to public-key encryption, the internet would be much more secure.\textsuperscript{13}

**Puzzles:** Another application of integers is imaginative problems that use integers. An example is the classic Chinese \textit{four stone problem}: Find the weight of four stones that can be used with a scale to weigh anything (e.g., salt, gold) between 0, 1, 2, \ldots, 40 [gm] (Fig. 3.3.3, p. 107 in Assignment AE-2).

As with the other problems, the answer is not as interesting as the method, since the problem may be easily recast into a related one. This type of problem can be found in airline magazines as amusement on a long flight. This puzzle is best cast as a linear algebra problem, with integer solutions. Again, once you know the trick, it is “easy.”\textsuperscript{14}

### 2.2 Lec 3: The role of physics in mathematics

**Bells, chimes and eigenmodes:** Integers naturally arose in art, music and science. Examples include the relations between musical notes, the natural eigenmodes (tones) of strings and other musical instruments. These relations were so common that Pythagoras believed that to explain the physical world (aka, the universe), one needed to understand integers. As discussed on p. 17, “all is integer” was a seductive song (Stillwell, 2010, p. 16).

As will be discussed in Sections 3.1 (p. 72), it is best to view the relationship between acoustics, music and mathematics as historical, since these topics inspired the development of mathematics. Today integers play a key role in quantum mechanics, again based on eigenmodes, but in this case, eigenmodes follow from solutions of Schrödinger equation, with the roots of the characteristic equation being purely imaginary. If there were a real part (i.e., damping), the modes would not be integers.

As discussed by Salmon (1946, p. 201), Schrödinger’s equation follows directly from the Webster horn equation. While Morse (1948, p. 281) fails to make the direct link, he comes close to the same view when he shows that the real part of the horn resistance goes exactly to zero below a cutoff frequency. He also discusses the trapped modes inside musical instruments due to the horn flair (p. 268). One may infer Morse read his student Salmon’s paper on horns, since he cites Salmon (Morse, 1948, Footnote 1, p. 271).

Engineers are so accustomed to working with real (or complex) numbers, the distinction between real (i.e., irrational) and fractional numbers is rarely acknowledged. Integers, on the other-hand, arise in many contexts. One cannot master programming computers without understanding integer, hexadecimal, octal, and binary representations, since all numbers in a computer are represented in numerical computations in terms of rationals ($\mathbb{Q} = \mathbb{Z} \cup \mathbb{F}$).\textsuperscript{15}

As discussed in Section 2.1 (p. 34), the primary reason integers are so important is their absolute precision. Every integer $n \in \mathbb{Z}$ is unique,\textsuperscript{16} and has the \textit{indexing property}, which is essential for making lists that are ordered, so that one can quickly look things up. The alphabet also has this property (e.g., a book’s index).

\textsuperscript{12}It would seem that public-key encryption could work by having two numbers with a common prime, and then using the Euclidean algorithm, the greatest common divisor (GCD) could be worked out. One of the integers could be the public-key and the second could be the private key.

\textsuperscript{13}https://fas.org/irp/agency/dod/jason/cyber.pdf

\textsuperscript{14}Whenever someone tells you something is “easy,” you should immediately appreciate that it is very hard, but once you learn a concept, the difficulty evaporates.

\textsuperscript{15}See Appendix A (p. 241) for a review of mathematical notation.

\textsuperscript{16}Check out the history of $1729 = 1^3 + 12^3 = 9^3 + 10^3$. 


Because of the integer’s absolute precision, the digital computer quickly overtook the analog computer, once it was practical to make logic circuits that were fast. From 1946 the first digital computer was thought to be the University of Pennsylvania’s Eniac. We now know that the code-breaking effort in Bletchley Park, England, under the guidance of Alan Turing, created the first digital computer (The Colossus), used to break the WWII German “Enigma” code. Due to the high secrecy of this war effort, the credit was only acknowledged in the 1970s when the project was finally declassified.

Table 2.1: The fundamental theorems of mathematics. See Flanders (1973) for a discussion on integration, relevant for stream 3.

1. Fundamental theorems of:

(a) **Number systems: Stream 1**
   - arithmetic
   - prime number

(b) **Geometry: Stream 2**
   - algebra

(c) **Calculus: Stream 3**
   - Leibniz $\mathbb{R}^1$
   - complex $\mathbb{C} \subset \mathbb{R}^2$
   - vectors $\mathbb{R}^3, \mathbb{R}^n, \mathbb{R}^\infty$
     - Gauss’s law (divergence theorem)
     - Stokes’s law (curl theorem, or Green’s theorem)
     - Vector calculus (Helmholtz’s theorem)

There is zero possibility of analog computing displacing digital computing, due to the importance of precision (and speed). But even with binary representation, there is a non-zero probability of error, for example on a hard drive, due to physical noise. To deal with this, error correcting codes have been developed, reducing the error by many orders of magnitude. Today error correction is a science, and billions of dollars are invested to increase the density of bits per area, to increasingly larger factors. A few years ago the terabyte drive was unheard of; today it is the standard. In a few years petabyte drives will certainly become available. It is hard to comprehend how these will be used by individuals, but they are essential for on-line (cloud) computing.

2.2.1 The role of mathematics in physics: The three streams

Modern mathematics is built on a hierarchical construct of fundamental theorems, as summarized in Table 2.1. The importance of such theorems cannot be overemphasized. Gauss’s and Stokes’s laws play a major role in understanding and manipulating Maxwell’s equations. Every engineering student needs to fully appreciate the significance of these key theorems. If necessary, memorize them. But that will not do over the long run, as each and every theorem must be fully understood. Fortunately most students already know several of these theorems, but perhaps not by name. In such cases, it is a matter of mastering the vocabulary.

These theorems are naturally organized, and may be thought of, in terms of Stillwell’s three streams. For Stream 1 there is the fundamental theorem of arithmetic and the prime number theorem. For Stream 2 there is the fundamental theorem of algebra while for Stream 3 there are a host of theorems on calculus, ordered by their dimensionality. Some of these theorems seem trivial (e.g., the fundamental theorem of arithmetic). Others are more challenging, such as the fundamental theorem of vector calculus and Green’s theorem.
Complexity should not be confused with importance. Each of these theorems, as stated, is fundamental. Taken as a whole, they are a powerful way of summarizing mathematics.

2.2.2 **Stream 1: Prime number theorems**

There are two easily described fundamental theorems about primes:

1. *The fundamental theorem of arithmetic*: This states that every integer \( n \in \mathbb{Z} \) may be uniquely factored into prime numbers. This raises the question of the meaning of *factor* (split into a product). The *product* of two integers \( m, n \in \mathbb{Z} \) is \( mn = \sum_m n = \sum_n m \). For example, \( 2 \times 3 = 2 + 2 + 2 = 3 + 3 \).

2. *The prime number theorem*: One would like to know how many primes there are. That is easy: \(|\mathbb{P}| = \infty\) (the size of the set of primes is infinite). One way of asking this questions is *What is the average density of primes, in the limit as \( n \to \infty \)?* This question was answered, for all practical purposes, by Gauss, who in his free time computed the first three million primes by hand. He discovered that, to a good approximation, the primes are equally likely on a log scale. This is nicely summarized by the jingle:

   Chebyshev said, and I say it again: There is always a prime between \( n \) and \( 2n \).

attributed to the mathematician Pafnuty Chebyshev, which nicely summarizes theorem 3 (Stillwell, 2010, p. 585).

When the ratio of two frequencies (pitches) is 2, the relationship is called an *octave*. Thus we might say, with a slight stretch of terminology, there is at least one prime per octave. Thus one might wonder about the maximum number of primes per octave, as a function of the number of primes less than \( N \), for example.

In modern western music the octave is further divided into 12 intervals called *semitones* (factors), equal to the \( \sqrt[12]{2} \). Twelve semitones is an octave. Thus one might ask how many primes there are in fractions of an octave. In the end, it is a question of the density of primes on a log-log (i.e., ratio) scale.

2.2.3 **Stream 2: Fundamental theorem of algebra**

This theorem states that every polynomial in \( x \) of degree \( N \)

\[
P_N(x) = \sum_{k=0}^{N} a_k x^k
\]

has at least one root (Section 3.3, p. 100). When a common root is factored out, the degree of the polynomial is reduced by 1. Applied recursively, a polynomial of degree \( N \) has \( N \) roots. Note there are \( N + 1 \) coefficients (i.e., \([a_N, a_{N-1}, \ldots, a_0]\)). If we are only interested in the roots of \( P_N(x) \) it is best to define \( a_N = 1 \), which defines the *monic polynomial*. If the roots are fractional numbers this might be possible. However if the roots are irrational numbers (likely), a perfect factorization is at least unlikely.

2.2.4 **Stream 3: Fundamental theorems of calculus**

In Sections 5.5 and 5.5.5 we will deal with each of the theorems for Stream 3, where we consider the several fundamental theorems of integration, starting with Leibniz’s formula for integration on the real line (\( \mathbb{R} \)), then progressing to complex integration in the complex plane (\( \mathbb{C} \)) (*Cauchy’s theorem*), which is required for computing the inverse Laplace transform. Gauss’s and Stokes’s laws for \( \mathbb{R}^2 \) require closed and open surfaces, respectively. One cannot manipulate Maxwell’s equations, fluid flow, or acoustics, without understanding these theorems. Any problem that deals with the wave equation in more than
one dimension requires an understanding of these theorems. They are the basis of the derivation of the Kirchhoff voltage and current laws.

Finally we define the four basic vector operations based on the gradient operator differential vector operator

$$\nabla \equiv \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z},$$

(2.5)

pronounced as “del” (preferred) or “nabla,” which are the gradient $\nabla()$, divergence $\nabla \cdot ()$, curl $\nabla \times ()$ and Laplacian $\nabla \cdot \nabla () = \nabla^2 ()$.

The first three operations are defined in terms of integral operations on a surface in 1, 2 or 3 dimensions, by taking the limit as that surface, or the volume contained within, goes to zero. These three differential operators are essential to fully understand Maxwell’s equations, the crown jewel of mathematical physics. Hence mathematics plays a key role in physics, as does physics in math.

### 2.2.5 Other key mathematical theorems

Besides the widely recognized fundamental theorems for the three streams, there are a number of equally important theorems that have not yet been labeled as “fundamental.”

The widely recognized Cauchy integral theorem is an excellent example, since it is a stepping stone to Green’s theorem and the fundamental theorem of complex calculus. In Section 4.4 (p. 163) we clarify the contributions of each of these special theorems.

Once these fundamental theorems of integration (Stream 3) have been mastered, the student is ready for the complex frequency domain, which takes us back to Stream 2 and the complex frequency plane ($s = \sigma + \omega \mathbf{i} \in \mathbb{C}$). While the Fourier and Laplace transforms are taught in mathematics courses, the concept of complex frequency is rarely mentioned. The complex frequency domain (p. 151) and causality are fundamentally related (Sects. 4.4.2–4.5.2, p. 164–175), and are critical for the analysis of signals and systems, and especially when dealing with the concept of impedance (Sect. 4.3, p. 149).

Without the concept of time and frequency, one cannot develop an intuition for the Fourier and Laplace transforms, especially within the context of engineering and mathematical physics. The Fourier transform covers signals, while the Laplace transform describes systems. Separating these two concepts, based on their representations as Fourier and Laplace transforms, is an important starting place for understanding physics and the role of mathematics. However, these methods, by themselves, do not provide the insight into physical systems necessary to be productive, or better, creative with these tools. One needs to master the tools of differential equations, and then partial differential equations, to fully appreciate the world that they describe. Electrical and mechanical networks, composed of inductors, capacitors and resistors, are isomorphic to mechanical systems composed of masses, springs and dashpots. Newton’s laws are analogous to those of Kirchhoff, which are the rules needed to analyze simple physical systems composed of linear (and nonlinear) sub-components. When lumped-element systems are taken to the limit, in several dimensions, we obtain Maxwell’s partial differential equations, the laws of continuum mechanics, and beyond.

The ultimate goal of this book is to make you aware of and productive in using these tools. This material can be best absorbed by treating it chronologically through history, so you can see how this body of knowledge came into existence, through the minds and hands of Galileo, Newton, Maxwell and Einstein. Perhaps one day you too can stand on the shoulders of the giants who went before you.
2.2. LECTURE 3: (WEEK 2) THE ROLE OF PHYSICS IN MATHEMATICS

2.2.6 Exercises NS-2

**Topic of this homework:** Prime numbers, greatest common divisors, the continued fraction algorithm

**Deliverable:** Answers to questions.

**Prime numbers**

**Problem # 1:** Every integer may be written as a product of primes.

–Q 1.1: Put the numbers 1,000,000, 1,000,004 and 999,999 in the form $N = \prod_k \pi_k^{\beta_k}$ (Hint: Use Matlab/Octave to find the prime factors).

–Q 1.2: Give a generalized formula for the natural logarithm of a number, $\ln(N)$, in terms of its primes $\pi_k$ and their multiplicities $\beta_k$. Express your answer as a sum of terms.

**Problem # 2: Using the computer**

–Q 2.1: Explain why the following brief Matlab/Octave program returns the prime numbers $\pi_k$ between 1 and 100.

```matlab
n=2:100;
k = isprime(n);
n(k)
```

–Q 2.2: How many primes are there between 2 and $N = 100$?

**Problem # 3: Prime numbers may be identified using a ‘sieve.’**

–Q 3.1: By hand, perform the sieve of Eratosthenes for $n = 1 \ldots 49$. Circle each prime $p$, then cross out each number which is a multiple of $p$.

–Q 3.2: What is the largest number you need to consider before only primes remain?

–Q 3.3: Generalize: for $n = 1 \ldots N$, what is the highest number you need to consider before only the primes remain?

–Q 3.4: Write each of these numbers as a product of primes:

$22 =$

$30 =$

$34 =$

$43 =$

$44 =$
–Q 3.5: Find the largest prime $\pi_k \leq 100$? Hint: Do not use Matlab/Octave other than to check your answer. Hint: Write out the numbers starting with 100 and counting backwards: 100, 99, 98, 97, ... Cross off the even numbers, leaving 99, 97, 95, ... Pull out a factor (only 1 is necessary to show that it is not prime).

–Q 3.6: Find the largest prime $\pi_k \leq 1000$? Hint: Do not use Matlab/Octave other than to check your answer.

–Q 3.7: Explain why $\pi_k^{-s} = e^{-s \ln \pi_k}$.

Greatest common divisors

Consider the Euclidean algorithm to find the greatest common divisor (GCD; the largest common prime factor) of two numbers. Note this algorithm may be performed using one of two methods:

<table>
<thead>
<tr>
<th>Method</th>
<th>Division</th>
<th>Subtraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>On each iteration...</td>
<td>$a_{i+1} = b_i$</td>
<td>$a_{i+1} = \max(a_i, b_i) - \min(a_i, b_i)$</td>
</tr>
<tr>
<td></td>
<td>$b_{i+1} = a_i - b_i \cdot \floor(a_i/b_i)$</td>
<td>$b_{i+1} = \min(a_i, b_i)$</td>
</tr>
<tr>
<td>Terminates when...</td>
<td>$b_i = 0 \ (\gcd = a)$</td>
<td>$b_i = 0 \ (\gcd = a)$</td>
</tr>
</tbody>
</table>

The division method (Eq. 2.1, Sect. 2.1.2, Lec 5, Ch. 2) is preferred because the subtraction method is much slower.

**Problem #1: Understand the Euclidean (GCD) algorithm**

–Q 1.1: Use the Octave/Matlab command `factor` to find the prime factors of $a = 85$ and $b = 15$.

–Q 1.2: What is the greatest common prime factor of these two numbers?

–Q 1.3: By hand, perform the Euclidean algorithm for $a = 85$ and $b = 15$.

–Q 1.4: By hand, perform the Euclidean algorithm for $a = 75$ and $b = 25$. Is the result a prime number?

–Q 1.5: Consider the first step of the GCD division algorithm when $a < b$ (e.g. $a = 25$ and $b = 75$). What happens to $a$ and $b$ in the first step? Does it matter if you begin the algorithm with $a < b$ vs. $b < a$?

–Q 1.6: Describe in your own words how the GCD algorithm works. Try the algorithm using numbers which have already been separated into factors (e.g. $a = 5 \cdot 3$ and $b = 7 \cdot 3$).
Problem #2: Coprimes

1. Define the term coprime.

2. How can the Euclidean algorithm be used to identify coprimes?

3. Give at least one application of the Euclidean algorithm.

–Q 2.1: Write a Matlab function, function x = mygcd(a, b), which uses the Euclidean algorithm to find the GCD of any two inputs a and b. Test your function on the (a,b) combinations from parts (a) and (b). Include a printout (or handwrite) your algorithm to turn in.

Hints and advice:

• Don’t give your variables the same names as Matlab functions! Since gcd is an existing Matlab/Octave function, if you use it as a variable or function name, you won’t be able to use gcd to check your gcd() function. Try clear all to recover from this problem.

• Try using a ‘while’ loop for this exercise (see Matlab documentation for help).

• You may need to make some temporary variables for a and b in order to perform the algorithm.

Algebraic generalization of the GCD (Euclidean) algorithm

Problem #1: In this problem we are looking for integer solutions \((m, n) \in \mathbb{Z}\) to the equations \(ma + nb = \gcd(a, b)\) and \(ma + nb = 0\) given positive integers \((a, b) \in \mathbb{Z}^+\).

Note that this requires that either \(m\) or \(n\) be negative. These solutions may be found using the Euclidean algorithm only if \((a, b)\) are coprime \((a \perp b)\). Note that integer (whole number) polynomial relations such as these are known as ‘Diophantine equations.’ The above equations are linear Diophantine equations, possibly the simplest form of such relations.

Example: \(\gcd(2, 3) = 1\): For \((a, b) = (2, 3)\), the result is as follows:

\[
\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & -2 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 2 \\ 3 \end{bmatrix} = \begin{bmatrix} -1 & 1 \\ 3 & -2 \end{bmatrix} \begin{bmatrix} 2 \\ m \\ n \end{bmatrix}
\]

Thus from the above equation we find the solution \((m, n)\) to the integer equation

\[2m + 3n = \gcd(2, 3) = 1,\]

namely \((m, n) = (-1, 1)\) (i.e., \(-2+3 = 1\)). There is also a second solution \((3, -2)\) (i.e., \(3 \cdot 2 - 2 \cdot 3 = 0\)), which represents the terminating condition. Thus these two solutions are a pair and the solution only exists if \((a, b)\) are coprime \((a \perp b)\).

Subtraction method: This method is more complicated than the division algorithm, because at each stage we must check if \(a < b\). Define

\[
\begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} a \\ b \end{bmatrix}, \quad Q = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix}, \quad S = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}
\]

where \(Q\) sets \(a_{i+1} = a_i - b_i\) and \(b_{i+1} = b_i\) assuming \(a_i > b_i\), and \(S\) is a ‘swap-matrix’ which swaps \(a_i\) and \(b_i\) if \(a_i < b_i\). Using these matrices, the algorithm is implemented by assigning

\[
\begin{bmatrix} a_{i+1} \\ b_{i+1} \end{bmatrix} = Q \begin{bmatrix} a_i \\ b_i \end{bmatrix} \quad \text{for} \quad a_i > b_i, \quad \begin{bmatrix} a_{i+1} \\ b_{i+1} \end{bmatrix} = QS \begin{bmatrix} a_i \\ b_i \end{bmatrix} \quad \text{for} \quad a_i < b_i.
\]
The result of this method is a cascade of Q and S matrices. For \((a, b) = (2, 3)\), the result is as follows:

\[
\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 1 \\ 3 & 1 \end{bmatrix}.
\]

Thus we find two solutions \((m, n)\) to the integer equation \(2m + 3n = \gcd(2, 3) = 1\).

**Q 1.1:** By inspection, find at least one integer pair \((m, n)\) that satisfies \(12m + 15n = 3\).

Using matrix methods for the Euclidean algorithm, find integer pairs \((m, n)\) that satisfy \(12m + 15n = 3\) and \(12m + 15n = 0\). Show your work!!!

**Q 1.2:** Does the equation \(12m + 15n = 1\) have integer solutions for \(n\) and \(m\)? Why, or why not?

**Problem #2: Matrix approach:**

It can be difficult to keep track of the a’s and b’s when the algorithm has many steps. We need an alternative way to run the Euclidean algorithm, using matrix algebra. Matrix methods provide a more transparent approach to the operations on \((a, b)\). Thus the Euclidean algorithm can be classified in terms of standard matrix operations.

**Q 2.1:** Write out the matrix approach, discussed at the end of Sect. 2.3.1 (Eq. ??, p. ??).

**Continued fractions**

**Problem #1:** Here we explore the continued fraction algorithm (CFA), Sect. 2.3.2, (p. 55).

In its simplest form the CFA starts with a real number, which we denote as \(\alpha \in \mathbb{R}\). Let us work with an irrational real number, \(\pi \in \mathbb{I}\), as an example, because its CFA representation will be infinitely long. We can represent the CFA coefficients \(\alpha\) as a vector of integers \(n_k, k = 1, 2 \ldots \infty\)

\[
\alpha = [n_1; n_2, n_3, n_4, \ldots]
\]

\[
= n_1 + \frac{1}{n_2 + \frac{1}{n_3 + \frac{1}{n_4 + \ldots}}}
\]

As discussed in Section 2.3.1 (p. 52), the CFA is recursive, with three steps per iteration:

For \(\alpha_1 = \pi, n_1 = 3, r_1 = \pi - 3\) and \(\alpha_2 \equiv 1/r_1\),

\[
\alpha_2 = 1/0.1416 = 7.0625 \ldots
\]

\[
\alpha_1 = n_1 + \frac{1}{\alpha_2} = n_1 + \frac{n_2}{\alpha_3} = \cdots
\]

In terms of a Matlab/Octave script

```matlab
alpha0 = pi;
K=10;
n=zeros(1,K); alpha=zeros(1,K);
alpha(1)=alpha0;

for k=2:K %k=1 to K
```

2.2. LECTURE 3: (WEEK 2) THE ROLE OF PHYSICS IN MATHEMATICS

\begin{verbatim}
n(k)=round(alpha(k-1));
% n(k)=fix(alpha(k-1));
alpha(k) = 1/(alpha(k-1) - n(k));
% disp([fix(k), round(n(k)), alpha(k)]); pause(1)
end
disp([n; alpha]);
% Now compare this to matlab's rat() function
rat(alpha0,1e-20)
\end{verbatim}

---Q 1.1: By hand (you may use Matlab/Octave as a calculator), find the first 3 values of \( n_k \) for \( \alpha = e^\pi \).

---Q 1.2: For part (1), what is the error (remainder) when you truncate the continued fraction after \( n_1, \ldots, n_3 \)? Give the absolute value of the error, and the percentage error relative to the original \( \alpha \).

---Q 1.3: Use the Matlab/Octave program provided to find the first 10 values of \( n_k \) for \( \alpha = e^\pi \), and verify your result using the Matlab/Octave command `rat()`.

---Q 1.4: Discuss the similarities and differences between the Euclidean algorithm (EA) and CFA.

---Q 1.5: Show that the CFA is the inverse operation (i.e., the CFA is the GCD, run in reverse) (Hint: see Sect. 2.3.1 (p. 52)).
2.3 Lec 4: Applications of prime number

If someone asked you for a theory of counting numbers, I suspect you would laugh and start counting. It sounds like either a stupid question, or a bad joke. Yet integers are a rich topic, so the question is not even slightly dumb. It is somewhat amazing that even birds and bees can count. While I doubt birds and bees can recognize primes, cicadas and other insects only crawl out of the ground in prime number cycles, (e.g., 13 or 17 year cycles). If you have ever witnessed such an event (I have), you will never forget it. Somehow they know. Finally, there is an analytic function, first introduced by Euler, based on his analysis of the sieve, now known as the Riemann zeta function $\zeta(s)$, which is complex analytic, with its poles at the logs of the prime numbers. The exact relationship between the primes and the poles will be discussed in Section 3.2.4 (p. 99). The properties of this function are truly amazing, even fun. Many of the questions and answers about primes go back to at least the early Chinese (c1500 BCE) (Stillwell, 2010).

1. Write out $N - 1$ integers $n$, starting from 2: $n \in \{2, 3, \ldots, N\}$. (e.g., $N = 4, n \in \{2, 3, 4\}$). Note that the first element $\pi_1 = 2$ is the first prime. Cross out all multiples of $\pi_1$. That is, cross out $n \cdot \pi_1 = 4, 6, 8, 10, \ldots, 50$, that is all $n$ where $\mod(n, \pi_1) = 0$.

   \[
   \begin{array}{cccccccc}
   2 & 3 & \mathcal{A} & 5 & \mathcal{A} & 7 & \mathcal{A} & 9 & \mathcal{A} \\
   11 & 13 & 17 & 19 & 23 & 29 & 31 & 37 & 41 \\
   43 & 47 & 50 & & & & & &
   \end{array}
   \]

   This first step $k = 1$ has identified the first prime $\pi_1 = 2$.

2. Let $k = 2$ and note that $\pi_2 = 3$. Cross out $n\pi_2 \cdot (2, 3, 4, 5, 6, 7, \ldots, 45)$, i.e., all $n$ where $\mod(n, \pi_2) = 0$.

   \[
   \begin{array}{cccccccc}
   2 & 3 & \mathcal{A} & 5 & \mathcal{A} & 7 & \mathcal{A} & \mathcal{A} & \mathcal{A} \\
   11 & 13 & 17 & 19 & 23 & 29 & 31 & 37 & 41 \\
   \mathcal{A} & 23 & 29 & 31 & 37 & 41 & 43 & 47 & 50 \\
   \end{array}
   \]

3. Let $k = 3, \pi_3 = 5$. Cross out $n\pi_3 \cdot (25, 35)$ (use $\mod(n, 5)$).

   \[
   \begin{array}{cccccccc}
   2 & 3 & \mathcal{A} & 5 & \mathcal{A} & 7 & \mathcal{A} & \mathcal{A} & \mathcal{A} \\
   11 & 13 & 17 & 19 & 23 & 29 & 31 & 37 & 41 \\
   \mathcal{A} & 23 & 29 & 31 & 37 & 41 & 43 & 47 & 50 \\
   \end{array}
   \]

4. Finally let $k = 4, \pi_4 = 7$ (use $\mod(n, 7)$). Cross out $n\pi_4$ (49). Thus there are 15 primes less than $N = 50$: $\pi_k = 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47$ (highlighted in red). Above 2, all end in odd numbers, and above 5, all end with 1, 3, 7, 9.

   Figure 2.2: Sieve of Eratosthenes for $N = 50$.

The importance of prime numbers: Each prime perfectly predicts multiples of that prime, but there seems to be no regularity in predicting primes themselves explaining irregularities of numbers. It

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18 Nice discussion of primes: https://www.quantamagazine.org/mathematicians-discover-prime-conspiracy-20160313/
follows that prime numbers are the key to the theory of numbers, because of the *fundamental theorem of arithmetic* (FTA),

Likely the first insight into the counting numbers started with the **sieve**, shown in Fig. 2.2. A sieve answers the question “How can one identify the prime numbers?” The answer comes from looking for irregular patterns in the counting numbers, by playing the counting numbers against themselves.

A recursive sieve method for finding primes was first devised by the Greek Eratosthenes\(^\text{19}\) (276-194, BCE).

For example, starting from \(\pi_1 = 2\) one strikes out all even numbers \(2 \cdot (2, 3, 4, 5, 6, \ldots)\), but not 2. By definition the multiples are products of the target prime (2 in our example) and every other integer \((n \geq 2)\). In this way all the even numbers are removed in this first iteration. The next remaining integer (3 in our example) is identified as the second prime \(\pi_2\). Then all the multiples of \(\pi_2 = 3\) are removed. The next remaining number is \(\pi_3 = 5\), so all multiples of \(\pi_3 = 5\) are removed (i.e., \(10, 15, 20 \text{ etc.} \), \(\ldots\)). This process is repeated until all the numbers of the list have either been canceled or identified as prime.

As the word **sieve** implies, this process takes a heavy toll on the integers, rapidly pruning the non-primes. In four iterations of the sieve algorithm, all the primes below \(N = 50\) are identified in red. The final set of primes is displayed in step 4 of Fig. 2.2.

Once a prime greater than \(N/2\) has been identified (25 in the example), the recursion stops, since twice that prime is greater than \(N\), the maximum number under consideration. Thus once \(\sqrt{49}\) has been reached, all the primes have been identified (this follows from the fact that the next prime \(\pi_n\) is multiplied by an integer \(n = 1, \ldots N\)).

When using a computer, memory efficiency and speed are the main considerations. There are various schemes for making the sieve more efficient. For example, the recursion \(n \pi_k = (n-1) \pi_k + \pi_k\) will speed up the process by replacing the multiply with an addition of \(\pi_k\).

**Two fundamental theorems of primes:** Early theories of numbers revealed two fundamental theorems (there are many more than two), as discussed on pages 41, 50 and Section G (p. 271). The first of these is the *fundamental theorem of arithmetic*, which says that every integer \(n \in \mathbb{N}\) greater than 1 may be uniquely factored into a product of primes

\[
n = \prod_{k=1}^{K} \pi_k^{\beta_k},
\]

where \(k = 1, \ldots, K\) indexes the integer’s \(K\) prime factors \(\pi_k \in \mathbb{P}\). Typically prime factors appear more than once, for example \(25 = 5^2\). To make the notation compact we define the **multiplicity** \(\beta_k\) of each prime factor \(\pi_k\). For example \(2312 = 2^3 \cdot 17^2 = \pi_1^3 \pi_2^2\) (i.e., \(\pi_1 = 2, \beta_1 = 3; \pi_2 = 17, \beta_2 = 2\)) and \(2313 = 3^2 \cdot 257 = \pi_3^2 \pi_{55}\) (i.e., \(\pi_2 = 3, \beta_2 = 2; \pi_{55} = 257, \beta_{55} = 1\)). Our demonstration of this is empirical, using the Matlab/Octave *factor*(\(N\)) routine, which factors \(N\).\(^\text{20}\)

What seems amazing is the unique nature of this theorem. Each counting number is *uniquely* represented as a product of primes. No two integers can share the same factorization. Once you multiply the factors out, the result is unique (\(N\)). Note that it’s easy to multiply integers (e.g., primes), but expensive to factor them. And factoring the product of three primes is significantly more difficult than factoring two.

Factoring is much more expensive than division. This is not due to the higher cost of division over multiplication, which is less than a factor of 2.\(^\text{21}\) Dividing the product of two primes, given one, is trivial, slightly more expensive that multiplying. Factoring the product of two primes is nearly impossible, as one needs to know what to divide by. Factoring means dividing by some integer and obtaining another integer *with remainder zero*.

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\(^\text{19}\)https://en.wikipedia.org/wiki/Sieve_of_Eratosthenes\#Euler.27s_Sieve

\(^\text{20}\)If you wish to be a mathematician, you need to learn how to prove theorems. If you’re a physicist, you are happy that someone else has already proved them, so that you can use the result.

\(^\text{21}\)https://streamcomputing.eu/blog/2012-07-16/how-expensive-is-an-operation-on-a-cpu/
Thus one could factor a product of primes \( N = \pi_k \pi_l \) by doing \( M \) divisions, where \( M \) is the number of primes less than \( N \). This assumes the list of primes less than \( N \) are known. However, most integers are not a simple product of two primes

But the utility has to do with the sheer density of primes (the prime number theorem, i.e., Gauss’s hypothesis). If we were simply looking up a few numbers from a short list of primes, it would be easy, but the density of primes among the integers is logarithmic (\( \gg 1 \) per octave).

This brings us to the prime number theorem (PNT). The security problem is the reason why these two theorems are so important: 1) Every integer has a unique representation as a product of primes, and 2) the density of primes is large (see the discussions on p. 43 and Section G.2, p. 271). Thus security reduces to the “needle in the haystack problem” due to the cost of a search.

**Examples of the GCD:** \( k = \gcd(m,n) \)

* Examples \((m,n,k \in \mathbb{Z})\):

  - \( 5 = \gcd(13 \cdot 5, 11 \cdot 5) \). The GCD is the common factor 5.
  - \( \gcd(13 \cdot 10, 11 \cdot 10) = 10 (\gcd(130, 110) = 10 = 2 \cdot 5, \text{ is not prime}) \)
  - \( \gcd(1234, 1024) = 2 (1234 = 2 \cdot 617, 1024 = 2^{10}) \)
  - \( \gcd(\pi_k \pi_m, \pi_n \pi_n) = \pi_k \)
  - \( k = \gcd(m,n) \) is the part that cancels in the fraction \( m/n \in F \)
  - \( m/\gcd(m,n) \in \mathbb{Z} \)

* Coprimes \((m \perp n)\) are numbers with no distinct common factors: i.e., \( \gcd(m,n)=1 \)

  - The GCD of two primes is always 1: \( \gcd(13,11) = 1, \gcd(\pi_m, \pi_n)=1 \) \( (m \neq n) \)
  - \( m = 7 \cdot 13, n = 5 \cdot 19 \Rightarrow (7 \cdot 13) \perp (5 \cdot 19) \)
  - If \( m \perp n \) then \( \gcd(m,n) = 1 \)
  - If \( \gcd(m,n) = 1 \) then \( m \perp n \)

* The GCD may be extended to polynomials: e.g., \( \gcd(ax^2 + bx + c, \alpha x^2 + \beta x + \gamma) \)

  - \( \gcd((x-3)(x-4), (x-3)(x-5))= (x-3) \)
  - \( \gcd(x^2 - 7x + 12, 3(x^2 - 8x + 15))= 3(x-3) \)
  - \( \gcd(x^2 - 7x + 12, 3x^2 - 24x + 45)=3(x-3) \)
  - \( \gcd ((x-2\pi)(x-4), (x-2\pi)(x-5))=(x-2\pi) \) (Needs long division)

Figure 2.3: The Euclidean algorithm for finding the GCD of two numbers is one of the oldest algorithms in mathematics, and is highly relevant today. It is both powerful and simple. It was used by the Chinese during the Han dynasty (Stillwell, 2010, p. 70) for reducing fractions. It may be used to find pairs of integers that are coprime (their GCD must be 1). The GCD may be used to identify factors of polynomials by long division. It has an important sister algorithm called the continued fraction algorithm (CFA), that generalizes the Euclidean algorithm.

### 2.3.1 Lec 5: Greatest common divisor (Euclidean algorithm)

The Euclidean algorithm is a method to find the greatest common divisor (GCD) \( k \) between two integers \( n, m \), denoted \( k = \gcd(n,m) \), where \( n, m, k \in \mathbb{N} \) (Graham et al., 1994). For example, \( 15 = \gcd(30, 105) \) since, when factored \( (30, 105) = (2 \cdot 3 \cdot 5, 7 \cdot 3 \cdot 5) = 3 \cdot 5 \cdot (2, 7) = 15 \cdot (2, 7) \). The Euclidean algorithm is a method for finding the largest common divisor without factoring the two numbers. It was known to the Chinese (i.e., not discovered by Euclid) (Stillwell, 2010, p. 41). The GCD may be used to find coprimes, as described below in Fig. 2.3.

There are six closely related numeric operators which return integers \( \in \mathbb{Z} \) (Sect. A.2, p. 244). In Matlab/Octave: \( \text{floor}(x), \text{ceil}(x), \text{round}(x) \) take \( x \in \mathbb{R} \), and \( \text{mod}(n,m) \) (modulo), \( \text{rem}(n,m) \) (remainder), \( \gcd(n,m) \) (greatest common divisor) take \( n,m \in \mathbb{N} \). Rounding schemes are used in continued fractions and the others are widely used when doing arithmetic, such as division.

The remainder function (modulo) for real arguments is closely related to the phase of a pure delay, since the Laplace transform of a delay [Sect. B.2 (p. 250)] (delayed Dirac) is related to the phase is the
2.3. LECTURE 4: (WEEK 3) APPLICATIONS OF PRIME NUMBER

remainder (modular) function \((\text{mod } 2\pi)\), since
\[
\angle e^{-i\omega T} = \text{rem}(\omega T, 2\pi).
\]
Interestingly, in this instance the arguments of the remainder function are real \((\in \mathbb{R})\). Modular arithmetic may be alternatively written as \(\text{mod}(t, T) = ((t))_T\). Thus modular functions are the group of periodic functions. In Matlab/Octave \texttt{unwrap()} is the inverse of \texttt{mod()}.

The Euclidean algorithm: The algorithm is best explained by a trivial example: Let the two numbers be \(6, 9\). At each step the smaller number \((6)\) is subtracted from the larger \((9)\) and the smaller number and the difference (the remainder) are saved. This process continues until the two resulting numbers are equal, which is the GCD. For our example: \(9 - 6 = 3\), leaving the smaller number \(6\) and the difference \(3\). Repeating this we get \(6 - 3 = 3\), leaving the smaller number \(3\) and the difference \(3\). Since these two numbers are the same we are done and the GCD\(=3\). We can easily verify this result by factoring \([e.g., (9, 6) = 3(3, 2)]\). The value may also be numerically verified using the Matlab/Octave GCD command \texttt{gcd(6, 9)}, which returns \(3\).

Direct matrix method: The GCD may be written as a matrix recursion given the starting vector \(\begin{pmatrix} m_0 \\ n_0 \end{pmatrix}^T\). The recursion is then
\[
\begin{bmatrix} m_{k+1} \\ n_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} m_k \\ n_k \end{bmatrix}.
\] (2.7)

This recursion continues until \(m_{k+1} < n_{k+1}\), at which point \(m\) and \(n\) must be swapped. The process is repeated until \(m = n\), which equals the GCD. The direct method is inefficient because it recursively subtracts \(n\) many times until the resulting \(m\) is less than \(n\), as shown in Fig. 2.4. It also must test for \(m \leq n\) at each iteration, and then swap \(m\) and \(n\) if they are not equal.

Since this matrix may be inverted, the process may be reversed, which is closely related to the continued fraction algorithm (CFA) (p. 56).

Why is the GCD important? The utility of the GCD algorithm arises directly from the fundamental difficulty in factoring large integers. Computing the GCD, using the Euclidean algorithm, is low cost, compared to factoring when finding the coprime factors, which is extremely expensive. This utility surfaces when the two numbers are composed of very large primes.

When two integers have no common factors they are said to be coprimes, and their GCD is \(1\). The ratio of two integers which are coprime is automatically in reduced form (they have no common factors). For example, \(4/2 \in \mathbb{Q}\) is not reduced since \(2 = \text{gcd}(4, 2)\) (with no remainder). Canceling out the common factor \(2\) gives the reduced form \(2/1 \in \mathbb{F}\). Thus if we wish to form the ratio of two integers, first compute the GCD, then remove it from the two numbers to form the ratio. This assures the rational number is in its reduced form (\(\in \mathbb{F}\) rather than \(\in \mathbb{Q}\)). If the GCD were \(10^3\) digits, it is obvious that any common factor would need to be be removed, thus greatly simplifying further computation. This will make a huge difference when using IEEE-754.

The floor function and the GCD are related in an important way, as discussed next.

Exercise: What does it mean to reach the turning point when using the Euclidean algorithm? Solution: When \(m/n - \lfloor m/n \rfloor < n\) we have reached a turning point. When the remainder is zero (i.e., \(m/n - \lfloor m/n \rfloor = 0\)), we have reached the GCD.

The GCD and long division: When one learns how to divide a smaller number into a larger one, they must learn how to use the GCD. For example, suppose we which to compute \(6 \div 110\). One starts by finding out how many times \(6\) goes into \(11\). Since \(6 \times 2 = 12\), which is larger than \(11\), the answer is \(1\). We then subtract \(6\) from \(11\) to find the remainder \(5\). This is, of course, the floor function (e.g., \([11/6] = 1, [11/5] = 2\)).
**Example:** Divide 10 into 99, the *floor* function (*floor(99/10)*) must be used, followed by the *remainder* function (*rem(99,10)*). **Solution:** When we divide a smaller number into a larger one, we must first find the floor followed by the remainder. For example 99/10 = 9 + 9/10 has a floor of 9 and a remainder of 9/10.

**Example:** Start with the two integers [873, 582]. In factored form these are [\(\pi^{25} \cdot 3^2, \pi^{25} \cdot 3 \cdot 2\)]. Given the factors, we see that the largest common factor is \(\pi^{25} \cdot 3 = 291\) (\(\pi^{25} = 97\)). When we take the ratio of the two numbers this common factor cancels \(\frac{873}{582} = \frac{\pi^{25} \cdot 3}{\pi^{25} \cdot 3 \cdot 2} = \frac{3}{2} = 1.5\). Of course if we divide 582 into 873 we will numerically obtain the answer \(1.5 \in \mathbb{F}\).

**Exercise:** Show that in Matlab/Octave \(\text{rat}(873/582) = 1 + 1/(−2)\) gives the wrong answer. **Solution:** Since \(\text{factor}(873) = 3 \cdot 3 \cdot 97\) and \(\text{factor}(582) = 2 \cdot 3 \cdot 97\), thus \(\frac{3}{2} = 1 + 1/2\) is the correct answer. But due to rounding methods, it is not 3/2. As an example, in Matlab/Octave \(\text{rat}(3/2) = 2 + 1/(−2)\). Matlab’s \(\text{rat()}\) command uses rounding rather than the floor function, which explains the difference. When the \(\text{rat()}\) function produces negative numbers, rounding is employed.

**Graphical description of the GCD:** The Euclidean algorithm is very simple when viewed graphically. In Fig. 2.4 we show what is happening as one approaches the threshold. After reaching the threshold, the two numbers must be swapped, which is addressed by the upper row of Eq. H.1. Below is a simple Matlab/Octave code to find \(k = \text{gcd}(m,n)\) based on the Stillwell (2010) definition of the EA:

```matlab
function k = gcd(m,n)
while m ~= 0
    A=m; B=n;
    m=max(A,B); n=min(A,B);  %m>n
    m=m-n;
```

![Figure 2.4: The Euclidean algorithm recursively subtracts n from m until the remainder m – kn is either less than n or zero. Note that this recursion is the same as mod(m, n). Thus the GCD recursively computes mod(m, n) until the remainder rem(m, n) is less than n. It then swaps m, n, so that n < m. This repeats, until it terminates on the GCD. For the case depicted here the value of k, that renders the remainder m – kn < n. If one more step were taken (k = 7) the remainder would become negative. By linear interpolation we can find that m – \(\alpha n = 0, \alpha \in \mathbb{R}\), where the solid line cross the abscissa. For this example k = 6.5, thus 6 = [m/n] < n. This is nonlinear (truncation) arithmetic, which is a property related to the GCD. The floor() functions finds the turning point, where we swap the two numbers, since by definition, m > n. In this example k = 6 = [m/n].]
This program loops until \( m = 0 \).

Multiplication is simply recursive addition, and finding the GCD takes advantage of this fact. Let’s take a trivial example, \((9, 6)\). Taking the difference \(9 - 6\) (the larger from the smaller), and writing multiplication as sums, one can see what is going on. The GCD may be written two equivalent ways:

\[
9 - 6 = (3 + 3 + 3) - (3 + 3) = 0 + 0 + 3 = 3, \\
\]

and

\[
9 - 6 = (3 + 3 + 3) - (2 + 2 + 2) = 1 + 1 + 1 = 3. \\
\]

Written the first way, it is 3, because subtracting \((3 + 3)\) from \((3 + 3 + 3)\) leaves 3. Written the second way, each 3 is matched with a \(-2\), leaving 3 ones, which add to 3. Of course the two decomposition must yield the same result because \(2 \cdot 3 = 3 \cdot 2\). Thus finding the remainder of the larger number minus the smaller yields the GCD of the two numbers.

**Coprimes:** When the GCD of two integers is 1, the only common factor is 1. This is of key importance when trying to find common factors between the two integers. When \(1 = \gcd(m, n)\) they are said to be coprime or “relatively prime,” which is frequently written as \(m \perp n\). By definition, the largest common factor of coprimes is 1. But since 1 is not a prime (\(\pi_1 = 2\)), they have no common primes. It can be shown (Stillwell, 2010, p. 41-42) that when \(a \perp b\), there exist \(m, n \in \mathbb{Z}\) such that

\[
am + bn = \gcd(a, b) = 1.
\]

A much more efficient method uses the \(\text{floor()}\) function, which is called division with rounding. Specifically the GCD may be written in one step as

\[
\begin{bmatrix} m \\ n \end{bmatrix}_{k+1} = \begin{bmatrix} 0 & 1 \\ 1 & -\left\lfloor \frac{m}{n} \right\rfloor \end{bmatrix} \begin{bmatrix} m \\ n \end{bmatrix}_k. \tag{2.8}
\]

This matrix is simply Eq. 2.7 to the power \(\left\lfloor \frac{m}{n} \right\rfloor\), followed by swapping the inputs (the smaller must always be on the bottom).

**2.3.2 Lec 6: Continued fraction algorithm**

As shown in Fig. 2.5, the continued fraction algorithm (CFA) starts from a single real decimal number \(x_o \in \mathbb{R}\), and recursively expands it as a fraction \(x \in \mathbb{F}\) (Graham et al., 1994). Thus the CFA may be used for forming rational approximations to any real number. For example, \(\pi \approx \frac{22}{7}\), and excellent approximation, well known to Chinese mathematicians.

The the Euclidean algorithm (i.e., GCD), on the other hand, operates on a pair of integers \(m, n \in \mathbb{N}\) and returns their greatest common divisor \(k \in \mathbb{N}\), such that \(m/k, n/k \in \mathbb{F}\) are coprime, thus reducing the ratio to its irreducible form (i.e., \(m/k \perp n/k\)). Note this is done without factoring \(m, n\).

Despite this seemingly irreconcilable difference between the GCD and CFA, the two are closely related, so close that Gauss called the Euclidean algorithm, for finding the GCD, as the continued fraction algorithm (CFA) (Stillwell, 2010, P. 48). At first glance it is not clear why Gauss would be so “confused.” One is forced to assume that Gauss had some deeper insight into this relationship. If so, that insight would be valuable to understand.\(^{22}\)

\(^{22}\)In some sense, to be explored, the GCD and CFA are inverses.
Definition of the CFA

1. Start with \( n = 0 \) and the positive input target \( x_o \in \mathbb{R}^+ \).
   \[ n = 0, m_0 = 0, x_o = \pi \]

2. Rounding: Let \( m_n = \lfloor x_n \rfloor \in \mathbb{N} \).
   \[ m_0 = \lfloor \pi \rfloor = 3 \]

3. The input vector is then: \( [x_n, m_n]^T \).
   \[ [\pi, 3]^T \]

4. Remainder: \( r_n = x_n - m_n \) \((-0.5 \leq r_n \leq 0.5)\).
   \[ r_0 = \pi - 3 \approx 0.14159 \]

5. Reciprocate:
   \[ x_{n+1} = \begin{cases} \frac{1}{r_n}, \text{ return to step 2} & r_n \neq 0 \\ 0, \text{ terminate} & r_n = 0. \end{cases} \]
   \[ x_1 = 1/0.14159 = 7.062646 \]

6. The output vector is \( [x_{n+1}, m_n]^T \).
   \[ [7.062646, 3]^T \]

Figure 2.5: The CFA of any positive number, \( x_o \in \mathbb{R}^+ \), is defined in this figure. Numerical values for \( n = 0, x_o = \pi, m_0 = 0 \) are given in blue on the far right. For \( n = 1 \) the input vector is \( [x_1, m_1]^T = [7.062646, 3]^T \). If at any step the remainder is zero, the algorithm terminates (Step 5). Convergence is guaranteed. The recursion may continue to any desired accuracy. Alternative rounding schemes are given on p. 244.

Notation: Writing out all the fractions can become tedious. For example, expanding \( e = 2.7183 \cdots \) using the Matlab/Octave command \( \text{rat}(\exp(1)) \) gives the approximation

\[
\exp(1) = 3 + 1/( -4 + 1/( 2 + 1/( 5 + 1/(-2 + 1/(-7)))) ) - o \left( 1.75 \times 10^{-6} \right), \\
= [3; -4, 2, 5, -2, -7] - o(1.75 \times 10^{-6}).
\]

Here we use a compact bracket notation, \( \hat{e}_6 \approx [3; -4, 2, 5, -2, -7] \) where \( o() \) indicates the error of the CFA expansion.

Since many entries are negative, we may deduce that rounding arithmetic is being used by Matlab/Octave (but this is not documented). Note that the leading integer part may be noted by an optional semicolon.23 If the process is carried further, the values of \( a_n \in \mathbb{N} \) give increasingly more accurate rational approximations.

Example: Let \( x_o \equiv \pi \approx 3.14159 \ldots \) Thus \( a_o = 3, r_o = 0.14159, x_1 = 7.065 \approx 1/r_o, \) and \( a_1 = 7. \) If we were to stop here we would have

\[ \hat{\pi}_2 \approx 3 + \frac{1}{7 + 0.0625} \approx 3 + \frac{1}{7} = \frac{22}{7}. \] (2.9)

This approximation of \( \pi \approx 22/7 \) has a relative error of 0.04%

\[ \frac{22/7 - \pi}{\pi} = 0.04 \]

Example: For a second level of approximation we continue by reciprocating the remainder \( 1/0.0625 \approx 15.9966 \) which rounds to 16 giving a negative remainder of \( \approx -1/300: \)

\[ \hat{\pi}_3 \approx 3 + 1/(7 + 16) = 3 + 16/(7 \cdot 16 + 1) = 3 + 16/113 = 355/113. \]

23 Unfortunately Matlab/Octave does not support the bracket notation.
With rounding the remainder is $-0.0034$, resulting in a much more rapid convergence. If floor rounding is used ($15.9966 = 15 - 0.9966$) the remainder is positive and close to 1, resulting in a much less accurate rational approximation for the same number of terms. It follows that there can be a dramatic difference depending on the rounding scheme, which, for clarity, should be specified, not inferred.

**Rational approximation examples**

$$\hat{\pi}_2 = \frac{22}{7} = [3; 7] \approx \hat{\pi}_2 + o(1.3 \times 10^{-3})$$

$$\hat{\pi}_3 = \frac{355}{113} = [3; 7, 16] \approx \hat{\pi}_3 - o(2.7 \times 10^{-7})$$

$$\hat{\pi}_4 = \frac{104348}{33215} = [3; 7, 16, -249] \approx \hat{\pi}_4 + o(3.3 \times 10^{-10})$$

Figure 2.6: The expansion of $\pi$ to various orders, using the CFA, along with the order of the error of each rational approximation, with rounding. For example, $\hat{\pi}_2 = 22/7$ has an absolute error ($|22/7 - \pi|$) of about 0.13%.

**CFA as a matrix recursion:** Start with $n_0 = 0 \in \mathbb{N}$, $x_0 \in \mathbb{I}$, $n_1 = [x_0] \in \mathbb{N}$, $r_1 = x - [x] \in \mathbb{I}$ and $x_1 = 1/r_1 \in \mathbb{I}$, $r_1 \neq 0$.

In matrix notation, with $k \in \mathbb{N}$

$$\begin{bmatrix} n \\ x \end{bmatrix}_{k+1} = \begin{bmatrix} 0 & [x_0] \\ 0 & \frac{1}{x_0-[x_0]} \end{bmatrix} \begin{bmatrix} n \\ x \end{bmatrix}_k$$

This generates the next CFA parameter $n_1$, and $x_1 = 1/r_1$ from $n_0$ and $x_0$.

**Example:** If $x_0 = \pi$, then $n_1 = [\pi] = 3$, $r_1 = \pi - n_1 = 0.141592656 \cdots$, and $x_1 = 1/r_1$:

$$\begin{bmatrix} 3 \\ 7.06251331 \end{bmatrix}_1 = \begin{bmatrix} 0 & [\pi] \\ 0 & \frac{1}{\pi-[\pi]} \end{bmatrix} \begin{bmatrix} 0 \\ \pi \end{bmatrix}_0$$

and for $n = 2$

$$\begin{bmatrix} 7 \\ 15.99659 \end{bmatrix}_2 = \begin{bmatrix} 7 \\ 0.06251331 \end{bmatrix}_2 = \begin{bmatrix} 0 & 7 \\ 0 & \frac{1}{0.06251331} \end{bmatrix} \begin{bmatrix} 3 \\ 7.06251331 \end{bmatrix}_1$$

For $n = 3$, $\pi_3 = [n_1; n_2, n_3] = [3; 7, 15]$. Continuing $n_4 = [1.003418] = 1$ and $n_5 = 292$. Clean up indexing.

**Exercise:** Find the CFA using the floor function, to 12th order.

**Solution:** $\hat{\pi}_{12} = [3; 7, 15, 1, 292, 1, 1, 2, 1, 3, 1]$.

**Example:** Matlab/Octave’s `rat(pi, 1e-20)` gives:

$$3 + 1/(7 + 1/(16 + 1/(-294 + 1/(3 + 1/(-4 + 1/(5 + 1/(-15 + 1/(-3))))))))$$

In bracket notation

$$\hat{\pi}_9 = [3; 7, 16, -294, 3, -4.5, -15, 03]$$

Because the sign changes, it is clear that Matlab/Octave use rounding rather than the floor function.
**Exercise:** Based on several examples, which rounding scheme is the most accurate? Explain why.

**Solution:** Rounding will result in a smaller remainder at each iteration, thus a smaller net error and thus improved convergence.

When the CFA is applied and the expansion terminates \((r_n = 0)\), the target is rational. When the expansion does not terminate (which is not always easy to determine, as the remainder may be ill-conditioned due to small numerical rounding errors), the number is irrational. Thus the CFA has important theoretical applications regarding irrational numbers. You may explore this using Matlab’s \texttt{rats(pi)} command.

Besides these five basic rounding schemes, there are two other important \(R \rightarrow N\) functions (i.e., mappings), which will be needed later: \(\text{mod}(x,y)\), \(\text{rem}(x,y)\) with \(x,y \in \mathbb{R}\). The base 10 numbers \(10\) may be generated from the counting numbers using \(y = \text{mod}(x,10)\).

**Exercise:**

1. Show how to generate a base-10 real number \(y \in \mathbb{R}\) from the counting numbers \(\mathbb{N}\) using the \(m = \text{mod}(n,10) + k10\) with \(n,k \in \mathbb{N}\). **Solution:** Every time \(n\) reaches a multiple of 10, \(m\) is reset to 0 and the next digit to the left is increased by 1, by adding 1 to \(k\), generating the digit pair \(km\). Thus the \(\text{mod}()\) function forms the underlying theory behind decimal notation.

2. How would you generate binary numbers (base 2) using the \(\text{mod}(x,b)\) function? **Solution:** Use the same method as in the first example above, but with \(b = 2\).

3. How would you generate hexadecimal numbers (base 16) using the \(\text{mod}(x,b)\) function? **Solution:** Use the same method as in the first example above, but with \(b = 16\).

4. Write out the first 19 numbers in hex notation, starting from zero. **Solution:** 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F, 10, 11, 12. Recall that \(10_{16} = 16_{10}\) thus \(12_{16} = 18_{10}\), resulting in a total of 19 numbers if we include 0.

5. What is \(FF_{16}\) in decimal notation? **Solution:** \texttt{hex2dec(’ff’)} = 255_{10}.

**Symmetry:** A continued fraction expansion can have a high degree of “recursive symmetry.” For example, the CFA of

\[
R_1 \equiv \frac{1 + \sqrt{5}}{2} = 1 + \frac{1}{1 + \frac{1}{\cdots}} = 1.618033988749895 \cdots. \tag{2.10}
\]

Here \(a_n\) in the CFA is always 1 \((R_1 \equiv [1, 1, 1, \cdots])\), thus the sequence cannot terminate, proving that \(\sqrt{5} \in \mathbb{Q}\). A related example is \(R_2 \equiv \text{rat}(1+\sqrt{2})\), which gives \(R_2 = [2, 2, 2, 2, \cdots]\).

When expanding a target irrational number \((x_o \in \mathbb{I})\), and the CFA is truncated, the resulting rational fraction approximates the irrational target. For the example above, if we truncate at three coefficients \(([1; 1])\) we obtain

\[
1 + \frac{1}{1 + \frac{1}{1+0}} = 1 + 1/2 = 3/2 = 1.5 = \frac{1 + \sqrt{5}}{2} + 0.118 \cdots.
\]

Truncation after six steps gives

\([1., 1, 1, 1, 1, 1] = 13/8 \approx 1.6250 = \frac{1 + \sqrt{5}}{2} + .0070 \cdots.\]

Because all the coefficients are 1, this example converges very slowly. When the coefficients are large (i.e., remainder small), the convergence will be faster. The expansion of \(\pi\) is an example of faster convergence.
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Exercise: Discuss the relationship between the CFA and the transmission line modeling method of Sect. 3.5 (p. 119). Solution: The solution is detailed in Sect. 2.3.1 (p. 52).

In summary: Every rational number m/n ∈ ℤ, with m > n > 1, may be uniquely expanded as a continued fraction, with coefficients a_k determined using the CFA. When the target number is irrational (x_o ∈ ℝ), the CFA does not terminate; thus, each step produces a more accurate rational approximation, converging in the limit as n → ∞.

Thus the CFA expansion is an algorithm that can, in theory, determine when the target is rational, but with an important caveat: one must determine if the expansion terminates. This may not be obvious. The fraction 1/3 = 0.33333 ⋯ is an example of such a target, where the CFA terminates yet the fraction repeats. It must be that

\[ 1/3 = 3 \times 10^{-1} + 3 \times 10^{-2} + 3 \times 10^{-3} + \cdots. \]

Here 3*3=9. As a second example

\[ 1/7 = 0.142857142857142857142857 \cdots = \frac{1}{7}. \]

There are several notations for repeating decimals such as 1/7 = 0.142857 and 1/7 = 0.\overline{1}\{(142857)\}. Note that 142857 = 999999/7. Related identities include 1/11 = 0.090909 ⋯ and 11 \times 0.090909 = 999999. When the sequence of digits repeats, the sequence is predictable, and it must be rational. But it is impossible to be sure that it repeats because the length of the repeat can be arbitrarily long.

One of the many useful things about the procedure is its generalizations to the expansion of transmission lines, as complex functions of the Laplace complex frequency s. In Assignment 4.5.5, [see Fig. 4.11 (p. 179)], a transmission line is analogized in terms of the CFA, but expanded in terms of the Laplace frequency s, rather than as integers. This method, called a Cauer synthesis, is based on the ABCD transmission line method of Secs. 3.5 (p. 119).

2.3.3 Lec 7: Pythagorean triplets (Euclid’s formula)

Euclid’s formula is a method for finding three integer lengths [a, b, c] ∈ ℤ that satisfy Eq. 1.1. It is important to ask: Which set are the lengths [a,b,c] drawn from? There is a huge difference, both practical and theoretical, if they are from the real numbers ℝ, or the counting numbers ℤ. Given p, q ∈ ℤ with p > q, the three lengths [a, b, c] ∈ ℤ of Eq. 1.1 are given by

\[ a = p^2 - q^2, \quad b = 2pq, \quad c = p^2 + q^2. \]  \hspace{1cm} (2.11)

Figure 2.7: Beads on a string form perfect right triangles when the number of unit lengths between beads for each side satisfies Eq. 1.1. For example, when p = 2, q = 1, the sides are [3, 4, 5].

This result may be directly verified, since

\[ [p^2 + q^2]^2 = [p^2 - q^2]^2 + [2pq]^2 \]

24Taking the Fourier transform of the target number, represented as a sequence, could help to identify an underlying periodic component. The number 1/7 ↔ [[1, 4, 2, 8, 5, 7]] has a 50 dB notch at 0.8π [rad] due to its 6 digit periodicity, carried to 15 digits (Matlab/Octave maximum precision), Hamming windowed, and zero padded to 1024 samples.
or
\[ p^4 + q^4 + 2p^2q^2 = p^4 + q^4 - 2p^2q^2 + 4pq^2. \]

Thus, Eq. 2.11 is easily proven, once given. Deriving Euclid’s formula is obviously much more difficult, and is shown in Fig. 3.4 (p. 98).

A well-known example is the right triangle depicted in Fig. 2.7 (p. 59), defined by the integers \([3, 4, 5] \in \mathbb{N}\), having angles \([0.54, 0.65, \pi/2]\) [rad], which satisfies Eq. 1.1 (p. 19). As quantified by Euclid’s formula (Eq. 2.11), there are an infinite number of Pythagorean triplets (PTs). Furthermore, the seemingly simple triangle, having angles of \([30, 60, 90] \in \mathbb{N}[\text{deg}]\) (i.e., \([\pi/6, \pi/3, \pi/2] \in \mathbb{I}[\text{rad}]\), has one irrational (I) length \((1, \sqrt{3}, 2)\).

Table 2.2: Table of Pythagorean triples computed from Euclid’s formula Eq. 2.11 for various \([p, q]\). The last three columns are the first, fourth and next to last, from “Plimpton-322,” along with their corresponding \([p, q]\). In all cases \(c^2 = a^2 + b^2\) and \(p = q + l\), where \(l = \sqrt{c^2 - b^2} \in \mathbb{N}\).

<table>
<thead>
<tr>
<th></th>
<th>q</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>125</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>a</td>
<td>3</td>
<td>8</td>
<td>15</td>
<td>5</td>
<td>12</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>b</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>c</td>
<td>5</td>
<td>10</td>
<td>17</td>
<td>13</td>
<td>20</td>
<td>29</td>
<td>169</td>
</tr>
</tbody>
</table>

The technique for proving Euclid’s formula for PTs \([a, b, c] \in \mathbb{Q}\), derived in Fig. 3.4 (p. 98) is much more interesting than the PTs themselves.

The set from which the lengths \([a, b, c]\) are drawn was not missed by the Indians, Chinese, Egyptians, Mesopotamians, Greeks, etc. Any equation whose solution is based on integers is called a Diophantine equation, named after the Greek mathematician Diophantus of Alexandria (c250 CE) (Fig. 1.1, p. 19).

A stone tablet having the numbers engraved on it, as shown in Fig. 2.8, was discovered in Mesopotamia, from the 19th century [BCE], and cataloged in 1922 by George Plimpton.\(^{25}\)\(^{26}\) These numbers are \([a, b, c]\) pairs from PTs \([a, b, c]\). Given this discovery, it is clear that the Pythagoreans were following those who

\(^{26}\)https://en.wikipedia.org/wiki/Plimpton_322
2.3. LECTURE 4: (WEEK 3) APPLICATIONS OF PRIME NUMBER

came long before them. Recently a second similar stone, dating between 350 and 50 [BCE] has been reported, that indicates early calculus on the orbit of Jupiter’s moons, the very same moons that Rømer observed to show that the speed of light was finite (p. 24).

2.3.4 Lec 8: Pell’s equation

Pell’s equation

\[
x_n^2 - Ny_n^2 = (x_n - \sqrt{N}y_n)(x_n + \sqrt{N}y_n) = 1,
\]

(2.12)

with non-square \( N \in \mathbb{N} \) specified and \( x, y \in \mathbb{N} \) unknown, has a venerable history in both physics (p. 33) and mathematics. Given its factored form it is obvious that every solution \( x_n, y_n \) has the asymptotic property

\[
\frac{x_n}{y_n} \quad n \to \infty \to \pm \sqrt{N}.
\]

It is believed that Pell’s equation is directly related to the Pythagorean theorem, and therefore to the Euclidean algorithm, since they are both simple binomials having integer coefficients (Stillwell, 2010, 48), with Pell’s equation being the hyperbolic version of Eq. 1.1. For example, with \( N = 2 \), a solution is \( x = 17, y = 12 \) (i.e., \( 17^2 - 2 \cdot 12^2 = 1 \)).

A 2 \times 2 matrix recursion algorithm likely due to the Chinese, and used by the Pythagoreans to investigate \( \sqrt{N} \), is

\[
\begin{bmatrix}
x \\
y
\end{bmatrix}_{n+1} = \begin{bmatrix}
1 & N \\
1 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y
\end{bmatrix}_n,
\]

(2.13)

where we indicate the index outside the vectors.

Starting with the trivial solution \( [x_0, y_0]^T = [1, 0]^T \) (i.e., \( x_0^2 - Ny_0^2 = 1 \)), additional solutions of Pell’s equations are determined, having the propriety \( x_n/y_n \to \sqrt{N} \in \mathbb{F} \) (Stillwell, 2010, p. 44). This approach was motivated by the Euclidean algorithm (GCD, p. 52, 275), since \( y_n/x_n \to \sqrt{2} \) (Stillwell, 2010, p. 37, 55).

Note that Eq. 2.13 is a 2x2 matrix composition method (see p. 102), since the output of one matrix multiply is the input to the next. Why Eqs. 2.13 and 2.12 are equivalent is explained in Section 3.2.3 (p. 92).

Asian solutions: The first solution of Pell’s equation was published by Brahmagupta (c628), who independently discovered the equation (Stillwell, 2010, p. 46). Brahmagupta’s novel solution also used the composition method, but different from Eq. 2.13 (Stillwell, 2010, p. 69). Then in 1150CE, Bhāskara II independently obtained solutions using Eq. 2.13 (Stillwell, 2010, p.69). This is the composition method we shall explore here, as summarized in Table F.1 (p. 270).

The best way to see how this recursion results in solutions to Pell’s equation is by example. Initial-

using a slightly modified matrix recursion. Note that the 2x2 matrix
\[ \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \]
may also be used to find approximations to Pell’s equation.

The following summarizes the solution (\( x_0, y_0 \)) of Pell’s equation for \( N = 2 \) using a slightly modified matrix recursion. Note that \( x_n/y_n \rightarrow \sqrt{2} \) as \( n \rightarrow \infty \), which was what the Pythagoreans were pursuing, and that the odd solutions are pure-imaginary.

Thus the recursion results in a modified version of Pell’s equation
\[ x_n^2 - 2y_n^2 = (-1)^n, \]
where only even values of \( n \) are solutions. This sign change had no effect on the Pythagoreans’ goal, since they only cared about the ratio \( y_n/x_n \rightarrow \pm \sqrt{2} \).

**Modified recursion:** The following summarizes the solution (\( \in \mathbb{C} \)) of Pell’s equation for \( N = 2 \) using a slightly modified matrix recursion. Note that \( x_n/y_n \rightarrow \sqrt{2} \) as \( n \rightarrow \infty \), which was what the Pythagoreans were pursuing, and that the odd solutions are pure-imaginary.

As shown below the recursion may be slightly modified to fix the \((-1)^n\) problem, by multiplying the 2x2 matrix by \( 1_j = \sqrt{-1} \). This results in Pell’s equation for every step of the recursion:

\[
\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = 1_j \begin{bmatrix} 1 \\ 1 \end{bmatrix} = 1_j \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = j^2 = 2 \cdot j^2 = 1 \\
\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = j^2 \begin{bmatrix} 3 \\ 2 \end{bmatrix} = j^2 \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = 3^2 = 2 \cdot 2^2 = 1 \\
\begin{bmatrix} x_3 \\ y_3 \end{bmatrix} = j^3 \begin{bmatrix} 7 \\ 5 \end{bmatrix} = j^3 \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 2 \end{bmatrix} = (7j)^2 = 2 \cdot (5j)^2 = 1 \\
\begin{bmatrix} x_4 \\ y_4 \end{bmatrix} = j^4 \begin{bmatrix} 17 \\ 12 \end{bmatrix} = j^4 \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 7 \\ 5 \end{bmatrix} = 17^2 = 2 \cdot 12^2 = 1 \\
\begin{bmatrix} x_5 \\ y_5 \end{bmatrix} = j^5 \begin{bmatrix} 41 \\ 29 \end{bmatrix} = j^5 \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 17 \\ 12 \end{bmatrix} = (41j)^2 = 2 \cdot (29j)^2 = 1 \\
\]

**Solution to Pell’s equation:** By multiplying the matrix by \( 1_j \), all the solutions \( x_k \in \mathbb{C} \) to Pell’s equation are determined. The \( 1_j \) factor corrects the alternation in sign, so every iteration yields a solution. Fig. F.1 (p. 270) shows that every output of this slightly modified matrix recursion gives solutions to Pell’s equation. For \( n = 0 \) (the initial solution) \( [x_0, y_0] = [1, 0] \), \( [x_1, y_1] = j[1, 1] \), and \( [x_2, y_2] = -[3, 2] \). These are easily checked using this recursion.

At each iteration, the ratio \( x_n/y_n \) approaches \( \sqrt{2} \) with increasing accuracy, coupling it to the CFA which may also be used to find approximations to \( \sqrt{N} \). The value of \( 41/29 \approx \sqrt{2} \), with a relative error of \(<0.03\%\). The solution for \( N = 3 \) is given in Appendix F.1.1 (p. 270).
2.3.5 Lec 9: Fibonacci sequence

Another classic problem, also formulated by the Chinese, was the Fibonacci sequence, generated by the relation
\[ f_{n+1} = f_n + f_{n-1}. \] (2.15)

Here the next number \( f_{n+1} \in \mathbb{N} \) is the sum of the previous two. If we start from \([0, 1]\), this difference equation leads to the Fibonacci sequence \( f_n = [0, 1, 1, 2, 3, 5, 8, 13, 21, 34, \ldots] \). Alternatively, if we define \( y_{n+1} = x_n \), then Eq. 2.15 may be compactly represented by a 2x2 companion matrix recursion (see Exercise on p. 63)
\[
\begin{bmatrix} x \\ y \end{bmatrix}_{n+1} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}_n,
\] (2.16)
which has eigenvalues \((1 \pm \sqrt{5})/2\).

The correspondence of Eqs. 2.15 and 2.16 is easily verified. Starting with \([x, y]^T_0 = [0, 1]^T\) we obtain for the first few steps

\[
\begin{bmatrix} 1 \\ 0 \end{bmatrix}_1 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix}_0, \quad \begin{bmatrix} 1 \\ 2 \end{bmatrix}_2 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix}_1, \quad \begin{bmatrix} 2 \\ 3 \end{bmatrix}_3 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \end{bmatrix}_2, \quad \begin{bmatrix} 3 \\ 5 \end{bmatrix}_4 = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 2 \\ 3 \end{bmatrix}_3, \ldots.
\]

From the above \( x_n = [0, 1, 1, 2, 3, 5, \ldots] \) is the Fibonacci sequence, since the next \( x_n \) is the sum of the previous two, and the next \( y_n \) is \( x_n \).

**Figure 2.9:** This construction is called the Fibonacci spiral. Note how it is constructed out of squares having areas given by the square of the Fibonacci numbers. In this way, the spiral is smooth and the radius increases as the Fibonacci numbers (e.g., \( 8=3+5, 13=5+8, \) etc.). (Adapted from https://en.wikipedia.org/wiki/Golden_spiral.)

**Exercise:** Use the Octave/Matlab command `compan(c)` to find the companion matrix of the polynomial coefficients defined by Eq. 2.15. **Solution:** Using the Matlab/Octave code:
```
c=[1, -1, -1]; C=companion(c);
```
returning
\[
C = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}
\] (2.17)

**Exercise:** Find the eigenvalues of matrix \( C \). **Solution:** The characteristic equation is
\[
\det \begin{bmatrix} 1 - \lambda & 1 \\ 1 & -\lambda \end{bmatrix} = 0
\]
or \( \lambda^2 - \lambda - 1 = (\lambda - 1/2)^2 - 1/4 - 1 = 0 \), which has roots \( \lambda_{\pm} = (1 \pm \sqrt{5})/2 \approx \{1.618, -0.618\} \).

**The mean-Fibonacci sequence:** Suppose that the Fibonacci sequence recursion is replaced by the mean of the last two values, namely let
\[ f_{n+1} = \frac{f_n + f_{n-1}}{2}. \] (2.18)

This seems like a small change. But how does the solution differ? To answer this question it is helpful to look at the corresponding 2x2 matrix.
**Exercise:** Find the 2x2 matrix corresponding to Eq. 2.18. The 2x2 matrix may be found using the companion matrix method (p. 81). **Solution:** Using Matlab/Octave code:

\[
A = \begin{bmatrix} 1 & -1/2 \\ -1/2 & 0 \end{bmatrix}
\]

\[
C = \text{companion}(A);
\]

which returns

\[
A = \begin{bmatrix} 1 & 1 \\ 2 & 0 \end{bmatrix}
\]

**Exercise:** Find the sequence from the mean-Fibonacci starting from \([1, 0]\). **Solution:** By inspection one steady-state solution is \([1, 1]_\infty\). What is the second steady-state in the solution?

**Relations to digital signal processing:** Today we recognize Eq. 2.15 as a *difference equation*, which is a pre-limit (pre Stream 3) form of a differential equation. The Greek 2x2 matrix form of Eq. 2.15 is an early precursor to 17th and 18th century developments in linear algebra. Thus the Greeks’ recursive solution for the \(\sqrt{2}\) and Bhāskara’s (1030 CE) solution of Pell’s equation are early precursors to discrete-time processing, as well as to calculus.

There are strong similarities between Pell’s equation and the Pythagorean theorem. As we shall see in Appendix G, Pell’s equation is related to the geometry of a hyperbola, just as the Pythagorean equation is related to the geometry of a circle. We shall show, as one might assume, that there is a Euclidean formula for the case of Pell’s equations, since these are all conic sections with closely related conic geometry. As we have seen, the solutions involve \(\sqrt{-1}\). The derivation is a trivial extension of that for the Euclidean algorithm. The early solution of Brahmagupta was not related to such a simple formula. Rather it was based on the recursion Eq. 2.15 (Stillwell, 2010).

It makes one wonder if Eq. 1.1, written as \(x_n^2 + y_n^2 = z_n^2\), with \(x_n, y_n, z_n \in \mathbb{N}\), has a 2x2 matrix composition solution.

**Exercise:** Work out the details of this conjecture. Hint: \(z^2 = x^2 + y^2 = (x+yz)(x-yz)\). **Solution:** The solution may be found in Allen (2019, p. ??).
2.3.6 Exercises NS-3

**Topic of this homework:** Pythagorean triples, Pell’s equation, Fibonacci sequence

**Deliverable:** Answers to problems

---

**Pythagorean triplets**

**Problem #1:** Euclid’s formula for the Pythagorean triplets \( a, b, c \) is: \( a = p^2 - q^2, \) \( b = 2pq, \) and \( c = p^2 + q^2. \)

\[-Q 1.1: \text{What condition(s) must hold for } p \text{ and } q \text{ such that } a, b, \text{ and } c \text{ are always positive and nonzero?}\]

\[-Q 1.2: \text{Solve for } p \text{ and } q \text{ in terms of } a, b \text{ and } c.\]

**Problem #2:** The ancient Babylonians (c2000BEC) cryptically recorded \((a,c)\) pairs of numbers on a clay tablet, archeologically denoted Plimpton-322.

\[-Q 2.1: \text{Find } p \text{ and } q \text{ for the first five pairs of } a \text{ and } c \text{ from the tablet entries. Table 1: First five } (a,c) \text{ pairs of Plimpton-322.}\]

<table>
<thead>
<tr>
<th>( a )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>119</td>
<td>169</td>
</tr>
<tr>
<td>3367</td>
<td>4825</td>
</tr>
<tr>
<td>4601</td>
<td>6649</td>
</tr>
<tr>
<td>12709</td>
<td>18541</td>
</tr>
<tr>
<td>65</td>
<td>97</td>
</tr>
</tbody>
</table>

Find a formula for \( a \) in terms of \( p \) and \( q \).

\[-Q 2.2: \text{Based on Euclid’s formula, show that } c > (a, b).\]

\[-Q 2.3: \text{What happens when } c = a?\]

\[-Q 2.4: \text{Is } b + c \text{ a perfect square? Discuss.}\]

---

**Pell’s equation:**

**Problem #1:** Pell’s equation is one of the most historic (i.e., important) equations of Greek number theory because it was used to show that \( \sqrt{2} \in \mathbb{I}. \) We seek integer solutions of

\[ x^2 - Ny^2 = 1. \]

As shown in Lec 8 of the lecture notes, the solutions \( x_n, y_n \) for the case of \( N = 2 \) are given by the 2x2 matrix recursion of the form

\[
\begin{bmatrix}
x_{n+1} \\
y_{n+1}
\end{bmatrix} =
\begin{bmatrix}
1 & 2 \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
x_n \\
y_n
\end{bmatrix} = J^n
\begin{bmatrix}
1 & 2 \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
x_0 \\
y_0
\end{bmatrix}.
\]
As shown in Lec 8 of the lecture notes, the solutions \( x_n, y_n \) for the case of \( N = 2 \) are given by the 2x2 matrix recursion
\[
\begin{bmatrix}
  x_{n+1} \\
  y_{n+1}
\end{bmatrix} = 1j \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_n \\
  y_n \end{bmatrix}
\]
with \([x_0, y_0]^T = [1, 0]^T\) and \(1j = \sqrt{-1} = e^{j\pi/2}\). It follows that the general solution to Pell’s equation for \( N = 2 \) is
\[
\begin{bmatrix} x_n \\
  y_n \end{bmatrix} = (e^{j\pi/2})^n \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\
  y_0 \end{bmatrix}
\]

To calculate solutions to Pell’s equation using the matrix equation above, we must calculate
\[
A^n = e^{j\pi n/2} \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}^n = e^{j\pi n/2} \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} \cdots \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}
\]
which becomes tedious for \( n > 2 \), since it requires \( n \times 2 \times 2 \) matrix multiplications.

**Diagonalization of a matrix (“eigenvalue/eigenvector decomposition”):** As derived in Appendix C of the lecture notes, the most efficient way to compute \( A^n \) is to diagonalize the matrix \( A \), by finding its eigenvalues and eigenvectors.

The eigenvalues \( \lambda_k \) and eigenvectors \( e_k \) of a square matrix \( A \) are related by
\[
A e_k = \lambda_k e_k, \quad (2.19)
\]
such that multiplying an eigenvector \( e_k \) of \( A \) by the matrix \( A \) is the same as multiplying by a scalar, \( \lambda_k \in \mathbb{C} \) (the corresponding eigenvalue). The complete eigenvalue problem may be written as
\[
A E = E \Lambda.
\]

If \( A \) is a \( 2 \times 2 \) matrix,\(^{28}\) the matrices \( E \) and \( \Lambda \) (of eigenvectors and eigenvalues, respectively) are
\[
E = \begin{bmatrix} e_1 & e_2 \end{bmatrix}, \quad \Lambda = \begin{bmatrix} \lambda_1 & 0 \\
  0 & \lambda_2 \end{bmatrix}.
\]

Thus, the matrix equation \( A E = [A e_1 \quad A e_2] = [\lambda_1 e_1 \quad \lambda_2 e_2] = E \Lambda \) contains Eq. 2.19 for each eigenvalue-eigenvector pair.

The diagonalization of the matrix \( A \) refers to the fact that the matrix of eigenvalues, \( \Lambda \), has non-zero elements only on the diagonal. The key result is found by post-multiplication of the eigenvalue matrix by \( E^{-1} \), giving
\[
A E E^{-1} = A = E \Lambda E^{-1}, \quad (2.20)
\]
If we now take powers of \( A \), the \( n \)th power of \( A \) is
\[
A^n = (E \Lambda E^{-1})^n = E \Lambda E^{-1} E \Lambda E^{-1} \cdots E \Lambda E^{-1} = E \Lambda^n E^{-1}. \quad (2.21)
\]
This is a very powerful result, because the \( n \)th power of a diagonal matrix is extremely easy to calculate:
\[
\Lambda^n = \begin{bmatrix} \lambda_1^n & 0 \\
  0 & \lambda_2^n \end{bmatrix}.
\]
Thus, from Eq. 2.21 we can calculate \( A^n \) using only two matrix multiplications
\[
A^n = E \Lambda^n E^{-1}.
\]

\(^{28}\)These concepts may be easily extended to higher dimensions.
Finding the eigenvalues: The eigenvalues $\lambda_k$ are determined by Eq. 2.19, by factoring out $e_k$

$$Ae_k = \lambda_k e_k$$

$$(A - \lambda_k I)e_k = 0.$$ 

Matrix $I = [1, 0; 0, 1]^T$ is the identity matrix, having the dimensions of $A$, with elements $\delta_{ij}$ (i.e., diagonal elements $\delta_{11,22} = 1$ and off-diagonal elements $\delta_{12,21} = 0$).

The vector $e_k$ is not zero, yet when operated on by $A - \lambda_k I$, the result must be zero. The only way this can happen is if the operator is degenerate (has no solution), that is

$$\det(A - \lambda I) = \det \begin{bmatrix} (a_{11} - \lambda) & a_{12} \\ a_{21} & (a_{22} - \lambda) \end{bmatrix} = 0.$$ (2.22)

This means that the two equations have the same slope (the equation is degenerate).

This determinant equation results in a second degree polynomial in $\lambda$:

$$(a_{11} - \lambda)(a_{22} - \lambda) - a_{12}a_{21} = 0,$$

the roots of which are the eigenvalues of the matrix $A$.

Finding the eigenvectors: An eigenvector $e_k$ can be found for each eigenvalue $\lambda_k$ from Eq. 2.19,

$$(A - \lambda_k I)e_k = 0.$$ 

The left side of the above equation becomes a column vector, where each element is an equation in the elements of $e_k$, set equal to 0 on the right side. These equations are always degenerate, since the determinant is zero. Thus the two equations have the same slope.

Solving for the eigenvectors is often confusing, because they have arbitrary magnitudes. $||e_k|| = \sqrt{e_k \cdot e_k} = \sqrt{e_{k,1}^2 + e_{k,2}^2} = d$. From Eq. 2.19, you can only determine the relative magnitudes and signs of the elements of $e_k$, so you will have to choose a magnitude $d$. It is common practice to normalize each eigenvector to have unit magnitude ($d = 1$).

–Q 1.1: Find the companion matrix, and thus the matrix $A$, having the same eigenvalues as Pell’s equation.

Hint: Use Matlab’s function $[E, \text{Lambda}] = \text{eig}(A)$ to check your results!

–Q 1.2: Solutions to Pell’s equation were used by the Pythagoreans to explore the value of $\sqrt{2}$. Explain why Pell’s equation is relevant to $\sqrt{2}$.

–Q 1.3: Find the first 3 values of $(x_n, y_n)^T$ by hand and show that they satisfy Pell’s equation for $N = 2$.

By hand, find the eigenvalues $\lambda_{\pm}$ of the $2 \times 2$ Pell’s equation matrix

$$A = \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}.$$ 

–Q 1.4: By hand, show that the matrix of eigenvectors, $E$, is

$$E = \begin{bmatrix} e_+ & e_- \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} -\sqrt{2} & \sqrt{2} \\ 1 & 1 \end{bmatrix}.$$ 

–Q 1.5: Using the eigenvalues and eigenvectors you found for $A$, verify that

$$E^{-1}AE = \Lambda \equiv \begin{bmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{bmatrix}.$$ 

–Q 1.6: Now that you have diagonalized $A$ (Equation 2.21), use your results for $E$ and $\Lambda$ to solve for the $n = 10$ solution $(x_{10}, y_{10})^T$ to Pell’s equation with $N = 2$. 


The Fibonacci sequence

The Fibonacci sequence is famous in mathematics, and has been observed to play a role in the mathematics of genetics. Let \(x_n\) represent the Fibonacci sequence,

\[
x_{n+1} = x_n + x_{n-1},
\]

(2.23)

where the current input sample \(x_n\) is equal to the sum of the previous two inputs. This is a ‘discrete time’ recurrence relation. To solve for \(x_n\), we require some initial conditions. In this exercise, let us define \(x_0 = 1\) and \(x_{n<0} = 0\). This leads to the Fibonacci sequence \(\{1, 1, 2, 3, 5, 8, 13, \ldots\}\) for \(n = 0, 1, 2, 3, \ldots\).

Equation 2.23 is equivalent to the 2 \(\times\) 2 matrix equation

\[
\begin{bmatrix}
  x_n \\
  y_n
\end{bmatrix} = A \begin{bmatrix}
  x_{n-1} \\
  y_{n-1}
\end{bmatrix}, \quad A = \begin{bmatrix}
  1 & 1 \\
  1 & 0
\end{bmatrix}.
\]

(2.24)

Problem #1: Here we seek the general formula for \(x_n\). Like the Pell’s equation, Eq. 2.23 has a recursive, eigen-decomposition solution. To find it we must recast \(x_n\) as a 2x2 matrix relation, and then proceed as we did for the Pell case.

–Q 1.1: By example, show that the Fibonacci sequence \(x_n\) as described above may be generated by

\[
\begin{bmatrix}
  x_n \\
  y_n
\end{bmatrix} = \begin{bmatrix}
  1 & 1 \\
  1 & 0
\end{bmatrix}^n \begin{bmatrix}
  x_0 \\
  y_0
\end{bmatrix} = \begin{bmatrix}
  1 \\
  0
\end{bmatrix}.
\]

(2.25)

–Q 1.2: What is the relationship between \(y_n\) and \(x_n\)?

–Q 1.3: Write a Matlab/Octave program to compute \(x_n\) using the matrix equation above. Test your code using the first few values of the sequence. Using your program, what is \(x_{40}\)?

Note: Consider using the eigen-decomposition of \(A\), described by Eq. 2.21 (p. 66).

–Q 1.4: Using the eigen-decomposition of the matrix \(A\) (and a lot of algebra), it is possible to obtain the general formula for the Fibonacci sequence

\[
x_n = \frac{1}{\sqrt{5}} \left[ \left( \frac{1 + \sqrt{5}}{2} \right)^{n+1} - \left( \frac{1 - \sqrt{5}}{2} \right)^{n+1} \right].
\]

(2.26)

–Q 1.5: What are the eigenvalues \(\lambda_{\pm}\) of the matrix \(A\)?

–Q 1.6: How is the formula for \(x_n\) related to these eigenvalues? Hint: find the eigen vectors.

–Q 1.7: What happens to each of the two terms

\[\left( (1 \pm \sqrt{5})/2 \right)^{n+1}\]

–Q 1.8: What happens to the ratio \(x_{n+1}/x_n\)?
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Problem # 2: Replace the Fibonacci sequence with

\[ x_n = \frac{x_{n-1} + x_{n-2}}{2}, \]

such that the value \( x_n \) is the average of the previous two values in the sequence.

–Q 2.1: What matrix \( A \) is used to calculate this sequence?

–Q 2.2: Modify your computer program to calculate the new sequence \( x_n \). What happens as \( n \to \infty \)?

–Q 2.3: What are the eigenvalues of your new \( A \)? How do they relate to the behavior of \( x_n \) as \( n \to \infty \)? Hint: you can expect the closed-form expression for \( x_n \) to be similar to Eq. 2.26.

–Q 2.4: What matrix \( A \) is used to calculate this sequence?

–Q 2.5: Modify your computer program to calculate the new sequence \( x_n \). What happens as \( n \to \infty \)?

–Q 2.6: What are the eigenvalues of your new \( A \)? How do they relate to the behavior of \( x_n \) as \( n \to \infty \)? Hint: you can expect the closed-form expression for \( x_n \) to be similar to Eq. 2.26.

Problem # 3: Consider the expression

\[ \sum_{1}^{N} f_n^2 = f_N f_{N+1}. \]

–Q 3.1: Prove this expression is always true.

---

\[^{29}\text{I found this problem on a worksheet for Math 213 midterm (213practice.pdf).} \]
Chapter 3

Algebraic Equations: Stream 2

The era of 1640 to 1900 (Fig. 3.1) produced a continuous stream of fundamental theorems. A few of the individuals who played notable roles in this development, in chronological (birth) order, include: Galileo, Mersenne, Newton, d’Alembert, Fermat, Huygens, Descartes and Helmholtz. These individuals were some of the first to develop the basic ideas, in various forms, that were then later reworked into the proofs, that today we recognize as the fundamental theorems of mathematics.

Chronological history from the 17th century

17th Newton 1642–1727, Bernoulli, Johann 1667–1748
18th Bernoulli, Daniel, Cauchy 1789–1857, Euler 1707–1783, d’Alembert 1717–1783, Gauss 1777–1855

Time Line

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Figure 3.1: timeline of the three centuries from the mid 17th to 20th CE, one of the most productive times of all, because mathematicians were sharing information. Figure 1.2 (p. 22) (Bombelli–Gauss) provides a closer look at the 16–19 CE, and Fig. 4.1 (p.144) (Bombelli–Einstein) provides the full view 16–20 CE.
3.1  Lec 10: The physics behind nonlinear Algebra (Euclidean geometry)

Following Stillwell’s history of mathematics, Stream 2 is geometry, which led to the merging of Euclid’s geometrical methods and the 9th century development of algebra by al-Khwarizmi (830 CE). This integration of ideas led Descartes and Fermat to develop analytic geometry.

The mathematics up to the time of the Greeks, documented and formalized by Euclid, served students of mathematics for more than two thousand years. Algebra and geometry were, at first, independent lines of thought. When merged, the focus returned to the Pythagorean theorem. Algebra generalized the analytic conic section, greatly extending the geometrical approach as taught in Euclid’s Elements. With the introduction of algebra, numbers, rather than lines, could be used to represent a geometrical length. Thus the appreciation for geometry grew, given the addition of the rigorous analysis using numbers.

**Physics inspires algebraic mathematics:** The Chinese used music, art, and navigation to drive mathematics. Unfortunately much of their knowledge has been handed down either as artifacts, such as musical bells and tools, or mathematical relationships documented, but not created, by scholars such as Euclid, Archimedes, Diophantus, and perhaps Brahmagupta. With the invention of algebra by al-Khwārizmī (830CE), mathematics became more powerful, and blossomed. During the 16th and 17th century, it had become clear that differential equations (DEs), such as the wave equation, can characterize a law of nature, at a single point in space and time. This principle was not obvious. A desire to understand motions of objects and planets precipitated many new discoveries. This period is illustrated in Fig. 1.2 (p. 22).

As previously described, the law of gravity was first formulated by Galileo using the concept of conservation of energy, which determines how masses are accelerated when friction is not considered and the mass is constant. Kepler investigated the motion of the planets. While Kepler was the first to observe that the orbits of planets are described by ellipses, it seems he under-appreciated the significance of his finding, and continued working on his incorrect epicycle planetary model. Following up on Galileo’s work (Galileo, 1638), Newton (c1687) went on to show that there must be a gravitational potential between two masses \( m_1, m_2 \) of the form

\[
\phi_{\text{New}}(r(t)) \propto \frac{m_1 m_2}{r(t)},
\]

where \( r = |x_1 - x_2| \) is the Euclidean distance between the two point masses at locations \( x_1 \) and \( x_2 \). Using algebra and his calculus, Newton formalized the equation of gravity, forces and motion (Newton’s three laws), the most important being

\[
f(t) = \frac{d}{dt} M v(t),
\]

and showed that Kepler’s discovery of planetary elliptical motion naturally follows from these laws (see p. 10). With the discovery of Uranus (1781) “Kepler’s theory was ruined” (i.e., proven wrong) (Stillwell, 2010, p. 23).

Once Newton proposed the basic laws of gravity (Eq. ??), and resolved the elliptical motion of the planets, he proceeded to calculate, for the first time, the speed of sound. This required some form of the pressure wave equation

\[
\frac{\partial^2}{\partial t^2} \rho(x, t) = \frac{1}{c_o^2} \frac{\partial^2}{\partial x^2} \rho(x, t),
\]

a key equation in mathematical physics. The speed of sound is

\[
c_o = \sqrt{\frac{\eta_o P_o}{\rho_o}} = 343, \quad [\text{m/s}]
\]
which is a function of the density $\rho_0 = 1.12$ [kg/m$^3$] and the dynamic stiffness $\eta P_o$ of air.$^1$ In other units the speed of sound is 767 [mph], 1125.3 [ft/s], 1.125 [ft/ms] and 1234.8 [km/h]. One of the earliest measurements was by Marin Mersenne in 1630 as 1,380 [Parisian feet per second]. 1 English foot is equal to 1.06575 Paris feet.

Exercise: How much smaller is one from Paris France than one from London England? Solution: The French seem to have been about 94[%] smaller than the English, according to this measure.

If we substitute for the pressure

$$p(x,t) = e^{i(\omega t \pm 2\pi k x)}$$

where $t$ is time and $x$ is position, we find that $2\pi k = 2\pi f/\lambda = 2\pi f/c_o$, because $f\lambda = c_o$.

Case of dispersive wave propagation: This classic relation $\lambda f = c$ is deceptively simple, thus confusing, because $k = 2\pi f/\lambda$ becomes complex (has both real and imaginary parts) in dispersive media (e.g., acoustic waves in tubes) when losses are considered (Kirchhoff, 1868; Mason, 1928). A more important example is the case of electron waves in silicon crystals (Brillouin, 1953). In these more general cases, the wave number $k(f) = 2\pi f/c$ is replaced with the complex analytic function we call the propagation function $\kappa(s)$ of $s$, i.e., the wave becomes the eigenfunction of the wave equation

$$p_\pm(x, t) = P_o(s)e^{st}e^{\pm\kappa(s)x}.$$  

In these more general cases the wave number $\kappa(s)$ must be a complex analytic function of the Laplace frequency $s = \sigma + \omega j$, as used with the Laplace transform. This is because electron “waves” in a dispersive semi-conductor, such as silicon, are “filtered” in magnitude and phase. Silicon is a highly dispersive “wave-filter,” forcing the wavelength to be a complex function of frequency. This view is elegantly explained by Brillouin (1953, Chap. 1) in his historic text. Modern acoustics contains a rich source of related examples (Morse, 1948; Beranek, 1954; Fletcher and Rossing, 2008; Ramo et al., 1965).

Newton’s *Principia* was finally published in 1687, and the general solution to Newton’s wave equation [i.e., $p(x,t) = G(t \pm x/c)$], where $G$ is any function, was first published 60 years later by d’Alembert (c1747), which showed that for single frequency sounds, the wavelength $\lambda$ and frequency $f$ were related by

$$f\lambda = c.$$ (3.6)

Today d’Alembert’s single-frequency analytic wave solution must be written as Eq. 3.5 having a complex wave number $\kappa(s) = 2\pi/\lambda(s)$ [m$^{-1}$]. This formulation led to the frequency domain concept of the Laplace analysis, based on the linearity (i.e., superposition) property of the wave equation (Postulate P2: Lec. 3.7.1, p. 132).

Newton’s value for the speed of sound in air $c_o$ was incorrect by the thermodynamic constant $\sqrt{\gamma_o}$, a problem that would take 200+ years to formulate. What was needed was the adiabatic process (the concept of constant-heat). For audio frequencies (0.02-20 [kHz]), the small temperature gradients cannot diffuse the distance of a wavelength in one cycle (Pierce, 1981; Boyer and Merzbach, 2011), “trapping” the heat energy in the wave.$^2$ The eventual fix to Newton’s formula for the sound speed was to define the dynamic stiffness of air $\eta_o P_o$, where $P_o$ (1 [atm] or $10^5$ [Pa]) is the static stiffness of air. But this fix still ignores losses (Kirchhoff, 1868).

Newton’s success was important because it quantified the physics behind the speed of sound, and demonstrated that momentum ($mv$), not mass $m$, was transported by the wave. His concept was correct, and his formulation using algebra and calculus represented a milestone in science. In air, assuming no visco-elastic losses, it is constant (i.e., $c_o = \sqrt{\gamma_o P_o/\rho_0}$). When including losses the wave number

---

1 $\eta_o = C_p/C_v = 1.4$ is the ratio of two thermodynamic constants and $P_o = 10^5$ [Pa] is the barometric pressure of air.

2 There were other physical enigmas, such as the observation that sound disappears in a vacuum or that a vacuum cannot draw water up a column by more than 34 feet.
becomes a complex function of frequency, leading to Eq. 3.5. In periodic structures, again the wave number becomes complex due to diffraction, as commonly observed in optics (e.g., diffraction gratings) and acoustics. Thus Eq. 3.6 only holds for the simplest cases, but in general it must be considered as a complex analytic function of \( s \), as \( \kappa(s) \) in Eq. 3.5.

The corresponding discovery for the formula for the speed of light was made 174 years after *Principia*, by Maxwell (c1861). Maxwell’s formulation also required great ingenuity, as it was necessary to hypothesize an experimentally unmeasured term in his equations, to get the mathematics to correctly predict the speed of light.

It is somewhat amazing that to this day, we have failed to understand gravity significantly better than Newton’s theory. Perhaps this is too harsh, given the 1905 work of Einstein.\(^3\)

### 3.1.1 The first Algebra

Prior to the invention of algebra, people worked out problems as sentences using an obtuse description of the problem (Stillwell, 2010, p. 93). Algebra changed this approach, resulting in a compact language of mathematics, where numbers are represented as abstract symbols (e.g., \( x \) and \( \alpha \)). The problem to be solved could be formulated in terms of sums of powers of smaller terms, the most common being powers of some independent variable (i.e., time or frequency). If we set \( a_n = 1 \)

\[
P_n(z) \equiv z^n + a_{n-1}z^{n-1} + \cdots + a_oz^0 = z^n + \sum_{k=0}^{n-1} a_k z^k = \prod_{k=0}^{n}(z - z_k).
\]

is called a *monic polynomial*. The coefficient \( a_n \) cannot be zero, or the polynomial would not be of degree \( n \). The resolution is to force \( a_n = 1 \), since this simplifies the expression and does not change the roots.

The key question is: What values of \( z = z_k \) result in \( P_n(z_k) = 0 \). In other words, what are the roots \( z_k \) of the polynomial? Answering this question consumed thousands of years, with intense efforts by many aspiring mathematicians. In the earliest attempts, it was a competition to evaluate mathematical acumen. Results were held as a secret to the death bed. It would be fair to view this effort as an obsession. Today the roots of any polynomial may be found, to high accuracy, by numerical methods. Finding roots is limited by the numerical limits of the representation, namely by IEEE-754 (p. 39). There are also a number of important theorems.

Of particular interest is composing a circle with a line, where the line does not touch the circle, and finding the intersection (root). There was no solution to this problem using geometry. The resolution of this problem is addressed in the assignments below.

### 3.1.2 Finding roots of polynomials

The problem of factoring polynomials has a history more than a millennium in the making. While the quadratic (degree \( N = 2 \)) was solved by the time of the Babylonians (i.e., the earliest recorded history of mathematics), the cubic solution was finally published by Cardano in 1545. The same year, Cardano’s student solved the quartic (\( N = 4 \)). In 1826 (281 years later) it was proved that the quintic (\( N = 5 \)) could not be factored by analytic methods.

As a concrete example we begin with the important but trivial case of the quadratic

\[
P_2(x) = ax^2 + bx + c.
\]

First note that if \( a = 0 \), the quadratic reduces to the monomial \( P_1(x) = bx + c \). Thus we have the necessary condition that \( a \neq 0 \). The best way to proceed is to divide \( a \) out and work directly with the normalized quadratic \( \tilde{P}_2(x) = \frac{1}{a}P_2(x) \). In this way we do not need to worry about the exception, \( a = 0 \).

\(^3\)Gravity waves were experimentally measured for the first time while I was formulating Section ??.
The roots are those values of \( x \) such that \( \hat{P}_2(x_k) = 0 \). One of the first results (recorded by the Babylonians, c2000 BCE) was the factoring of this equation by completing the square (Stillwell, 2010, p. 93). One may isolate \( x \) by rewriting Eq. 3.8 as

\[
\frac{1}{a}P_2(x) = (x + b/2a)^2 - (b/2a)^2 + c/a.
\]

This is easily verified by expanding the squared term and canceling \((b/2a)^2\)

\[
\frac{1}{a}P_2(x) = [x^2 + (b/a)x + (b/2a)^2] - (b/2a)^2 + c/a.
\]

Setting Eq. 3.9 to zero and solving for the two roots \( x_\pm \) gives the quadratic formula

\[
x_\pm = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.
\]

The roots of \( \hat{P}_2(x) \), with \( a = 1 \), simplify to

\[
x_\pm = -\frac{1}{2}b \pm \sqrt{\frac{b}{2}} - c.
\]

This can be further simplified. The term \( b^2 - c > 0 \) under the square root is called the discriminant, and in physics and engineering problems, \( >99.9\% \) of the time it is negative. Finally \( b/2 \ll \sqrt{c} \); thus, the most natural way (i.e., corresponding to the most common physical cases) of writing the solution is

\[
x_\pm = -\frac{1}{2}b \pm j\sqrt{c - (b/2)^2} \approx -b/2 \pm j\sqrt{\omega_0}.
\]

This form separates the real and imaginary parts of the solution in a natural way. The term \( b/2 \) is called the damping, which accounts for losses in a resonant circuit, while the term \( \sqrt{c} \), for mechanical, acoustical and electrical networks, is called the resonant frequency, typically written as \( \omega_0 \). The last approximation ignores the (typically) minor correction to the resonant frequency, which in engineering practice is typically always ignored. Knowing that there is a correction is highlighted by this formula, making one aware it exists.

It is not required that \( a, b, c \in \mathbb{R} \), but for physical problems of interest, this is always true (\( >99.9\% \) of the time).

**Summary:** The quadratic equation and its solution are ubiquitous in physics and engineering. It seems obvious that instead of memorizing the meaningless Eq. 3.10, one should learn the physically meaningful solution, Eq. 3.12, obtained via Eq. 3.9, with \( a = 1 \). Arguably, the factored and normalized form (Eq. 3.9) is easier to remember, as a method (completing the square), rather than as a formula to be memorized.

Additionally, the real \( (b/2) \) and imaginary \( \pm \sqrt{c} \) parts of the two roots have physical significance as the damping and resonant frequency. Equation 3.10 has none.

No insight is gained by memorizing the quadratic formula. To the contrary, an important concept is gained by learning how to complete the square, which is typically easier than identifying \( a, b, c \) and blindly substituting them into Eq. 3.10. Thus it’s worth learning the alternate solution (Eq. 3.12) since it is more common in practice and requires less algebra to interpret the final answer.

---

4This is the case for mechanical and electrical circuits having small damping. Physically \( b > 0 \) is the damping coefficient and \( \sqrt{c} > 0 \) is the resonant frequency. One may then simplify the form as \( x^2 + 2bx + c^2 = (x + b + j\sqrt{c})(x + b - j\sqrt{c}) \).
Exercise: By direct substitution demonstrate that Eq. 3.10 is the solution of Eq. 3.8. Hint: Work with \( \hat{P}_2(x) \). Solution: Setting \( a = 1 \) the quadratic formula may be written

\[
x_\pm = \frac{-b \pm \sqrt{b^2 - 4c}}{2}.
\]

Substituting this into \( \hat{P}_2(x) \) gives

\[
\hat{P}_\pm(x_\pm) = x_\pm^2 + bx_\pm + c
\]
\[
= \left(\frac{-b \pm \sqrt{b^2 - 4c}}{2}\right)^2 + b \left(\frac{-b \pm \sqrt{b^2 - 4c}}{2}\right) + c
\]
\[
= \frac{1}{4} \left( b^2 \pm 2b \sqrt{b^2 - 4c} + (b^2 - 4c) \right) + \frac{1}{4} \left( -2b^2 \pm 2b \sqrt{b^2 - 4c} \right) + c
\]
\[
= 0.
\]

Exercise: By direct substitution, show that Eq. 3.12 satisfies Eq. 3.10. Solution: Putting Eq. 3.10 into Eq. 3.10 in factored form gives

\[
\hat{P}_2(x) = (x - x_+)(x - x_-)
\]
\[
= \left( x + \frac{1}{2}b + j\sqrt{c - (b/2)^2} \right) \left( x + \frac{1}{2}b - j\sqrt{c - (b/2)^2} \right)
\]
\[
= \left( x + \frac{b}{2} \right)^2 + (c - \frac{b^2}{4})
\]
\[
= (x^2 + bx + \frac{b^2}{4}) + (c - \frac{b^2}{4})
\]
\[
=x^2 + bx + c.
\]

In third grade I learned the times-table trick for 9:

\[
9 \cdot n = (n - 1) \cdot 10 + (10 - n).
\] (3.13)

With this simple rule I did not need to depend on my memory for the 9 times tables.\(^5\) Learning an algorithm is much more powerful than memorization of the 9 times tables. Note that the two terms \((n - 1)\) and \((10 - n)\), add to 9. How one thinks about a problem can have great impact.

Newton's method for finding roots of \( P_n(s) \) Newton is well known for an approximate but efficient method to find the roots of a polynomial.\(^6\) Consider polynomial \( P_n(s) \in \mathbb{C} \) for \( s \in \mathbb{C} \)

\[
P_n(s) = c_n(s - s_0)^n + c_{n-1}(s - s_0)^{n-1} + \cdots + c_1(s - s_0) + c_0,
\]

where we may use Taylor's formula (p. 87) to determine the coefficients

\[
c_n = \frac{1}{n!} \frac{d^n}{ds^n} P_n(s) \bigg|_{s=s_0}.
\]

\(^5\)E.g.: \(9 \cdot 7 = (7 - 1) \cdot 10 + (10 - 7) = 60 + 3\) and \(9 \cdot 3 = (3 - 1) \cdot 10 + (9 - 3) = 20 + 7\). By expanding the above, one can see why it works: \(9n = n10 - 10 + 10 - n = n(10 - 1)\).

\(^6\)https://en.wikipedia.org/wiki/Newton’s_method
If our initial guess for the root \( s_0 \) is close to a root, then \( |(s - s_0)|^n \ll |(s - s)| \) for \( n \geq 2 \in \mathbb{N} \). Thus we may truncate \( P_n(s - s_0) \) to its linear term

\[
P_n(s) \approx (s - s_0) \frac{d}{ds} P_n(s) \bigg|_{s=s_0} + P_n(s_0)
\]

\[
= (s - s_0) P'(s_0) + P_n(s_0),
\]

where \( P'_n(s) \) is shorthand for \( dP_n(s)/ds \).

This equation may be found by iteration, defining a sequence \( s_n \) that converges to the root, such that \( P_n(s_n) = 0 \) as \( n \to \infty \). Replacing \( s \) with \( s_n \), and \( s_0 \) with \( s_n - 1 \), the formula becomes a recursion for the root \( s_n \)

\[
(s_n - s_{n+1}) P'_n(s_{n+1}) + P_n(s_{n+1}) = P_n(s_n) \to 0
\]

as \( n \to \infty \). Solving for \( s_n \) gives the key formula behind Newton’s famous root-finding method, involving the reciprocal of the logarithmic derivative \( P'/P_n \)

\[
s_n = s_{n-1} - \frac{P_n(s_{n-1})}{P'(s_{n-1})}.
\]

(3.14)

Here \( s_{n-1} \) is the expansion point and \( s_n \) is the \( n^{th} \) approximation to the root. With every step, the expansion point moves closer to the root, converging to the root in the limit. As it comes closer, the linearity assumption becomes more accurate, ultimately resulting in the convergence to the root.

This expression is related to the log-derivative \( d \log P(x)/dx = P'(x)/P(x) \). It follows that even for cases where fractional derivatives of roots are involved, Newton’s method should converge, since the log-derivative linearized them.\(^7\)

---

\(^7\)This seems like an obvious way toward understanding fractional, even irrational, roots.

\(^8\)https://en.wikipedia.org/wiki/Argument_principle

---

Figure 3.2: Newton’s method applied to the polynomial having real roots \([1, 2, 3, 4]\) (left) and 5 complex roots (right). A random starting point was chosen, and each curve shows the values of \( s_n \) as Newton’s method converges to the root. Different random starting points converge to different roots. The method always results in convergence to a root. Claims to the contrary (Stewart, 2012, p. 347) are a result of forcing the roots to be real. For convergence, one must work with \( s_n \in \mathbb{C} \).

---

**Newton’s view:** Newton believed that imaginary roots and numbers have no meaning (p. 145), thus he sought only real roots (Stillwell, 2010, p. 119). In this case Newton’s relation may be explored as a graph, which puts Newton’s method in the realm of analytic geometry. The function \( P'_n(x) \) is the slope of the polynomial \( P_n(x) \) at \( x_n \). The ratio \( P_n(x)/P'_n(x) \) has poles at the roots of \( P' \) and zeros at the roots we seek.

\(^9\)https://en.wikipedia.org/wiki/Argument_principle
Example: When the polynomial is \( P_2 = 1 - x^2 \), and \( P_2'(x) = -2x \), Newton’s iteration becomes

\[
x_{n+1} = x_n + \frac{1 - x_n^2}{2x_n}.
\]

Note the roots are \( x_\pm = \pm 1 \). For the case of \( N = 2 \) the root of \( P_2'(x) \) is always the average of the roots of \( P_2(x) \).

To start the iteration \((n = 0)\) we need an initial guess for \( x_0 \), which is an “initial random guess” of where a root might be. For \( P_2(x) = 1 - x^2 \),

\[
x_1 = x_0 + \frac{1 - x_0^2}{2x_0} = x_0 + \frac{1}{2}(-x_0 + 1/x_0).
\]

1. Let \( P_2(x) = 1 - x^2 \), and \( x_0 = 1/2 \). Draw a graph describing the first step of the iteration.

Solution: Start with an \((x, y)\) coordinate system and put points at \( x_0 = (1/2, 0) \) and the vertex of \( P_2(x) \), i.e.: \((0,1) (P_2(0) = 1)\). Then draw \( 1 - x^2 \), along with a line from \( x_0 \) to \( x_1 \).

2. Calculate \( x_1 \) and \( x_2 \). What number is the algorithm approaching? Is it a root of \( P_2 \)?

Solution: First we must find \( P_2'(x) = -2x \). Thus the equation we will iterate is

\[
x_{n+1} = x_n + \frac{1 - x_n^2}{2x_n} = \frac{x_n^2 + 1}{2x_n}.
\]

By hand

\[
x_0 = 1/2
\]

\[
x_1 = (1/2)^2 + 1 = 1/4 + 1 = 5/4 = 1.25
\]

\[
x_2 = (5/4)^2 + 1 = (25/16) + 1 = 41/40 = 1.025.
\]

These estimates rapidly approach the positive real root \( x = 1 \). Note that if one starts at the root of \( P'(x) = 0 \) (i.e., \( x_0 = 0 \)), the first step is indeterminate.

3. Write an Octave/Matlab script to check your answer for part (a).

Solution:

```octave
x=1/2;
for n = 1:3
x = x+(1-x*x) / (2*x);
end
```

(a) For \( n = 4 \), what is the absolute difference between the root and the estimate, \(|x_r - x_4|\)?

Solution: 4.6E-8 (very small!)

(b) What happens if \( x_0 = -1/2 \)? Solution: You converge on the negative root, \( x = -1 \).

4. Does Newton’s method work for \( P_2(x) = 1 + x^2 \)? Why

Solution: In this case \( P_2'(x) = 2x \) thus the iteration gives

\[
x_{n+1} = x_n - \frac{1 + x_n^2}{2x_n}.
\]

In this case the roots are \( x_\pm = \pm 1 \), namely purely imaginary. Obviously Newton’s method fails because there is no way for the answer to become complex. If like Newton, you didn’t believe in complex numbers, your method would fail to converge to the complex roots (i.e., real in, real out).

This is because Octave/Matlab assumes \( x \in \mathbb{C} \), since it is initialized as \( \mathbb{C} \).

---

9https://en.wikipedia.org/wiki/Newton’s_method#Complex_functions
5. What if you let \( x_0 = (1 + j)/2 \) for the case of \( P_2(x) = 1 + x^2 \)? \textbf{Solution:} By starting with a complex initial value, we fix the Real in = Real out problem.

\textbf{Fractal diagrams:} When the initial guess is real, but the nearest root is complex, Newton’s iteration fails, as discussed in the exercises above. This failure to converge gives rise to fractal patterns, called the Mandelbrot set.\(^\text{10}\)

\textbf{Example:} Assume that polynomial \( P_3(s) = (s - a)^2/(s - b)^\pi \). Then

\[
\ln P_3(s) = 2 \ln(s - a) - \pi \ln(s - b)
\]

and

\[
\frac{d}{ds} \ln P_3(s) = \frac{2}{s - a} + \frac{\pi}{s - b}.
\]

\textbf{Reduction by the logarithmic derivative to simple poles:} As shown by the above trivial example, any polynomial, having zeros of arbitrary degree (i.e., \( \pi \) in the example), may be reduced to the ratio of two polynomials, by taking the logarithmic derivative, since

\[
L_N(s) = \frac{N(s)}{D(s)} = \frac{d}{ds} \ln P_n(s) = \frac{P_n'(s)}{P_n(s)}.
\]  

(3.15)

Here the starting polynomial is the denominator \( D(s) = P_n(s) \) while the numerator \( N(s) = P_n'(s) \) is the derivative of \( D(s) \). Thus the logarithmic derivative can play a key role in analysis of complex analytic functions, as it reduces higher order poles, even those of irrational degree, to simple poles.

The logarithmic derivative \( L_N(s) \) has a number of special properties:

1. \( L_N(s) \) has simple poles \( s_p \) and zeros \( s_z \).

2. The poles of \( L_N(s) \) are the zeros of \( P_n(s) \).

3. The zeros of \( L_N(s) \) (i.e., \( P_n'(s_z) = 0 \)) are the zeros of \( P_n'(s) \).

4. \( L_N(s) \) is analytic everywhere other than its poles.

5. Since the zeros of \( P_n(s) \) are simple (no second-order poles), it is obvious that the zeros of \( L_N(s) \) always lie close to the line connecting the two poles. One may easily demonstrate the truth of the statement numerically, and has been quantified by the Gauss-Lucas theorem which specifies the relationship between the roots of a polynomial and those of its derivative. Specifically, the roots of \( P_{n-1}' \) lie inside the convex hull of the roots of \( P_n \).

6. Newton’s method may be expressed in terms of the reciprocal of the logarithmic derivative, since

\[
s_{k+1} = s_k + \epsilon_o/L_N(s),
\]

where \( \epsilon_o \) is called the \textit{step size}, which is used to control the rate of convergence of the algorithm. If the step size is too large, the root-finding path may jump to a different domain of convergence, thus a different root of \( P_n(s) \).

7. Not surprisingly, given all the special properties, \( L_N(x) \) plays an key role in mathematical physics.

\(^{10}\)https://en.wikipedia.org/wiki/Mandelbrot_set
Euler’s product formula: Counting may be written as a recursion, simply by adding 1 to the previous value starting from 0. The even numbers may be generated by adding 2, starting from 0. Multiples of 3 may be similarly generated by adding 3 to the previous value, starting from 0. Such recursions are fundamentally related to prime numbers \( n \in \mathbb{P} \), as first shown by Euler, starting from the counting numbers \( n \in \mathbb{N} \). The logic is based on the properties of the sieve (Lec. 2.3, p. 50). The basic idea is both simple and basic, taking almost everyone by surprise, likely even Euler. It is related on the old idea that the integers may be generated by the geometric series, when viewed as a recursion.

Example: Let’s look at counting modulo prime numbers. For example

\[
n = k \mod (2) \cdot k \mod (3) \cdot k \mod (5).
\]

Figure 3.3: This feedback network is described by a time-domain difference equation with delay \( M \) [s], has an all-pole transfer function, given by Eq. 4.44. THICKEN LINES

To see this define the step function \( u_n = 0 \) for \( n < 0 \) and \( u_n = 1 \) for \( n \geq 0 \) and the counting number function \( N_n = 0 \) for \( n < 0 \). The counting numbers may be recursively generated from the recursion

\[
N_{n+1} = N_{n-M} + u_n.
\]

which for \( M = 1 \) gives \( N_n = n \). For \( M = 2 \) \( N_n = 0, 2, 4, \ldots \) are the even numbers.

Exercise: Show that \( N_n = n \) follows from the above recursion. Solution: If \( n = -1 \) we have \( N_n = 0 \) and \( u_n = 0 \). For \( n = 0 \) the recursion gives \( N_1 = N_0 + u_0 \), thus \( N_1 = 0 + 1 \). When \( n = 1 \) we have \( N_2 = N_1 + 1 = 1 + 1 = 2 \). For \( n = 2 \) the recursion gives \( N_3 = N_2 + 1 = 3 \). Continuing the recursion we find that \( N_n = n \). Today we denote such recursions of this form as digital filters. The state diagram for \( N_n \) is given in Fig. 3.3.

To start the recursion define \( u_n = 0 \) for \( n < 0 \). Thus \( u_0 = u_{-1} + 1 \). But since \( u_{-1} = 0 \), \( u_0 = 1 \). The counting numbers follow from the recursion. Thus we have
Exercise: Write an Octave/Matlab program that generates \( N_n = \{0, 3, 6, 9, \cdots\} \). Solution:

\[
M = 10; \quad D = [1 \ -1 \ 0]; \quad N = [3]; \quad u = \text{ones}(1, M); \quad u(1) = 0; \quad n = \text{filter}(N, D, u)
\]

The output is \( n = [0, 1, 2, 3, \ldots] \).

Exercise: Write an Octave/Matlab program that generates removes all the even number, to give the odds \( N_n = \{1, 0, 3, 0, 5, 0, 7, 0, 9, \cdots\} \).

Solution:

\[
M = 50; \quad N = (0 : M - 1); \quad u = \text{ones}(1, M); \quad u(1) = 0; \quad D = [1 \ 0 \ -1]; \quad N = [0 \ 0 \ 1]; \quad n = \text{filter}(N, D, u);
\]

\[
y_2 = n \ast N; \quad F_1 = N - y_2
\]

which gives: \( F_1 = [0, 1, 0, 3, 0, 5, 0, 7, 0, \cdots] \).

Exercise: Write a program to recursively down-sample \( N_n \) by 2:1. Solution:

\[
N = [1 \ 0 \ 3 \ 0 \ 5 \ 0 \ 7 \ 0 \ 9 \ 0 \ 11 \ 0 \ 13 \ 0 \ 15]
\]

\[
k = 1; \quad \text{while} \ 2 \ast k - 1 < \text{length}(N) \quad 2 \ast k - 1; \quad M(k) = N(2 \ast k + 1); \quad k = k + 1;
\]

which gives: \( M = [3, 5, 7, 9, 11, 13, 15] \)

Here is a 1 line code that does the same thing:

\[
N = 1:15; \quad M = N(1:2:15)
\]

which returns the odd numbers between 1 and 15 (i.e., 1:2:15)

For the next step in the sieve, generate all the multiples of 3 (the second prime) and subtract these from the list. This will either zero out these number from the list, or create negative items which are then removed. Numbers are negative when the number has already been removed because it has a second factor. For example, 6 is already removed because it is a multiple of 2, thus was removed when removing the multiples of prime number 2.

3.1.3 Matrix formulation of the polynomial

There is a one-to-one relationship between every constant coefficient differential equation, its characteristic polynomial and the equivalent matrix form of that differential equation, defined by the companion matrix (Horn and Johnson, 1988, p. 146).
The companion matrix: The $N \times N$ companion matrix

\[
C_N = \begin{bmatrix}
0 & 0 & -c_0 \\
1 & 0 & -c_1 \\
0 & 1 & -c_2 \\
\vdots & \vdots & \vdots \\
0 & 1 & -c_{N-2} \\
0 & 1 & -c_{N-1}
\end{bmatrix}
\]  \tag{3.17}

is derived from the monic polynomial of degree $N$

\[
P_N(s) = s^N + c_{N-1}s^{N-1} + \cdots + c_2 s^2 + c_1 s + c_0
\]

having coefficient vector

\[c_{N-1}^T = [1, c_{N-1}, c_{N-2}, \cdots, c_0]^T.
\]

The roots of the monic polynomial are the eigenvalues of the companion matrix $C_N$. The degrees of freedom (DoF) of a polynomial, and thus of its companion matrix, are the number of non-zero eigenvalues.

Exercise: Show that the eigenvalues of the 3x3 companion matrix are the same as the roots of $P_3(s)$.

Solution: Expanding the determinant of $C_3 - sI_3$ along the right-most column:

\[
\begin{vmatrix}
-s & 0 & -c_0 \\
1 & -s & -c_1 \\
0 & 1 & -(c_2 + s)
\end{vmatrix} = c_0 + c_1 s + (c_2 + s)s^2 = s^3 + c_2 s^2 + c_1 s + c_0.
\]

This is the negative of the characteristic polynomial ($-P_3(s)$), which has the same roots.

Exercise: Find the companion matrix for the Fibonacci sequence, defined by the recursion (i.e., difference equation)

\[f_{n+1} = f_n + f_{n-1},\]

initialized with $f_n = 0$ for $n < 0$ and $f_0 = 1$. Solution: Taking the “Z transform” gives the polynomial $z^2 = z^0 - z^{-1} = 0$ having coefficient vector $Z = [1, -1, -1]$, resulting in the Fibonacci companion matrix

\[C = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix},\]

as discussed Section 2.3.5 on page 63.

Example: Matlab/Octave: A polynomial is represented in Matlab/Octave in terms of its coefficient vector. When the polynomial vector for the poles of a differential equation is

\[c_N = [1, c_{N-1}, c_{N-2}, \cdots, c_0]^T,
\]

the coefficient $c_N = 1$. This normalization guarantees that the leading term is not zero, and the number of roots ($N$) is equal to the degree of the monic polynomial.
3.1.4 Working with polynomials in Matlab/Octave:

In Matlab/Octave there are seven related functions you must become familiar with:

1. \( \text{R}=\text{root}(A) \)  
   
   Vector \( A = [a_N, a_{N-1}, \ldots, a_0] \in \mathbb{C} \) are the complex coefficients of polynomial \( P_N(z) = \sum_{n=0}^{N} a_n z^n \in \mathbb{C} \), where \( N \in \mathbb{N} \) is the degree of the polynomial. It is convenient to force \( a_N = 1 \), corresponding to dividing the polynomial by this value, when it is not 1, guaranteeing it cannot be zero, as mentioned above. Further \( \text{R} \) is the vector of roots, \([z_1, z_2, \cdots, z_n] \in \mathbb{C} \) such that \( \text{polyval}(A, z_k) = 0 \).

2. \( y=\text{polyval}(A,x) \): This evaluates the polynomial defined by vector \( A \in \mathbb{C}^N \) evaluated at \( x \in \mathbb{C} \), returning vector \( y(x) \in \mathbb{C} \).

3. \( P=\text{poly}(R) \): This is the inverse of \( \text{root}() \), returning a vector of polynomial coefficients \( P \in \mathbb{C}^N \) of the corresponding characteristic polynomial, starting from either a vector of roots \( R \), or a matrix \( A \), for example, defined with the roots on the diagonal. The characteristic polynomial is defined as the determinant of \( |A - \lambda I| = 0 \) having roots \( R \).

   Due to IEEE-754 scaling issues, this can give strange results that are numerically correct, but only within the limits of IEEE-754 accuracy.

4. \( \text{R}=\text{polyder}(N) \) This routine takes the coefficients of a polynomial \( N \) and returns the \( N-1 \) coefficients of the derivative of the polynomial. This is useful when working with Newton’s method, since each step is proportional to \( P_N(x)/P_N'(x) \).

5. \( [K,R]=\text{residue}(N,D) \): Given the ratio of two polynomials \( N,D \), \( \text{residue}(N,D) \) returns vectors \( K,R \) such that
   \[
   \frac{N(s)}{D(s)} = \sum_{k} \frac{K_k}{s-s_k},
   \]
   where \( s_k \in \mathbb{C} \) are the roots of the denominator \( D \) polynomial and \( K \in \mathbb{C} \) is a vector of residues, which characterize the roots of the numerator polynomial \( N(s) \). The use of \( \text{residue}() \) will be discussed in Sect. ?? (p. ??), and in greater detail in Sect. 5.3.1 (p. 199), and in Appendix B, p. 252.

6. \( C=\text{conv}(A,B) \): Vector \( C \in \mathbb{C}^{N+M-1} \) contains the polynomial coefficients of the convolution of the two vector of coefficients of polynomials \( A,B \in \mathbb{C}^N \) and \( B \in \mathbb{C}^M \):

   \[ [1, 2, 1]=\text{conv}([[1, 1], [1, 1]]) \]

7. \( [C,R]=\text{deconv}(N,D) \): Vectors \( C,N,D \in \mathbb{C} \). This operation uses long division of polynomials to find \( C(s) = N(s)/D(s) \) with remainder \( R(s) \), where \( N = \text{conv}(D,C)+R \), namely

   \[
   C = \frac{N}{D} \quad \text{remainder} \quad R.
   \]

   **Example:**  
   Defining the coefficients of two polynomials as \( A = [1, a_1, a_2, a_3] \) and \( B = [1, b_1, b_2, b_3] \), one may find the coefficients of the product from \( C=\text{conv}(A,B) \), and recover \( B \) from \( C \) with \( B=\text{deconv}(C,A) \).

8. \( A=\text{companion}(D) \): Vector \( D = [1, d_{N-1}, d_{N-2}, \cdots, d_0]^T \in \mathbb{C} \) contains the coefficients of the monic polynomial

   \[
   D(s) = s^N + \sum_{k=1}^{N} d_{N-k}s^k,
   \]
   and \( A \) is the companion matrix of vector \( D \) (Eq. B.3, p. 252). The eigenvalues of \( A \) are the roots of monic polynomial \( D(s) \).
Exercise: Practice the use of Matlab’s/Octave’s related functions, which manipulate roots, polynomials and residues: `root()`, `conv()`, `deconv()`, `poly()`, `polyval()`, `polyder()`, `residue()`, `compan()`.

Solution: Try Newton’s method for various polynomials. Use N=poly(R) to provide the coefficients of a polynomial given the roots R. Then use `root()` to factor the resulting polynomial. Then use Newton’s method and show that the iteration converges to the nearest root.\(^{11}\)

Exercise: Write a Matlab/Octave code that finds the companion matrix for the Fibonacci recursion formula. Solution: Z=[1, -1, -1]; C=companion(Z)

### 3.2 Lec 11: Eigenanalysis I: eigenvalues of a matrix

At this point we turn a corner in the discussion, to discuss the important topic of eigenanalysis, which starts with the computation of the eigenvalues and their eigenvectors of a matrix. As briefly discussed in Lecture 2.2 (p. 41), eigenvectors are mathematical generalizations of resonances, or modes, naturally found in physical systems.

When you pluck the string of a violin or guitar, or hammer a bell or tuning fork, there are natural resonances that occur. These are the eigenmodes of the instrument. The frequency of each mode is related to the eigenvalue, which in physical terms is the frequency of the mode. But this idea goes way beyond simple acoustical instruments. Wave-guides and atoms can be resonant systems. The resonances of the hydrogen atom are called the Lyman series,\(^{12}\) a generalization of the Rydberg series and Rydberg atom.

Thus this topic runs deep in both physics and, eventually, mathematics. In some real sense, eigenanalysis was what the Pythagoreans were seeking to understand. This relationship is rarely spoken about in the open literature, but once you see it, it can never be forgotten, as it colors your entire view of all aspects of modern physics.

#### 3.2.1 Eigenvalues of a matrix

The method for finding eigenvalues is best described by an example.\(^{13}\) Starting from the matrix Eq. 2.3.5 (p. 64), the eigenvalues are defined by the eigenmatrix equation

\[
\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 2 & 0 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \lambda \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}.
\]

The unknowns here are the eigenvalue \(\lambda\) and the eigenvector \(e = [e_1, e_2]^T\). First find \(\lambda\) by subtracting the right from the left

\[
\frac{1}{2} \begin{bmatrix} 1 & 1 \\ 2 & 0 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} - \lambda \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 - 2\lambda & 1 \\ 2 & -2\lambda \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = 0
\]

The only way that this equation for \(e\) can have a solution is if the matrix is singular.

Example: The determinant of the above 2x2 example is the product of the diagonal elements, minus the product of the off-diagonal elements, which results in the quadratic equation

\[-2\lambda(1 - 2\lambda) - 2 = 4\lambda^2 - 2\lambda - 2 = 0.\]

---

\(^{11}\)A Matlab/Octave program that does this may be downloaded from [http://jontalle.web.engr.illinois.edu/uploads/493/M/NewtonJPD.m](http://jontalle.web.engr.illinois.edu/uploads/493/M/NewtonJPD.m).


\(^{13}\)Appendix D (p. 261) is an introduction to the topics of eigenanalysis for 2x2 matrices.
Completing the square gives
\[(\lambda - 1/4)^2 - (1/4)^2 - 1/2 = 0, \quad (3.21)\]
thus the roots (i.e., eigenvalues) are \(\lambda \pm \frac{1+3}{4} = \{1, -1/2\}\).

**Exercise:** Expand Eq. 3.21 and recover the quadratic equation. **Solution:**

\[(\lambda - 1/4)^2 - (1/4)^2 - 1/2 = \lambda^2 - \lambda/2 + \frac{1}{4} - (1/4)^2 - 1/2 = 0.\]

Thus completing the square is equivalent to the original equation.

**Exercise:** Find the eigenvalues of matrix Eq. 2.12. (Hint: see p. 262) **Solution:** Briefly

\[\det \begin{bmatrix} 1 - \lambda & N \\ 1 & 1 - \lambda \end{bmatrix} = (1 - \lambda)^2 - N = 0.\]

Thus \(\lambda = 1 \pm \sqrt{N}\).

**Exercise:** Starting from \([x_n, y_n]^T = [1, 0]^T\) compute the first 5 values of \([x_n, y_n]^T\). **Solution:** Here is a Matlab/Octave code for computing \(x_n\):

```matlab
x(1:2,1)=[1;0];
A=[1 1;2 0]/2;
for k=1:10; x(k+1)=A*x(:,k); end
```

which gives the rational \((x_n \in \mathbb{Q})\) sequence: \(1, 1/2, 3/4, 5/8, 11/2^4, 21/2^5, 43/2^6, 85/2^7, 171/2^8, 341/2^9, 683/2^{10}, \cdots\).

**Exercise:** Show that the solution to Eq. 2.18 is bounded, unlike that of the divergent Fibonacci sequence. Explain what is going on. **Solution:** Because the next value is the mean of the last two, the sequence is bounded. To see this one needs to compute the eigenvalues of the matrix Eq. 2.3.5 (p. 64).

**Eigenanalysis:** The key to the analysis of such equations is called the *eigenanalysis*, or modal-analysis method. These are also known as *resonant modes* in the physics literature. Eigenmodes describe the naturally occurring “ringing” found in physical wave-dominated boundary value problems. Each mode’s “eigenvalue” quantifies the mode’s natural frequency. Complex eigenvalues result in damped modes, which decay in time due to energy losses. Common examples include tuning forks, pendulums, bell, and strings of musical instruments, all of which have a characteristic frequency.

Two modes with the same frequency are said to be *degenerate*. This is a very special condition, with a high degree of symmetry.

Cauchy’s residue theorem is used to find the time-domain response of each frequency-domain complex eigenmode. Thus eigenanalysis and eigenmodes of physics are the same thing (see Sect. 4.3, p. 149), but are described using different (i.e., mutually unrecognizable) notional methods.\(^{14}\) The “eigen method” is summarized in Appendix E, p. 265.

Taking a simple example of a 2x2 matrix \(T \in \mathbb{C}\), we start from the definition of the two eigen-equations

\[Te_{\pm} = \lambda_{\pm} e_{\pm}, \quad (3.22)\]

corresponding to two eigenvalues \(\lambda_{\pm} \in \mathbb{C}\) and two 2x1 eigenvectors \(e_{\pm} \in \mathbb{C}\).

\(^{14}\)During the discovery or creation of quantum mechanics, two alternatives were developed: Schrödinger’s differential equation method and Heisenberg’s matrix method. Eventually it was realized the two were equivalent.
**Example:** Assume that $T$ is the Fibonacci matrix Eq. 2.16. The eigenvalues $\lambda_{\pm}$ may be merged into a $2 \times 2$ diagonal eigenvalue matrix

$$\Lambda = \begin{bmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{bmatrix},$$

while the two eigenvectors $e_+$ and $e_-$ are merged into a $2 \times 2$ eigenvector matrix

$$E = [e_+, e_-] = \begin{bmatrix} e_1^+ & e_1^- \\ e_2^+ & e_2^- \end{bmatrix},$$

(3.23)
corresponding to the two eigenvalues. Using matrix notation, this may be compactly written as

$$TE = EL.$$

(3.24)

Note that while $\lambda_{\pm}$ and $E_{\pm}$ commute, $EL \neq LE$.

From Eq. 3.24 we may obtain two very important forms:

1. the diagonalization of $T$

$$\Lambda = E^{-1}TE,$$

(3.25)

and

2. the eigen-expansion of $T$

$$T = EL^{-1},$$

(3.26)

which is useful for computing power of $T$ (i.e., $T^{100} = E^{-1}\Lambda^{100}E$).

**Example:** If we take

$$T = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix},$$

then the eigenvalues are given by $(1 - \lambda_+)(1 + \lambda_+) = -1$, thus $\lambda_\pm = \pm \sqrt{2}$. This method of eigenanalysis is discussed in Section ?? (p. ??) and Appendix F (p. 269).

**Exercise:** Use the formula for the generalized diagonalization of a matrix to find the general solution of the mean-Fibonacci sequence. **Solution:** The eigenvalues are given by the roots of

$$0 = -\lambda(1/2 - \lambda) - 1/2 = (\lambda - 1/4)^2 - 9/16$$

which are $[1, -1/2]$.

By studying the eigenvalues of Eq. 2.3.5 one finds that the steady state solution approaches 1. Namely $f_n \to 1 = (f_{n-1} + f_{n-2})/2$ is the solution, as $n \to \infty$. Namely the average of the last two values must approach 1 for large $n$.

**Exercise:** Show that the geometric series formula holds for $2 \times 2$ matrices. Starting with the $2 \times 2$ identity matrix $I_2$ and $a \in \mathbb{C}$, with $|a| < 1$, show that

$$I_2(a - aI_2)^{-1} = I_2 + aI_2 + a^2I_2^2 + a^3I_2^3 + \cdots.$$

**Solution:** Since $a^kI_2^k = a^kI_2$, we may multiply both sides by $I_2 - aI_2^2$ to obtain

$$I_2 = I_2 + aI_2 + a^2I_2^2 + a^3I_2^3 + \cdots - aI_2(aI_2 + a^2I_2^2 + a^3I_2^3 + \cdots)$$

$$= [1 + (a + a^2 + a^3 + \cdots) - (a + a^2 + a^3 + a^4 + \cdots)]I_2$$

$$= I_2.$$
Exercise: Show that when $T$ is not a square matrix, Eq. 3.22 can be generalized to

$$T_{m,n} = U_{m,m} \Lambda_{m,n} V_{n,n}^\dagger.$$  

This important generalization of eigenanalysis is called a singular value decomposition (SVD).

Summary: The GCD (Euclidean algorithm), Pell’s equation and the Fibonacci sequence may all be written as compositions of $2 \times 2$ matrices. Thus Pell’s equation and the Fibonacci sequence are special cases of $2 \times 2$ matrix composition

$$\begin{bmatrix} x \\ y \end{bmatrix}_{n+1} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}_n.$$  

This is an important and common thread of these early mathematical findings. It will turn out that this $2 \times 2$ matrix recursion plays a special role in physics, mathematics and engineering, because such equations are solved using the eigenanalysis method. More than several thousand years of mathematical, by trial and error, set the stage for this breakthrough. But it took even longer to be fully appreciated.

The key idea of the $2 \times 2$ matrix solution, widely used in modern engineering, can be traced back to Brahmagupta’s solution of Pell’s equation, for arbitrary $N$. Brahmagupta’s recursion, identical to that of the Pythagoreans’ $N = 2$ case (Eq. 2.13), eventually led to the concept of linear algebra, defined by the simultaneous solutions of many linear equations. The recursion by the Pythagoreans ($6^{th}$ BCE) predated the creation of algebra by al-Khwārizmī ($9^{th}$ CE century) (Fig. 1.1) (Stillwell, 2010, p. 88).

3.2.2 Taylor series

An analytic function is one that

1. may be expanded in a Taylor series

$$P(x) = \sum_{n=0}^{\infty} c_n (x - x_o)^n, \quad (3.27)$$

2. converges for $|x - x_o| < 1$, called the RoC, with coefficients $c_n$ that are determined by the derivatives of $P(x)$, evaluated at the expansion point $x = x_o$.

The Taylor series representation of $P(x)$ has special applications for solving differential equations because

1. it is single valued
2. all its derivatives and integrals are uniquely defined
3. it may be trivially continued into the complex plane by extending $x \in \mathbb{C}$.

Analytic continuation: A limitation of the Taylor series expansion is that it is not valid outside of its RoC. One method for avoiding this limitation is to move the expansion point. This is called analytic continuation. However, analytic continuation is a non-trivial operation because it (1) requires manipulating an infinite number of derivatives of $P(x)$, (2) at the new expansion point $x_o$, where (3) $P(x - x_o)$ may not have derivatives, due to possible singularities. (4) Thus one needs to know where the singularities of $P(s)$ are in the complex $s$ plane. Due to these many problems, analytic continuation is rarely used, other than as an important theoretical concept.

The Taylor series coefficients $c_n$ are defined by taking derivatives of $P(x)$ and evaluating them at the expansion point $x_0$, namely

$$c_n = \frac{1}{n!} \left. \frac{d^n}{dx^n} P(x - x_o) \right|_{x=x_o}. \quad (3.28)$$
The Taylor formula is a prescription for how to uniquely define the coefficients \( c_n \). Without the Taylor series formula, we would have no way of determining \( c_n \). The proof of the Taylor formula is transparent, simply by taking successive derivatives of Eq. 3.27, and then evaluating the result at the expansion point. If \( P(x) \) is analytic then this procedure will always work. If \( P(x) \) fails to have a derivative of any order, then the function is not analytic and Eq. 3.27 is not valid for \( P(x) \). For example, if \( P(x) \) has a pole at \( x_o \) then it is not analytic at that point.

**Example:** The trivial (corner) case is the geometric series \( P(x) = 1/(1 - x) \) about the expansion point \( x = 0 \). The function \( P(x) \) is defined everywhere, except at the singular point \( x = 1 \), whereas the geometric series is only valid for \( |x| < 1 \).

**Exercise:** Verify that \( c_0 \) and \( c_1 \) of Eq. 3.27 follow from Eq. 3.28. **Solution:** To obtain \( c_0 \), for \( n = 0 \), there is no derivative (\( d^n/dx^n \) indicates no derivative is taken), so we must simply evaluate \( P(x - x_o) = c_0 + c_1(x - x_o) + \cdots \) at \( x = x_o \), leaving \( c_0 \). To find \( c_1 \) we take one derivative which results in \( P'(x) = c_1 + 2c_2(x - x_o) + \cdots \). Evaluating this at \( x = x_0 \) leaves \( c_1 \). Each time we take a derivative we reduce the degree of the series by 1, leaving the next constant term.

**Exercise:** Suppose we truncate the Taylor series expansion to \( N \) terms. What is the name of such functions and what are their properties? **Solution:** When an infinite series is truncated the resulting function is called an \( N \)th degree polynomial

\[
P_N(x) = 
\sum_{n=0}^{N} c_n = c_0 + c_1(x - x_o) + c_2(x - x_o)^2 \cdots c_N(x - x_o)^N.
\]

We can find \( c_0 \) by evaluating \( P_N(x) \) at the expansion point \( x_o \), since from the above formula \( P_N(x_o) = c_0 \). From the Taylor formula \( c_1 = P'_N(x) |_{x_o} \).

**Exercise:** How many roots do \( P_N(x) \) and \( P'_N(x) \) have? **Solution:** According to the fundamental theorem of algebra \( P_N(x) \) has \( N \) roots. \( P'_N(x) \) has \( N - 1 \) roots. The Gauss-Lucas theorem states that the \( N - 1 \) roots of \( P'_N(x) \) lie inside the convex hull of the \( N \) roots of \( P_N(x) \).

To understand the meaning of the convex hull, consider the following construction: If stakes are placed at each of the \( N \) roots of \( P_N(x) \), and a string is then wrapped around the stakes, with all the stakes inside the string, the convex hull is then the closed set inside the string. One can then begin to imagine how the \( N - 1 \) roots of the derivative must evolve with each set inside the convex hull of the previous set. This concept may be recursed to \( N - 2 \), and below.

**Exercise:** Would it be possible to find the inverse Gauss-Lucas theorem that states where the roots of the integral of a polynomial might be? **Solution:** With each integral there is a new degree of freedom that must be taken into account, thus this problem is much more difficult. But since there is only 1 extra degree of freedom, it does not seem impossible. To solve this problem more constraints will be needed.

**Role of the Taylor series:** The Taylor series plays a major role in the mathematics of differential equations and their solution, as the coefficients of the series uniquely determine the analytic series representation via its derivatives. The implications and limitations of the power series representation are very specific: if the series fails to converge (i.e., outside the RoC), it is essentially meaningless.

A very important fact about the RoC: It is only relevant to the series, not the function being expanded. Typically the function has a pole at the radius of the RoC, where the series fails to converge. However the function being expanded is valid everywhere, other than at the pole. It seems that this point has been poorly explained in many texts. Besides the RoC is the region of divergence RoD, which is the RoC’s complement.
The Taylor series does not need to be infinite to converge to the function it represents, since it obviously works for any polynomial \( P_N(x) \) of degree \( N \). But in the finite case \( (N < \infty) \), the RoC is infinite, and the series is the function \( P_N(x) \) exactly, everywhere. Of course \( P_N(x) \) is called a polynomial of degree \( N \). When \( N \to \infty \), the Taylor series is only valid within the RoC, and it is (typically) the representation of the reciprocal of a polynomial.

These properties are both the curse and the blessing of the analytic function. On the positive side, analytic functions are the ideal starting point for solving differential equations, which is exactly how they were used by Newton and others. Analytic functions are “smooth” since they are infinitely differentiable, with coefficients given by Eq. 3.28. They are single valued, so there can be no ambiguity in their interpretation.

Two well-known analytic functions are the geometric series \((|x| < 1)\)

\[
\frac{1}{1 - x} = 1 + x + x^2 + x^3 + \ldots = \sum_{n=0}^{\infty} x^n
\]  
(3.29)

and exponential series \((|x| < \infty)\)

\[
e^x = 1 + x + \frac{1}{2} x^2 + \frac{1}{3 \cdot 2} x^3 + \frac{1}{4 \cdot 3 \cdot 2} x^4 + \ldots = \sum_{n=0}^{\infty} \frac{1}{n!} x^n.
\]  
(3.30)

**Exercise:** Relate the Taylor series expressions for Eq. 3.29 to the following functions:

1. \( F_1(x) = \int \frac{1}{1 - x} \, dx \)  
   **Solution:** \( x + \frac{1}{2} x^2 + \frac{1}{3} x^3 + \ldots \).

2. \( F_2(x) = \frac{d}{dx} \frac{1}{1 - x} \)  
   **Solution:** \( 1 + 2x + 3x^2 \ldots \).

3. \( F_3(x) = \ln \frac{1}{1 - x} \)  
   **Solution:** \( 1 + \frac{1}{2} x + \frac{1}{3} x^2 \).

4. \( F_4(x) = \frac{d}{dx} \ln \frac{1}{1 - x} \)  
   **Solution:** \( 1 + x + s^2 + s^3 \ldots \).

**Exercise:** Using symbolic manipulation (Matlab, Octave, Mathematica), expand the given function \( F(s) \) in a Taylor series, and find the recurrence relation between the Taylor coefficients \( c_n, c_{n-1}, c_{n-2} \). Assume \( a \in \mathbb{C} \) and \( T \in \mathbb{R} \).

1. \( F(s) = e^{as} \)  
   **Solution:** A Google search on “octave sym taylor” is useful to answer this question. The Matlab/Octave code is to expand this in a taylor series is

\begin{verbatim}
syms s
taylor(exp(s),s,0,’order’,10)
\end{verbatim}
**Exercise:** Find the coefficients of the following functions by the method of Eq. 3.28, and give the RoC.

1. \( w(x) = \frac{1}{1-x} \). **Solution:** From a straightforward expansion we know the coefficients are
   \[
   \frac{1}{1-x} = 1 + x + (x)^2 + (x)^3 \cdots = 1 + x - x^2 - jx^3 \cdots .
   \]

   Working this out using Eq. 3.28 is more work:
   \[
c_0 = \frac{1}{\pi} w|_{0} = 1; \quad c_1 = \frac{1}{\pi} \frac{d}{dx} w|_{0} = -\frac{j}{(1-x)^2} \bigg|_{x=0} = j; \quad c_2 = \frac{1}{\pi} \frac{d^2}{dx^2} w|_{0} = \frac{1}{\pi} \frac{-2}{(1-x)^3} \bigg|_{0} = -1; \quad c_3 = \frac{1}{\pi} \frac{d^3}{dx^3} w|_{0} = -\frac{j}{(1-x)^4} \bigg|_{0} = -j.
   \]

   However, if we take derivatives of the series expansion it is much easier, and one can even figure out the term for \( c_n \):
   \[
c_0 = 1; \quad c_1 = \frac{d}{dx} \sum (jx)^n|_{0} = j; \quad c_2 = \frac{d^2}{dx^2} \sum (jx)^n|_{0} = 2(j)^2; \quad c_3 = \frac{d^3}{dx^3} \sum (jx)^n|_{0} = (j)^3 = -j;
   \]
   \[
   \vdots \\
   c_n = \frac{1}{\pi} j^n n! = j^n.
   \]

   The RoC is \(|xj| = |x| < 1\).

2. \( w(x) = e^{xj} \). **Solution:** \( c_n = \frac{1}{n!} j^n \). The RoC is \(|x| < \infty\). Functions with an \( \infty \) RoC are called **entire**.

**Brune impedances:** A third special **family of functions** is formed from ratios of two polynomials \( Z(s) = N(s) / D(s) \), commonly used to define an impedance \( Z(s) \), denoted the **Brune impedance**. Impedance functions are a very special class of complex analytic functions because they must have a non-negative real part
   \[
   \Re Z(s) = \Re \frac{N(s)}{D(s)} \geq 0,
   \]

   so as to obey conservation of energy. A physical Brune impedance cannot have a negative resistance (the real part); otherwise it would act like a power source, violating conservation of energy. Most impedances used in engineering applications are in the class of Brune impedances, defined by the ratio of two polynomials, of degrees \( m \) and \( n \)

   \[
   Z_{\text{Brune}}(s) = \frac{P_M(s)}{P_N(s)} = \frac{s^M + a_1 s^{M-1} \cdots a_0}{s^N + b_1 s^{N-1} \cdots b_0} \tag{3.35}
   \]

   where \( M = N \pm 1 \) (i.e., \( N = M \pm 1 \)). This fraction of polynomials is sometimes known as a “Padé approximation,” but more specifically this ratio is a **Brune impedance**, with poles and zeros, defined as the complex roots of the two polynomials. The key property of the Brune impedance is that the real part of the impedance is non-negative (positive or zero) in the right \( s \) half-plane

   \[
   \Re Z(s) = \Re [R(\sigma, \omega) + jX(\sigma, \omega)] = R(\sigma, \omega) \geq 0 \quad \text{for} \quad \Re s = \sigma \geq 0. \tag{3.36}
   \]

   Since \( s = \sigma + \omega j \), the complex frequency \( (s) \) right half-plane (RHP) corresponds to \( \Re s = \sigma \geq 0 \). This condition defines the class of **positive-real** functions, also known as the **Brune condition**, which is frequently written in the abbreviated form

   \[
   \Re Z(\Re s \geq 0) \geq 0.
   \]

As a result of this **positive-real** constraint on impedance functions, the subset of Brune impedances (those given by Eq. 3.35 satisfying Eq. 3.36) must be complex analytic in the entire right \( s \) half-plane. This is a powerful constraint that places strict limitations on the locations of both the poles and the zeros of every positive-real Brune impedance.
Exercise: Show that $Z(s) = 1/\sqrt{s}$ is positive real, but not a Brune impedance. Solution: Since it may not be written as the ratio of two polynomials, it is not in the Brune impedance class. By writing $Z(s) = |Z(s)|e^{\phi s}$ in polar coordinates, since $-\pi/4 \leq \phi \leq \pi/4$ when $|\angle s| < \pi/2$, $Z(s)$ satisfies the Brune condition, thus is positive real.

Determining the region of convergence (RoC): Determining the RoC for a given analytic function is quite important, and may not always be obvious. In general the RoC is a circle whose radius extends from the expansion point out to the nearest pole. Thus when the expansion point is moved, the RoC changes since the location of the pole is fixed.

Example: For the geometric series (Eq. 3.29), the expansion point is $x_0 = 0$, and the RoC is $|x| < 1$, since $1/(1 - x)$ has a pole at $x = 1$. We may move the expansion point by a linear transformation, for example, by replacing $x$ with $z + 3$. Then the series becomes $1/((z + 3) - 1) = 1/(z + 2)$, so the RoC becomes 2 because in the $z$ plane the pole has moved to $-2$.

Example: A second important example is the function $1/(x^2 + 1)$, which has the same RoC as the geometric series, since it may be expressed in terms of its residue expansion (aka, partial fraction expansion)

$$\frac{1}{x^2 + 1} = \frac{1}{(x + 1j)(x - 1j)} = \frac{1}{2j} \left( \frac{1}{x - 1j} - \frac{1}{x + 1j} \right).$$

Each term has an RoC of $|x| < |1j| = 1$. The amplitude of each pole is called the residue, defined in Section 4.4 Eq. 4.36, p. 163. The residue for the pole at $1j$ is $1/2j$.

In summary, the function $1/(x^2 + 1)$ is the sum of two geometric series, with poles at $\pm 1j$ which are not as obvious because the roots are complex and conjugate. Once factored, it becomes clear what is going on.

Exercise: Verify the above expression is correct, and show that the residues are $\pm 1/2j$. Solution: Cross-multiply and cancel, leaving 1, as required. The RoC is the coefficient on the pole. Thus the residue of the pole at $xj$ is $j/2$.

Exercise: Find the residue of $\frac{d}{dz} z^\pi$. Solution: Taking the derivative gives $z^{\pi - 1}$ which has a pole at $z = 0$. Applying the formula for the residue (Eq. 4.36, p. 163) we find

$$e^{-1} = \lim_{z \to 0} z z^{\pi - 1} = \lim_{z \to 0} z^\pi = 0.$$  

Thus the residue is zero. The exponential series converges for every finite value of $x \in \mathbb{R}$ (the RoC is the entire real line), thus the exponential is called an entire function.

Exercise: Find the residue of $\frac{d}{dz} (z - 1)^{-\pi}$. Solution: Add solution.

### 3.2.3 Analytic functions:

Any function that has a Taylor series expansion is called an analytic function. Within the RoC, the series expansion defines a single-valued function. Polynomials $1/(1 - x)$ and $e^x$ are examples of analytic functions that are real functions of their real argument $x$. This is not the entire story. Because analytic functions are easily manipulated term by term, they may be used to find solutions of differential equations since the derivatives of a series are uniquely determined within the RoC, due to Eq. 3.28.

Every analytic function has a corresponding differential equation, which is determined by the coefficients $a_k$ of the analytic power series. An example is the exponential, which has the property that it is the eigenfunction of the derivative operation

$$\frac{d}{dx} e^{\alpha x} = \alpha e^{\alpha x},$$
which may be verified using Eq. 3.30. This relationship is a common definition of the exponential function, which is very special because it is the eigenfunction of the derivative.

The complex analytic power series (i.e., complex analytic functions) may also be integrated, term by term, since

\[ \int f(x)dx = \sum \frac{a_k}{k + 1} x^{k+1}. \]  

(3.37)

Newton took full advantage of this property of the analytic function and used the analytic series (Taylor series) to solve analytic problems, especially for working out integrals, allowing him to solve differential equations. To fully understand the theory of differential equations, one must master single-valued analytic functions and their analytic power series.

**Single- vs. multi-valued functions:** Polynomials and their \( \infty \)-degree extensions (analytic functions) are single valued: for each \( x \) there is a single value for \( P_N(x) \). The roles of the domain and codomain may be swapped to obtain an inverse function, with properties that can be different from those of the function. For example, \( y(x) = x^2 + 1 \) has the inverse \( x = \pm \sqrt{y - 1} \), which is double valued, and complex when \( y < 1 \). Periodic functions such as \( y(x) = \sin(x) \) are even more “exotic” since \( x(y) = \arcsin(x) = \sin^{-1}(x) \) has an infinite number of \( x(y) \) values for each \( y \). This problem was first addressed in Riemann’s 1851 PhD thesis, written while he was working with Gauss.

**Exercise:** Let \( y(x) = \sin(x) \). Then \( dy/dx = \cos(x) \). Show that \( dx/dy = -1/\sqrt{1-x^2} \). Hint: \( x(y) = \cos^{-1}(y) = \arccos(y) \). **Solution:** See the implicit function theorem (D’Angelo, 2017, p. 104). Add solution.

**Exercise:** Let \( y(x) = \sin(x) \). Then \( dy/dx = \cos(xj) \). Show that \( dx/dy = -j/\sqrt{1+x^2} \). **Solution:** Add solution.

**Exercise:** Find the Taylor series coefficients of \( y = \sin(x) \) and \( x = \sin^{-1}(y) \). **Solution:** Add solution.

**Complex analytic functions:** When the argument of an analytic function \( F(x) \) is complex, that is, \( x \in \mathbb{R} \) is replaced by \( s = \sigma + \omega j \in \mathbb{C} \) (recall that \( \mathbb{R} \subset \mathbb{C} \))

\[ F(s) = \sum_{n=0}^{\infty} c_n (s - s_o)^n, \]  

(3.38)

with \( c_n \in \mathbb{C} \), that function is said to be a complex analytic.

For example, when the argument of the exponential becomes complex, it is periodic on the \( \omega \) axis, since

\[ e^{st} = e^{(\sigma + \omega j)t} = e^{\sigma t}e^{\omega j t} = e^{\sigma t} [\cos(\omega t) + j \sin(\omega t)]. \]  

(3.39)

Taking the real part gives

\[ \Re\{e^{st}\} = e^{\sigma t} \frac{e^{\omega j t} + e^{-\omega j t}}{2} = e^{\sigma t} \cos(\omega t), \]

and \( \Im\{e^{st}\} = e^{\sigma t} \sin(\omega t) \). Once the argument is allowed to be complex, it becomes obvious that the exponential and circular functions are fundamentally related. This exposes the family of entire circular functions [i.e., \( e^s, \sin(s), \cos(s), \tan(s), \cosh(s), \sinh(s) \)] and their inverses \([\ln(s), \arcsin(s), \arccos(s), \arctan(s), \cosh^{-1}(s), \sinh^{-1}(s)]\), first fully elucidated by Euler (c1750) (Stillwell, 2010, p. 315). Note that because a function, such as \( \sin(\omega t) \), is periodic, its inverse must be multi-valued. What is needed is some systematic way to account for this multi-valued property. Euler also studied the Gamma function \( (\Gamma(s)) \), which generalizes the factorial operation for real, and eventually by Gauss, for complex arguments \((s, \Gamma(s) \in \mathbb{C})\):

\[ s! = \Gamma(s + 1). \]
Given a complex analytic function of a complex variable, one must resort to the extended complex plane, Riemann sheets and branch cuts, as discussed in Section 3.8.1 (p. 136). The extended complex plane is a tool that extends the domain of complex analytic functions to include the point at infinity. This topic is critically important in engineering mathematics and will be discussed at length in Sections 3.8.1-3.7 (pp. 136-130).

**Definition of the Taylor series of a complex analytic function:** However, there is a fundamental problem: we cannot formally define the Taylor series for the coefficients \( c_k \) until we have defined the derivative with respect to the complex variable \( dF(s)/ds \), with \( s \in \mathbb{C} \). Thus simply substituting \( s \) for \( x \) in an analytic function leaves a major hole in one’s understanding of the complex analytic function.

To gain a feeling for the nature of the problem, we make take derivatives of a function with respect to various variables. For example,

\[
\frac{d}{dt} e^{st} = se^{st},
\]

\[
e^{\sigma \tau} \frac{d}{d\sigma} e^{\sigma t} = \sigma e^{st},
\]

and

\[
e^{\sigma t} \frac{d}{d\omega} e^{\omega t} = \omega je^{st}.
\]

It was Cauchy (1814) (Fig. 3.1) who uncovered much deeper relationships within complex analytic functions (Sect. 3.8, p. 134) by defining differentiation and integration in the complex plane, leading to several fundamental theorems of complex calculus, including the fundamental theorem of complex integration, and Cauchy’s formula. We shall explore this and several fundamental theorems in Sect. 4.2 (p. 146).

There seems to be some disagreement as to the status of multi-valued functions: Are they functions, or is a function strictly single valued? If so, then we are missing out on a host of interesting possibilities, including all the inverses of nearly every complex analytic function. For example, the inverse of a complex analytic function is a complex analytic function (e.g., \( e^s \) and \( \log(s) \)).

**Impact of complex analytic mathematics on physics:** It seems likely, if not obvious, that the success of Newton was his ability to describe physics by the use of mathematics. He was inventing new mathematics at the same time he was explaining new physics. The same might be said for Galileo. It seems likely that Newton was extending the successful techniques and results of Galileo’s work on gravity (Galileo, 1638). Galileo died on Jan 8, 1642, and Newton was born Jan 4, 1643, just short of one year later. Certainly Newton was well aware of Galileo’s great success, and naturally would have been influenced by it (see p. 22).

The application of complex analytic functions to physics was dramatic, as may be seen in the six volumes on physics by Arnold Sommerfeld (1868-1951), and from the productivity of his many (36) students (e.g., Debye, Lenz, Ewald, Pauli, Guillemin, Bethe, Heisenberg, and Seebach, to name a few), notable coworkers (i.e., Leon Brillouin) and others (i.e., John Bardeen) upon whom Sommerfeld had a strong influence. Sommerfeld is famous for training many students who were awarded the Nobel Prize in Physics, yet he never won a Nobel (the prize is not awarded in mathematics). Sommerfeld brought mathematical physics (the merging of physical and experimental principles via mathematics) to a new level with the use of complex integration of analytic functions to solve otherwise difficult problems, thus following the lead of Newton who used real integration of Taylor series to solve differential equations (Brillouin, 1960, Ch. 3 by Sommerfeld, A.).

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15 http://muse.tau.ac.il/museum/galileo/galileo_low_of_fall.html
3.2.4 Exercises AE-1

**Topic of this homework:** Fundamental theorem of algebra, polynomials, analytic functions and their inverse, convolution, roots.

**Deliverable:** Answers to problems

**Note:** The term ‘analytic’ is used in two different ways. (1) An analytic function is a function that may be expressed as a locally convergent power series; (2) analytic geometry refers to geometry using a coordinate system.

**Polynomials and the fundamental theorem of algebra (FTA)**

A polynomial of degree $N$ is defined as

$$P_N(x) = a_0 + a_1x + a_2x^2 \cdots a_Nx^N$$

1. How many coefficients $a_n$ does a polynomial of degree $N$ have?

2. How many roots does $P_N(x)$ have?

3. The fundamental theorem of algebra (FTA)
   - State the FTA.
   - Using the FTA, prove your answer to question (2) above.

4. Consider the polynomial function $P_2(x) = 1 + x^2$ of degree $N = 2$, and the related function $F(x) = 1/P_2(x)$.
   - What are the roots (e.g. ‘zeros’) $x_{\pm}$ of $P_2(x)$?
   - $F(x)$ may be expressed as $(A, B, x_{\pm} \in \mathbb{C})$

$$F(x) = \frac{A}{x - x_+} + \frac{B}{x - x_-}, \quad (3.40)$$

where $x_{\pm}$ are the roots (zeros) of $P_2(x)$, which become the poles of $F(x)$, and $A, B$ are the residues. The expression for $F(x)$ is sometimes called a ‘partial fraction expansion’ or ‘residue expansion,’ and it appears in many engineering applications.

- Find $A, B \in \mathbb{C}$ in terms of the roots $x_{\pm}$ of $P_2(x)$.
- Verify your answers for $A, B$ by showing that this expression for $F(x)$ is indeed equal to $1/P_2(x)$.

5. The poles of a function $G(x)$ are defined as values $x_p$ where $G(x_p) \to \infty$; the zeros are defined as values $x_z$ where $G(x_z) = 0$.

**Hint:** Do not forget to consider $f(x)$ as $x \to \pm \infty$

- Give the values of the poles and zeros of $P_2(x)$.
- Give the values of the poles and zeros of $F(x) = 1/P_2(x)$. 

3.2. LECTURE 11: (WEEK 4) EIGENANALYSIS

**Analytic functions**

Analytic functions are defined by infinite (power) series. The function \( f(x) \) is analytic at any value of \( x = x_0 \) where there exists a convergent power series

\[
P(x) = \sum_{n=0}^{\infty} a_n x^n
\]

such that \( P(x_0) = f(x_0) \). The local power series for \( f(x) \) near \( x = x_0 \) is often obtained by finding the Taylor series:

\[
f(x) \approx f(x_0) + \frac{df}{dx} \bigg|_{x=x_0} (x-x_0) + \frac{1}{2!} \frac{d^2 f}{dx^2} \bigg|_{x=x_0} (x-x_0)^2 + \ldots
\]

\[
= \sum_{n=0}^{\infty} \frac{1}{n!} \frac{d^n f}{dx^n} \bigg|_{x=x_0} (x-x_0)^n.
\]

The point \( x = x_0 \) is called the series expansion point.

When the expansion point is at \( x_0 = 0 \), the series is denoted a MacLaurin series. Two classic examples are the geometric series\(^{16}\) where \( a_n = 1 \)

\[
\frac{1}{1-x} = 1 + x + x^2 + x^3 + \ldots = \sum_{n=0}^{\infty} x^n,
\]

and the exponential function where \( a_n = 1/n! \)

\[
e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \ldots = \sum_{n=0}^{\infty} \frac{x^n}{n!}.
\]

The coefficients for both series may be derived from the Taylor formula (or MacLaurin formula, when the expansion point is zero).

- The geometric series

1. What is the region of convergence (RoC) for the power series of \( 1/(1-x) \) given above (e.g. where does the power series \( P(x) \) converge to the function value \( f(x) \))? State your answer as a condition on \( x \). Hint: What happens to the power series when \( x > 1 \)?

2. In terms of the pole, what is the RoC for the geometric series (Eq. 3.1)?

3. How does the RoC relate to the location of the pole of \( 1/(1-x) \)?

4. Where are the zeros, if any, in Eq. 3.1?

5. Assuming \( x \) is in the RoC, prove that the geometric series correctly represents \( 1/(1-x) \) by multiplying both sides of Eq. 3.1 by \( (1-x) \).

6. Use the geometric series to study the degree \( N \) polynomial (It is very important to note that all the coefficients of this polynomial are 1)

\[
P_N(x) = 1 + x + x^2 + \ldots + x^N = \sum_{n=0}^{N} x^n.
\]

\[
= \text{Prove that }
\]

\[
P_N(x) = \frac{1 - x^{N+1}}{1 - x}
\]

\(^{16}\) The geometric series is not defined as the function \( 1/(1-x) \), it is defined as the series \( 1 + x + x^2 + x^3 + \ldots \), such that the ratio of consecutive terms is \( x \).
What is the RoC for Eq. 3.2?
what is the RoC for Eq. 3.3?
What is the RoC for Eq. 3.4?
Evaluate $P_N(x)$ at $x = 0$ and $x = .9$ for the case of $N = 100$, and compare the result to that from Matlab.

```matlab
%sum the geometric series and P_100(0.9)
clear all; close all; format long
N=100; x=0.9; S=0;
for n=0:N
    S=S+x^n
end
P100=(1-x^(N+1))/(1-x);
disp(sprintf('S= %g, P100= %g, error= %g',S,P100, S-P100))
```

How many poles does $P_N(x)$ have? Where are they?

How many zeros does $P_N(x)$ have? State where are they in the complex plane?

Does the above expression have both poles and zeros? Explain.

Explain why Eq. 3.3 and 3.4 have different numbers of poles and zeros.

7. Is the function $1/(1-x)$ analytic outside of the RoC stated in part (a)? Hint: Can it be represented by a different power series outside this RoC?

• The exponential series

1. What is the region of convergence (RoC) for the exponential series given above (e.g. where does the power series $P(x)$ converge to the function value $f(x)$)?
2. Let $x = j$ in Eq. 3.2, and write out the series expansion of $e^x$ in terms of its real and imaginary parts.
3. Let $x = j\theta$ in Eq. 3.2, and write out the series expansion of $e^x$ in terms of its real and imaginary parts. How does your result relate to Euler’s identity ($e^{j\theta} = \cos(\theta) + j\sin(\theta)$)?

**Inverse analytic functions and composition**

It may be surprising, but every analytic function has an inverse function. Starting from the function $(x, y \in \mathbb{C})$

$$y(x) = \frac{1}{1-x}$$

the inverse is

$$x = \frac{y - 1}{y} = 1 - \frac{1}{y}.$$  

1. Considering the inverse function described above
   • Where are the poles and zeros of $x(y)$?
   • Where (for what condition on $y$) is $x(y)$ analytic?

2. Considering the exponential function $z(x) = e^x$ ($x, z \in \mathbb{C}$)
   • Find the inverse $x(z)$.
   • Where are the poles and zeros of $x(z)$?

3. Compose these two functions $(y \circ z)(x)$
   • Give the expression for $(y \circ z)(x) = y(z(x))$.
   • Where are the poles and zeros of $(y \circ z)(x)$?
   • Where (for what condition on $x$) is $(y \circ z)(x)$ analytic?
Convolution

Multiplying two polynomials, when they are short or simple, is not demanding. However if they have many terms, it can become tedious. For example, multiplying two 10\textsuperscript{th} degree polynomials is not something one would want to do every day.

An alternative is a method called convolution, as described in Lecture 13.

• Convolution of sequences

Practice convolution (by hand!!) using a few simple examples. Show your work!! You may check your solution using Matlab.

- Convolve the sequence [0 1 1 1 1] with itself.
- Convolve [1 1] with itself, then convolve the result with [1 1] again (e.g., calculate [1, 1] \ast [1, 1]).

• Multiplication of polynomials

In class, it was shown that multiplying two polynomials is the same as convolving their coefficients. Consider

\[ f(x) = x^3 + 3x^2 + 3x + 1 \]
\[ g(x) = x^3 + 2x^2 + x + 2 \]

In Matlab, compute \( h(x) = f(x) \cdot g(x) \) two ways using (a) the commands \texttt{roots} and \texttt{poly}, and (b) the convolution command \texttt{conv}. Confirm that both methods give the same result. That is, compute the convolution \( [1, 1, 1, 1] \ast [1, 1, 1, 1] \).

What is \( h(x) \)?

Intersection and analytic geometry

To find Euclid’s formula, it was necessary to study the intersection of a circle and a secant line. Consider the unit circle of radius 1, centered at \((x, y) = (0, 0)\)

\[ x^2 + y^2 = 1 \]

and the line through \((-1, 0)\)

\[ y = t(x + 1) \]

having slope \( t \) and intercept \( x = -1 \). If the slope \( 0 < t < 1 \), the line intersects the circle at a second point \((a, b)\) in the positive \(x, y\) quadrant. The goal is to find \( a, b \in \mathbb{N} \) and then show that \( c^2 = a^2 + b^2 \).

Since the construction gives a right triangle with short sides \( a, b \in \mathbb{N} \), then it follows that \( c \in \mathbb{N} \).

Newton’s root-finding method

Newton used the iteration Eq. 3.14 (p. 77) to find roots of the polynomial

\[ P_3(x) = 1 - x^3. \]

Draw a graph describing the first step of the iteration starting with \( x_0 = (1/2, 0) \).

1. Calculate \( x_1 \) and \( x_2 \). What number is the algorithm approaching?

2. Write a Matlab script to check your answer for part (a).

• For \( n = 4 \), what is the absolute difference between the root and the estimate, \(|x_r - x_4|\)?
Euclidean Proof:
1) \(2\phi + \eta = \pi\)
2) \(\eta + \Theta = \pi\)
3) \(\therefore, \phi = \Theta/2\)

Diophantus’s Proof:
1) \(c^2 = a^2 + b^2\)
2) \(b(a) = t(a + c)\)
3) \(\zeta(t) \equiv a + jb = \frac{1-t^2+2it}{1-t^2}\)
4) \(\zeta = |c|e^{i\theta} = |c|(\cos(\theta) + i\sin(\theta))\)

Pythagorean triplets:
1) \(t = p/q \in \mathbb{Q}\)
2) \(a = p^2 - q^2\)
3) \(b = 2pq\)
4) \(c = p^2 + q^2\)

Figure 3.4: Derivation of Euclid’s formula for the Pythagorean triplets \([a, b, c]\), based on a composition of a line, having a rational slope \(t = p/q \in \mathbb{Q}\), and a circle \(c^2 = a^2 + b^2\), \([a, b, c] \in \mathbb{N}\). This analysis is attributed to Diophantus (Di-o-phân’·tus) (250 CE), and today such equations are called Diophantine (Di-o-phân’tine) equations. PTs have applications in architecture and scheduling, and many other practical problems.

- What happens if \(x_0 = -1/2\)?

3. Does Newton’s method work for \(P_2(x) = 1 + x^2\)? Why?

4. What if you let \(x_0 = (1 + j)/2\) for the case of \(P_2(x) = 1 + x^2\)?

Riemann zeta function \(\zeta(s)\)

Definitions and preliminary analysis

The zeta function \(\zeta(s)\) is defined by the complex analytic power series

\[
\zeta(s) \equiv \sum_{n=1}^{\infty} \frac{1}{n^s} = \frac{1}{1^s} + \frac{1}{2^s} + \frac{1}{3^s} + \frac{1}{4^s} + \cdots. \tag{3.5}
\]

This series converges, and thus is valid, only in the region of convergence (ROC) given by \(\Re s = \sigma > 1\) since there \(|n^{-\sigma}| < 1\). To determine its formula in other regions of the \(s\) plane one must extend the series via analytic continuation.

Euler product formula: As was first published by Euler in 1737, one may recursively factor out the leading prime term, resulting in Euler’s product formula.\(^{18}\) Multiplying \(\zeta(s)\) by the factor \(1/2^s\), and subtracting from \(\zeta(s)\), removes all the terms \(1/(2n)^s\) (e.g., \(1/2^s + 1/4^s + 1/6^s + 1/8^s + \cdots\))

\[
\left(1 - \frac{1}{2^s}\right) \zeta(s) = 1 + \frac{1}{2^s} + \frac{1}{3^s} + \frac{1}{4^s} + \frac{1}{5^s} + \cdots - \left(\frac{1}{2^s} + \frac{1}{4^s} + \frac{1}{6^s} + \frac{1}{8^s} + \frac{1}{10^s} + \cdots\right), \tag{3.6}
\]

which results in

\[
\left(1 - \frac{1}{2^s}\right) \zeta(s) = 1 + \frac{1}{3^s} + \frac{1}{5^s} + \frac{1}{7^s} + \frac{1}{9^s} + \frac{1}{11^s} + \frac{1}{13^s} + \cdots. \tag{3.7}
\]

1. What is the RoC for Eq. 3.7

\(^{17}\)https://en.wikipedia.org/wiki/Newton%27s_method#Complex_functions

\(^{18}\)This is known as Euler’s sieve, as distinguish from the Eratosthenes sieve.
2. Repeat this with a lead factor $1/3^s$ applied to Eq. 3.7.

3. Repeat this process, with all prime scale factors (i.e., $1/5^s, 1/7^s, \cdots, 1/\pi_k^s, \cdots$), and show that

$$
\zeta(s) = \prod_{\pi_k \in \mathbb{P}} \frac{1}{1 - \pi_k^{-s}} = \prod_{\pi_k \in \mathbb{P}} \zeta_k(s)
$$

(3.8)

where $\pi_p$ represents the $p^{th}$ prime.

4. Given the product formula we may identify the poles of $\zeta_p(s) (p \in \mathbb{Z})$, which is important for defining the ROC of each factor. For example, the $p^{th}$ factor of Eq. 3.8, expressed as an exponential, is

$$
\zeta_p(s) \equiv \frac{1}{1 - \pi_p^{-s}} = \frac{1}{1 - e^{-sT_p}},
$$

(3.9)

where $T_p \equiv \ln \pi_p$.

Plot $\zeta_p(s)$ using zviz for $p = 1$. Describe what you see.
3.3 Lec 12: Root classification by convolution

Following the exploration of algebraic relationships by Fermat and Descartes, the first theorem was being formulated by d’Alembert. The idea behind this theorem is that every polynomial of degree $N$ (Eq. 3.7) has at least one root. This may be written as the product of the root and a second polynomial of degree of $N - 1$. By the recursive application of this concept, it is clear that every polynomial of degree $N$ has $N$ roots. Today this result is known as the fundamental theorem of algebra:

Every polynomial equation $P(z) = 0$ has a solution in the complex numbers. As Descartes observed, a solution $z = a$ implies that $P(z)$ has a factor $z - a$. The quotient

$$Q(z) = \frac{P(z)}{z - a} = \frac{P(z)}{a} \left[ 1 + \frac{z}{a} + \left(\frac{z}{a}\right)^2 + \left(\frac{z}{a}\right)^3 + \cdots \right] \quad (3.10)$$

is then a polynomial of one lower degree. ... We can go on to factorize $P(z)$ into $n$ linear factors.


The ultimate expression of this theorem is given by Eq. 3.7 (p. 74), which indirectly states that an $n^{th}$ degree polynomial has $n$ roots. We shall use the term degree when speaking of polynomials and the term order when speaking of differential equations. A general rule is that order applies to the time domain and degree to the frequency domain, since the Laplace transform of a differential equation, having constant coefficients, of order $N$, is a polynomial of degree $N$ in Laplace frequency $s$.

Today this theorem is so widely accepted we fail to appreciate it. Certainly about the time you learned the quadratic formula, you were prepared to understand the concept of polynomials having roots. The simple quadratic case may be extended to a higher degree polynomial. The Octave/Matlab command \texttt{roots} ([1, $a_2$, $a_1$, $a_0$]) provides the roots [s$_1$, s$_2$, s$_3$] of the cubic equation, defined by the coefficient vector [1, $a_2$, $a_1$, $a_0$]. The command \texttt{poly} ([s$_1$, s$_2$, s$_3$]) returns the coefficient vector. I don’t know the largest degree that can be accurately factored by Matlab/Octave, but I’m sure its well over $N = 10^3$. Today, finding the roots numerically is a solved problem.

Factorization versus convolution: The best way to gain insight into the polynomial factorization problem is through the inverse operation, multiplication of monomials. Given the roots $x_k$, there is a simple algorithm for computing the coefficients $a_k$ of $P_N(x)$ for any $n$, no matter how large. This method is called convolution. Convolution is said to be a trap-door function since it is easy, while the inverse, factoring (deconvolution), is hard, and analytically intractable for degree $N \geq 5$ (Stillwell, 2010, p. 102).

3.3.1 Convolution of monomials

As outlined by Eq. 3.7, a polynomial has two descriptions, first as a series with coefficients $a_n$ and second in terms of its roots $x_r$. The question is: What is the relationship between the coefficients and the roots? The simple answer is that they are related by convolution.

Let us start with the quadratic

$$(x + a)(x + b) = x^2 + (a + b)x + ab, \quad (3.11)$$

where in vector notation $[-a, -b]$ are the roots and $[1, a + b, ab]$ are the coefficients.

To see how the result generalizes, we may work out the coefficients for the cubic ($N = 3$). Multiplying the following three factors gives (p. ??)

$$(x - 1)(x - 2)(x - 3) = (x^2 - 3x + 2)(x - 3) = x(x^2 - 3x + 2) - 3(x^2 - 3x + 2) = x^3 - 6x^2 + 11x - 6.$$
When the roots are \([1, 2, 3]\) the coefficients of the polynomial are \([1, -6, 11, -6]\). To verify, substitute the roots into the polynomial, and show that they give zero. For example, \(r_1 = 1\) is a root since \(P_3(1) = 1 - 6 + 11 - 6 = 0\).

As the degree increases, the algebra becomes more difficult. Imagine trying to work out the coefficients for \(N = 100\). What is needed is a simple way of finding the coefficients from the roots. Fortunately, convolution keeps track of the book-keeping, by formalizing the procedure.

**Convolution of two vectors:** To get the coefficients by convolution, write the roots as two vectors \([1, a]\) and \([1, b]\). To find the coefficients we must convolve the vectors, indicated by \([1, a] \ast [1, b]\), where \(\ast\) denotes convolution. Convolution is a recursive operation. The convolution of \([1, a] \ast [1, b]\) is done as follows: reverse one of the two monomials, padding unused elements with zeros. Next slide one monomial against the other, forming the local scalar product (element-wise multiply and add):

\[
\begin{array}{cccc}
  a & 1 & 0 & 0 \\
  0 & 0 & 1 & b \\
\end{array}
\begin{array}{cccc}
  a & 1 & 0 & 0 \\
  0 & 1 & b & 0 \\
\end{array}
\begin{array}{cccc}
  0 & a & 1 & 0 \\
  1 & b & 0 & 1 \\
\end{array}
\begin{array}{cccc}
  0 & a & 1 & 1 \\
  0 & b & 0 & 0 \\
\end{array}
\]

resulting in coefficients \([\cdot \cdot \cdot, 0, 0, 1, a + b, ab, 0, 0, \cdot \cdot \cdot]\).

By reversing one of the polynomials, and then taking successive scalar products, all the terms in the sum of the scalar product correspond to the same power of \(x\). This explains why convolution of the coefficients gives the same answer as the product of the polynomials.

As seen by the above example, the positions of the first monomial coefficients are reversed, and then slid across the second set of coefficients, the dot-product is computed, and the result placed in the output vector. Outside the range shown, all the elements are zero. In summary,

\[
[1, -1] \ast [1, -2] = [1, -1 - 2, 2] = [1, -3, 2].
\]

In general

\[
[a, b] \ast [c, d] = [ac, bc + ad, bd],
\]

Convolving a third term \([1, -3]\) with \([1, -3, 2]\) gives (p. ??)

\[
[1, -3] \ast [1, -3, 2] = [1, -3 - 3, 9 + 2, -6] = [1, -6, 11, -6],
\]

which is identical to the cubic example, found by the algebraic method.

By convolving one monomial factor at a time, the overlap is always two elements, thus it is never necessary to compute more than two multiplies and an add for each output coefficient. This greatly simplifies the operations (i.e., they are easily done in your head). Thus the final result is more likely to be correct. Comparing this to the algebraic method, convolution has the clear advantage.

**Exercise:**

1. What are the three nonlinear equations that one would need to solve to find the roots of a cubic?

**Solution:** From our formula for the convolution of three monomials we may find the nonlinear "deconvolution" relations between the roots\(^\text{19}\) \([-a, -b, -c]\) and the cubic’s coefficients \([1, \alpha, \beta, \gamma]\)

\[
(x + a) \ast (x + b) \ast (x + c) = (x + c) \ast (x^2 + (a + b)x + ab)
\]

\[
= x \cdot (x^2 + (a + b)x + ab) + c \cdot (x^2 + (a + b)x + ab)
\]

\[
= x^3 + (a + b + c)x^2 + (ab + ac + cb)x + abc
\]

\[
= [1, a + b + c, ab + ac + cb, abc].
\]

\(^\text{19}\)By working with the negative roots we may avoid an unnecessary and messy alternating sign problem.
It follows that the nonlinear equations must be
\[ \alpha = a + b + c \]
\[ \beta = ab + ac + bc \]
\[ \gamma = abc. \]

Clearly these are solved by the classic cubic solution which appears to be a deconvolution problem, also known as long division of polynomials. It follows that the following long-division of polynomials must be true:
\[
\frac{x^3 + (a + b + c)x^2 + (ab + ac + bc)x + abc}{x + a} = x^2 + (b + c)x + bc
\]

The product of monomial \( P_1(x) \) with a polynomial \( P_N(x) \) gives \( P_{N+1}(x) \): This statement is another way of stating the fundamental theorem of algebra. Each time we convolve a monomial with a polynomial of degree \( N \), we obtain a polynomial of degree \( N + 1 \). The convolution of two monomials results in a quadratic (degree 2 polynomial). The convolution of three monomials gives a cubic (degree 3). In general, the degree \( k \) of the product of two polynomials of degree \( n, m \) is the sum of the degrees \( (k = n + m) \). For example, if the degrees are each 5 \((n = m = 5)\), then the resulting degree is 10.

While we all know this theorem from high school algebra class, it is important to explicitly identify the fundamental theorem of algebra.

Note that the degree of a polynomial is one less than the length of the vector of coefficients. Since the leading term of the polynomial cannot be zero, else the polynomial would not have degree \( N \), when looking for roots, the coefficient can (and should always) be normalized to 1.

In summary, the product of two polynomials of degree \( m, n \) having \( m \) and \( n \) roots gives a polynomial of degree \( m + n \). This is an analysis process of merging polynomials, by coefficient convolution.

Multiplying polynomials is a merging process, into a single polynomial.

Composition of polynomials: Convolution is not the only important operation between two polynomials. Another is composition, which may be defined for two functions \( f(z), g(z) \). Then the composition \( c(z) = f(z) \circ g(z) = f(g(z)) \). As a specific example, suppose \( f(z) = 1 + z + z^2 \) and \( g(z) = e^{2z} \). With these definitions
\[
f(z) \circ g(z) = 1 + e^{2z} + (e^{2z})^2 = 1 + e^{2z} + e^{4z}.
\]

Note that \( f(z) \circ g(z) \neq g(z) \circ f(z) \).

Exercise: Find \( g(z) \circ f(z) \). Solution: \( e^{2f(z)} = e^{2(1+z+z^2)} = e^2 e^{(1+z+z^2)} = e^3 e^z e^{z^2} \).

3.3.2 Residue expansions of rational functions

As discussed in Section ??, p. 83, there are five important Matlab/Octave routines that are closely related: \texttt{conv()}, \texttt{deconv()}, \texttt{poly()}, \texttt{polyder()}, \texttt{polyval()}, \texttt{residue()}, \texttt{root()}. Several of these are complements of each other, or do a similar operation in a slightly different way. Routines \texttt{conv()} and \texttt{poly()} build polynomials from the roots, while \texttt{root()} solves for the roots given the polynomial coefficients. The operation \texttt{residue()} converts the ratio of two polynomials and expands it in a partial fraction expansion, with poles and residues.

When lines and planes are defined, the equations are said to be linear in the independent variables. In keeping with this definition of linear, we say that the equations are non-linear when the equations have degree greater than 1 in the independent variables. The term bilinear has a special meaning, in that
both the domain and codomain are linearly related by lines (or planes). As an example, impedance is defined in frequency as the ratio of the voltage over the current, but it frequently has a representation as the ratio of two polynomials $N(s)$ and $D(s)$

$$Z(s) = \frac{N(s)}{D(s)} = sL_o + R_o + \sum_{k=0}^{K} \frac{K_k}{s - s_k}. \quad (3.12)$$

Here $Z(s)$ is the impedance and $V$ and $I$ are the voltage and current at radian frequency $\omega$.\(^{20}\)

Such an impedance is typically specified as a rational or bilinear function, namely the ratio of two polynomials, $P_N(s) = N(s) = [a_N, a_{n-1}, \ldots, a_0]$ and $P_K(s) = D(s) = [b_K, b_{K-1}, \ldots, b_0]$ of degrees $N, K \in \mathbb{N}$, as functions of complex Laplace frequency $s = \sigma + j\omega$, having simple roots. Most impedances are rational functions since they may be written as $D(s)V = N(s)I$. Since $D(s)$ and $N(s)$ are both polynomials in $s$, rational functions are also called bilinear transformation or in the mathematical literature M"{o}bius transformation, which comes from a corresponding scalar differential equation, of the form

$$\sum_{k=0}^{K} b_k \frac{d^k}{dt^k} i(t) = \sum_{n=0}^{N} a_n \frac{d^n}{dt^n} v(t) \leftrightarrow I(\omega) \sum_{k=0}^{K} b_k s^k = V(\omega) \sum_{n=0}^{N} a_n s^n. \quad (3.13)$$

This construction is also known as the ABCD method in the engineering literature (Eq. 3.36, p. 119). This equation, as well as 3.12, follows from the Laplace transform (see Section 3.7, p. 130) of the differential equation (on left), by forming the impedance $Z(s) = V/I = A(s)/B(s)$. This form of the differential equation follows from Kirchhoff’s voltage and current laws (KCL, KVL) or from Newton’s laws (for the case of mechanics).

The physical properties of an impedance: Based on d’Alembert’s observation that the solution to the wave equation is the sum of forward and backward traveling waves, the impedance may be rewritten in terms of forward and backward traveling waves (see p. 202)

$$Z(s) = \frac{V}{I} = \frac{V^+ + V^-}{I^+ - I^-} = r_o \frac{1 + \Gamma(s)}{1 - \Gamma(s)}, \quad (3.14)$$

where $r_o = P^+/I^+$ is called the surge impedance of the transmission line (e.g., wire) connected to the load impedance $Z(s)$, and $\Gamma(s) = P^-/P^+ = I^-/I^+$ is the reflection coefficient corresponding to $Z(s)$. Any impedance of this type is called a Brune impedance due to its special properties (discussed on p. ??) (Brune, 1931a). Like $Z(s)$, $\Gamma(s)$ is causal and complex analytic. Note that the impedance and the reflectance function must both be complex analytic, since they are connected by the bilinear transformation, which assures the mutual complex analytic properties.

Due to the bilinear transformation, the physical properties of $Z(s)$ and $\Gamma(s)$ are very different. Specifically, the real part of the load impedance must be non-negative ($\Re\{Z(\omega j)\} \geq 0$, if and only if $|\Gamma(s)| \leq 1$). In the time domain, the impedance $z(t) \leftrightarrow Z(s)$ must have a value of $r_o$ at $t = 0$. Correspondingly, the time domain reflectance $\gamma(t) \leftrightarrow \Gamma(s)$ must be zero at $t = 0$.

This is the basis of conservation of energy, which may be traced back to the properties of the reflectance $\Gamma(s)$.

Exercise: Show that if $\Re\{Z(s)\} \geq 0$ then $|\Gamma(s)| \leq 1$. Solution: Taking the real part of Eq. 3.14, which must be $\geq 0$, we find

$$\Re\{Z(s)\} = \frac{r_o}{2} \left[ \frac{1 + \Gamma(s)}{1 - \Gamma(s)} + \frac{1 + \Gamma^*(s)}{1 - \Gamma^*(s)} \right] = r_o \frac{1 - |\Gamma(s)|^2}{|1 + \Gamma(s)|^2} \geq 0.$$ 

Thus $|\Gamma| \leq 1$.\(^{20}\)

\(^{20}\)Note that the relationship between the impedance and the residues $K_k$ is a linear one, best solved by setting up a linear system of equations in the unknown residues. Methods for doing this will be discussed in Appendix B (p. 252).
Nonlinear (quadratic) to linear equations

In the following problems we deal with algebraic equations in more than one variable, that are not linear equations. For example, the circle \( x^2 + y^2 = 1 \) is just such an equation. It may be solved for \( y(x) = \pm \sqrt{1-x^2} \).

If we let \( z = x + yj = x + j\sqrt{1-x^2} = e^{j\theta} \), we obtain the equation for half a circle \((y > 0)\). The entire circle is described by the magnitude of \( z \), as \(|z|^2 = (x+yj)(x-yj) = 1\).

- Given the curve defined by the equation:
  \[ x^2 + xy + y^2 = 1 \]  
  (3.15)

  1. Find the function \( y(x) \).

  2. Using Matlab/Octave, plot \( y(x) \), and describe the graph.

  3. What is the name of this curve?

- Find the solution (in \( x \), \( p \), and \( q \)) to the following equations:
  \[
  \begin{align*}
  x + y &= p \\
  xy &= q 
  \end{align*}
  \]

- Find an equation that is linear in \( y \) starting from equations that are quadratic (2\(^{nd}\) degree) in the two unknowns \( x, y \):
  \[
  \begin{align*}
  x^2 + xy + y^2 &= 1 \\
  4x^2 + 3xy + 2y^2 &= 3 
  \end{align*}
  \]  
  (3.16)  
  (3.17)

Gaussian elimination

1. Find the inverse of \( A \):
   \[
   A = \begin{bmatrix} 1 & 2 \\ 4 & 3 \end{bmatrix}.
   \]

2. Verify that \( A^{-1}A = AA^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \).

3. Find the solution to the following 3x3 matrix equation \( Ax = b \) by Gaussian elimination. Show your intermediate steps. You can check your work at each step using Matlab.
   \[
   \begin{bmatrix} 1 & 1 & -1 \\ 3 & 1 & 1 \\ 1 & -1 & 4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 9 \\ 8 \end{bmatrix}.
   \]
(a) Show (i.e., verify) that the first GE matrix $G_1$, which zeros out all entries in the first column, is given by

\[
G_1 = \begin{bmatrix}
1 & 0 & 0 \\
-3 & 1 & 0 \\
-1 & 0 & 1 \\
\end{bmatrix}
\]

Identify the elementary row operations that this matrix performs.

(b) Find a second GE matrix, $G_2$, to put $G_1 A$ in upper triangular form. Identify the elementary row operations that this matrix performs.

(c) Find a third GE matrix, $G_3$, which scales each row so that its leading term is 1. Identify the elementary row operations that this matrix performs.

(d) Finally, find the last GE matrix, $G_4$, that subtracts a scaled version of row 3 from row 2, and scaled versions of rows 2 and 3 from row 1, such that you are left with the identity matrix $(G_4 G_3 G_2 G_1 A = I)$.

(e) Solve for $[x_1, x_2, x_3]^T$ using the augmented matrix format $G_4 G_3 G_2 G_1 [A | b]$ (where $[A | b]$ is the augmented matrix). Note that if you’ve performed the preceding steps correctly, $x = G_4 G_3 G_2 G_1 b$.

**Permutations and Pivots**

(a) Find the pivot matrix $G$ that rescales the third row of the augmented matrix $A | b$ by 1/3.

**Two linear equations**

In this exercise we transition from a general pair of equations

\[
\begin{align*}
 f(x, y) &= 0 \\
 g(x, y) &= 0
\end{align*}
\]

to the important case of two linear equations

\[
\begin{align*}
 y &= ax + b \\
 y &= \alpha x + \beta
\end{align*}
\]

Note that, to help keep track of the variables, Roman coefficients $(a, b)$ are used for the first equation and Greek $(\alpha, \beta)$ for the second.

- What does it mean, graphically, if these two linear equations have
  - a unique solution,
  - a non-unique solution, or
  - no solution?

- Assuming the two equations have a unique solution, find the solution for $x$ and $y$.
- When will this solution fail to exist (for what conditions on $a, b, \alpha,$ and $\beta$)?
- Write the equations as a 2x2 matrix equation of the form $A x = b$, where $x = [x, y]^T$.
- Finding the inverse of the 2x2 matrix, and solve the matrix equation for $x$ and $y$.
- Discuss the properties of the determinant of the matrix $(\Delta)$ in terms of the slopes of the two equations $(a$ and $\alpha)$.
• An application of linear functional relationships between two variables:

2x2 matrices are used to describe 2-port networks, as will be discussed in Lec 16. Transmission lines are a great example, where both voltage and current must be tracked as they travel along the line. Figure 3.5 shows an example segment of a transmission line.

\[ L = \frac{\rho}{A(x)} \]

\[ V_2 - V_1 + I_2 - I_1 = 0 \]

\[ C = \frac{\mu}{\varepsilon(x)} \]

Figure 3.5: This figure shows a cell from an LC transmission line. The index 1 is at the input on the left and 2 represents the output, on the right.

Suppose you are given the following pair of linear relationships between the input (source) variables \( V_1 \) and \( I_1 \), and the output (load) variables \( V_2 \) and \( I_2 \) of the transmission line.

\[
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix}
= 
\begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix}
\begin{bmatrix}
V_2 \\
I_2
\end{bmatrix}.
\]

– Let the output (the load) be \( V_2 = 1 \) and \( I_2 = 2 \) (i.e., \( V_2/I_2 = 1/2 \) [\( \Omega \)]). Find the input voltage and current, \( V_1 \) and \( I_1 \).

– Let the input (source) be \( V_1 = 1 \) and \( I_1 = 2 \). Find the output voltage and current \( V_2 \) and \( I_2 \).

Linear equations with three unknowns

This problem is similar to the previous problem, except we consider 3 dimensions. Consider two linear equations in unknowns \( x, y, z \), representing planes:

\[ a_1 x + b_1 y + z = c_1 \]  
\[ a_2 x + b_2 y + z = c_2 \]

• In terms of the geometry (i.e., think graphically), under what conditions do these two linear equations have (a) a unique solution, (b) a non-unique solution, or (c) no solution?

• Given 2 equations in 3 unknowns, the closest we can come to a ‘unique’ solution is an equation in \( (x, y) \), \( (y, z) \), or \( (x, z) \). Find a solution in terms of \( x \) and \( y \) by substituting one equation into the other.

• Now consider the intersection of the planes at some arbitrary constant height, \( z = z_0 \). Write the modified plane equations as a 2x2 matrix equation in the form \( A x = b \) where \( x = [x, y]^T \), and find the unique solution in \( x \) and \( y \) using matrix operations.

• When will this solution fail to exist (for what conditions on \( a_1, a_2, b_1, b_2 \), etc.)?

• Now, write the system of equations as a 3x3 matrix equation in \( x, y, z \) given the additional equation \( z = z_0 \) (e.g. put it in the form \( A x = b \) where \( x = [x, y, z]^T \)).

• The determinant of a 3x3 matrix is given by

\[
\begin{vmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{vmatrix} = a_{11} \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix}
\]
For the 3x3 matrix equation you wrote in the previous part, find the determinant. How is the determinant related to the 2x2 case? Why?

- Put the following systems of equations in matrix form, and use Matlab to find (i) the determinant of the matrix, (ii) the matrix inverse, and (iii) the solution \((x, y, z)\). If it is not possible to complete (i-iii), state why.

1. 
   \[
   \begin{align*}
   x + 3y + 2z &= 1 \\
   x + 4y + z &= 1 \\
   x + y &= 1 
   \end{align*}
   \]

2. 
   \[
   \begin{align*}
   x + 3y + 2z &= 1 \\
   2x + 6y + 4z &= 1 \\
   x + y &= 1 
   \end{align*}
   \]

### Integer equations: applications and solutions

Any equation for which we seek only integer solutions is called a Diophantine equation.

**A practical example of using a Diophantine equation:** “A merchant had a 40-pound weight that broke into 4 pieces. When the pieces were weighed, it was found that each piece was a whole number of pounds and that the four pieces could be used to weigh every integral weight between 1 and 40 pounds. What were the weights of the pieces?” - Bachet de Bèziriac (1623 CE)

Here, weighing is performed using a balance scale having two pans, with weights being put on either pan. Thus, given weights of 1 and 3 pounds, one can weigh a 2-pound weight by putting the 1-pound weight in the same pan with the 2-pound weight, and the 3-pound weight in the other pan. Then, the scale will be balanced. A solution to the four weights for Bachet’s problem is \(1 + 3 + 9 + 27 = 40\) pounds.

![Diagram of weighing](image)

**Problem:** Show how the combination of 1, 3, 9, & 27 pound weights may be used to weigh 1, 2, 3, ..., 8, 28, and 40 pounds of milk (or something else, such as flour). Assuming that the milk is in the left pan, provide the position of the weights using a negative sign ‘-‘ to indicate the left pan and a positive sign ‘+‘ to indicate the right pan. For example, if the left pan has 1 pound of milk, then 1 pound of milk in the right pan, ‘+1’ will balance the scales.

**Hint:** It is helpful to write the answer in matrix form. Set the vector of values to be weighed equal to a matrix indicating the pan assignments, multiplied by a vector of the weights \([1, 3, 9, 27]^T\). The pan assignments matrix should only contain the values -1 (left pan), +1 (right pan), and 0 (leave out). You can indicate these using ‘-‘, ‘+‘, and blank spaces.

---

22Taken from: Joseph Rotman, “A first course in abstract algebra,” *Chapter 1, Number Theory* p.50
CHAPTER 3. STREAM 2: ALGEBRAIC EQUATIONS (12 LECTURES)

Ohm’s Law

In general, impedance is defined as the ratio of a force over a flow. For electrical circuits, the voltage is the ‘force’ and the current is the ‘flow.’ Ohm’s law states that the voltage across and the current through a circuit element are related by the impedance of that element (which may be a function of frequency).

For resistors, the voltage over the current is called the resistance, and is a constant (e.g. the simplest case, \(V/I = R\)). For inductors and capacitors, the voltage over the current is a frequency-dependent impedance (e.g. \(V/I = Z(s)\), where \(s\) is the complex frequency \(s \in \mathbb{C}\)).

The impedance concept also holds in mechanics and acoustics. In mechanics, the ‘force’ is equal to the mechanical force on an element (e.g. a mass, dashpot, or spring), and the ‘flow’ is the velocity.

In acoustics, the ‘force’ is pressure, and the ‘flow’ is the volume velocity or particle velocity of air molecules.

<table>
<thead>
<tr>
<th>Case</th>
<th>Force</th>
<th>Flow</th>
<th>Impedance</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>voltage (V)</td>
<td>current (I)</td>
<td>(Z)</td>
<td>Ohms [(\Omega)]</td>
</tr>
<tr>
<td>Mechanics</td>
<td>force (F)</td>
<td>velocity (V)</td>
<td>(Z)</td>
<td>Mechanical Ohms [(\Omega)]</td>
</tr>
<tr>
<td>Acoustics</td>
<td>pressure (P)</td>
<td>particle velocity (U)</td>
<td>(Z)</td>
<td>Acoustic Ohms [(\Omega)]</td>
</tr>
<tr>
<td>Thermal</td>
<td>temperature (T)</td>
<td>heat-flux (J)</td>
<td>(Z)</td>
<td>Thermal Ohms [(\Omega)]</td>
</tr>
</tbody>
</table>

1. The resistance of an incandescent (filament) lightbulb, measured cold, is about 100 ohms. As it lights up, the resistance of the metal filament increases. Ohm’s law says that the current

\[
\frac{V}{T} = R(T).
\]

where \(T\) is the temperature. In the United States, the voltage is 120 volts (RMS) at 60 [Hz]. Find the current when the light is first switched on.

2. The power, in Watts [W], is the product of the force and the flow. What is the power of the light bulb of this example?

3. State the impedance \(Z(s)\) of each of the following circuit elements:
   - A resistor with resistance \(R\)
   - An inductor with inductance \(L\)
   - A capacitor with capacitance \(C\)

2-port network analysis

Perform a simple analysis of electrical 2-port networks, shown in Fig. ???. This can be a mechanical system if the capacitors are taken to be springs, and inductors taken as mass, as in the suspension of the wheels of a car. In an acoustical circuit, the low-pass filter could be a car muffler. While the physical representations will be different, the equations and the analysis are exactly the same.

![Figure 3.1: Left: A low-pass RC electrical filter. The circuit elements \(R_1, R_2,\) and \(C\) are defined in the problems below. Right: A band-pass acoustic filter. Here, the pressure \(P\) is analogous to voltage, and the velocity \(U\) is analogous to current. The circuit elements are labeled with their \(L\) and \(C\) values as integers, to make the algebra simple.](image-url)
The definition of the ABCD transmission matrix \((T)\) is
\[
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_2 \\
-I_2
\end{bmatrix}.
\] (3.20)

The impedance matrix, where the determinant \(\Delta_T = AD - BC\), is given by
\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = \frac{1}{C}
\begin{bmatrix}
A & \Delta_T \\
1 & D
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}.
\] (3.21)

1. Derive the formula for the impedance matrix (Eq. 4.51) given the transmission matrix definition (Eq. ??). Show your work.

2. Consider a single circuit element with impedance \(Z(s)\)
   (a) What is the ABCD matrix for this element if it is in ‘series’?
   (b) What is the ABCD matrix for this element if it is ‘shunt’?

3. Find the ABCD matrix for each of the circuits of Figure ??.
   (a) Left circuit (let \(R_1 = R_2 = 10 \text{ k}\Omega\) ‘kilo-ohms’, and \(C = 10 \text{ nF}\) ‘nano-farads’)
   (b) Right circuit (use \(L\) and \(C\) values given in the figure), where the pressure \(P\) is analogous to the voltage \(V\), and the velocity \(U\) is analogous to the current \(I\).

4. Convert both transmission (ABCD) matrices to impedance matrices using Equation 4.51. Do this for the specific frequency \(s = 1j\), as in the previous part (feel free to use Matlab for your computation).
3.4 Lec 13: Introduction to Analytic Geometry

Analytic geometry came about with the merging of Euclid’s geometry with algebra. The combination of Euclid’s (323 BCE) geometry and al-Khwarizmi’s (830 CE) algebra resulted in a totally new and powerful tool, analytic geometry, independently worked out by Descartes and Fermat (Stillwell, 2010). The addition of matrix algebra during the 18th century enabled analysis in more than three dimensions, which today is one of the most powerful tools used in artificial intelligence, data science and machine learning. The utility and importance of these new tools cannot be overstated. The timeline for this period is provided in Fig. 3.2.

<table>
<thead>
<tr>
<th>1596</th>
<th>1650</th>
<th>1700</th>
<th>1750</th>
<th>1800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descartes</td>
<td>Johann Bernoulli</td>
<td>Gauss</td>
<td>Fermat</td>
<td>Euler</td>
</tr>
<tr>
<td>Daniel Bernoulli</td>
<td>d’Alembert</td>
<td>Newton</td>
<td>Lagrange</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2: Expanded timeline of Fig. 3.1 (p. 71) covering the two centuries from 1596CE to 1855CE, covering the development of the modern theories of analytic geometry, calculus, differential equations and linear algebra. The vertical red lines indicate mentor-student relationships. Lagrange had a role in the development of linear algebra. Note the overlap between Newton and Johann and his son Daniel Bernoulli, and Euler. Gauss had the advantage of input from Newton, Euler, d’Alembert and Lagrange. Likely Cauchy had an influence on Gauss as well.

There are many important relationships between Euclidean geometry and 16th century algebra. An attempt at a detailed comparison is summarized in Table 3.1. Important similarities include vectors, their Pythagorean lengths $[a, b, c]$

$$c = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2},$$

(a, b, c)

$$a = x_2 - x_1 \quad \text{and} \quad b = y_2 - y_1,$$

and the angles. Euclid’s geometry had no concept of coordinates, thus of vectors. One of the main innovations of analytic geometry is that one may compute with real, and soon after, complex numbers.

There are several new concepts that come with the development of analytic geometry:

1. Composition of functions: If $y = f(x)$ and $z = g(y)$ then the composition of functions $f$ and $g$ is denoted $z(x) = g \circ f(x) = g(f(x))$.

2. Elimination: Given two functions $f(x,y)$ and $g(x,y)$, elimination removes either $x$ or $y$. This procedure, known to the Chinese, is called Gaussian elimination.

3. Intersection: While one may speak of the intersection of two lines to give a point, or two planes to give a line, the term intersection is also an important but very different concept in set theory. This is a special case of elimination when the functions $f(x,y), g(x,y)$ are linear in their arguments.

4. Vectors: Analytic geometry provides the concept of a vector (see Appendix A), as a line with length and orientation (i.e., direction). Analytic geometry defines vectors in any number of dimensions, as ordered sets of points.

5. Analytic geometry extends the ideas of Euclidean geometry with the introduction of the scalar (dot) product of two vectors $\mathbf{f} \cdot \mathbf{g}$, and the vector (cross) product $\mathbf{f} \times \mathbf{g}$ (see Fig. 3.3, p. 112).

6. All of these exist independently of any coordinate system, thus are more general than analytic geometry.
Table 3.1: An ad-hoc comparison between Euclidean geometry and analytic geometry. I am uncertain as to the classification of the items in the third column.

<table>
<thead>
<tr>
<th>Euclidean geometry: $\mathbb{R}^3$</th>
<th>Analytic geometry: $\mathbb{R}^n$</th>
<th>Uncertain</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Proof</td>
<td>(a) Numbers</td>
<td>(a) Cross product ($\mathbb{R}^3$)</td>
</tr>
<tr>
<td>(b) Line length</td>
<td>(b) Algebra</td>
<td>(b) Recursion</td>
</tr>
<tr>
<td>(c) Line intersection</td>
<td>(c) Power series</td>
<td>(c) Iteration $\in \mathbb{C}^2$ (e.g., Newton’s method)</td>
</tr>
<tr>
<td>(d) Point</td>
<td>(d) Analytic functions</td>
<td>(d) Iteration $\in \mathbb{R}^n$</td>
</tr>
<tr>
<td>(e) Projection (e.g., scalar product)</td>
<td>(e) Complex analytic functions: e.g., $\sin \theta, \cos \theta, e^{i\theta}, \log z$</td>
<td></td>
</tr>
<tr>
<td>(f) Line direction</td>
<td>(f) Composition</td>
<td></td>
</tr>
<tr>
<td>(g) Vector (sort of)</td>
<td>(g) Elimination</td>
<td></td>
</tr>
<tr>
<td>(h) Conic section</td>
<td>(h) Integration</td>
<td></td>
</tr>
<tr>
<td>(i) Square roots (e.g., spiral of Theodorus)</td>
<td>(i) Derivatives</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(j) Calculus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(k) Polynomial $\in \mathbb{C}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(l) Fund. thm. algebra</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(m) Normed vector spaces</td>
<td></td>
</tr>
</tbody>
</table>

What algebra also added to geometry was the ability to compute with complex numbers. For example, the length of a line (Eq. 3.22) was measured in Geometry with a compass: numbers played no role. Once algebra was available, the line’s Euclidean length could be computed numerically, directly from the coordinates of the two ends, defined by the 3-vector

$$e = x\hat{x} + y\hat{y} + z\hat{z} = [x, y, z]^T,$$

which represents a point at $(x, y, z) \in \mathbb{R}^3 \subset \mathbb{C}^3$ in three dimensions, having direction, from the origin $(0, 0, 0)$ to $(x, y, z)$. An alternative matrix notation is $e = [x, y, z]^T$, a column vector of three numbers. These two notations are different ways of representing exactly the same thing.

By defining the vector, analytic geometry allows Euclidean geometry to become quantitative, beyond the physical drawing of an object (e.g., a sphere, triangle or line). With analytic geometry we have the Euclidean concept of a vector, a line having a magnitude (length) and direction, but analytic defined in terms of physical coordinates (i.e., numbers). The difference between two vectors defines a third vector, a concept already present in Euclidean geometry. For the first time, complex numbers were allowed into geometry (but rarely used until Cauchy and Riemann).

As shown in Fig. 3.3, there are two types of products: the 1) scalar $A \cdot B$ and 2) vector $A \times B$ products.

**Scalar product of two vectors:** When using algebra, many concepts, obvious with Euclid’s geometry, may be made precise. There are many examples of how algebra extends Euclidean geometry, the most basic being the *scalar product* (aka dot product) between vectors $x, \kappa \in \mathbb{C}^3$

$$x \cdot \kappa = (x\hat{x} + y\hat{y} + z\hat{z}) \cdot (\alpha\hat{x} + \beta\hat{y} + \gamma\hat{z}), \quad \in \mathbb{C}$$

$$= \alpha x + \beta y + \gamma z.$$
Figure 3.3: Vectors $A, B, C$ are used to define the scalar product $A \cdot B$, vector (cross) product $A \times B$ and triple product $C \cdot (A \times B)$. The two vector products complement each other, one proportional to the $\sin \theta$ of the angle $\theta$ between them and the other to the $\cos \theta$. It follows that $||A|| ||B||^2 + ||A \times B||^2 = ||A||^2 ||B||^2$. The scalar product computes the projection of one vector on the other. The vector product $A \times B$ computes the area of the trapezoid formed by the two vectors, while the triple product $C \cdot (A \times B)$ defines the volume of the formed parallelepiped (i.e., prism). When all the angles are $90^\circ$, the volume becomes a cuboid. Discuss $A_\parallel$ and $A_\perp$.

In matrix notation the scalar product is written as

$$x \cdot \kappa = \begin{bmatrix} x \\ y \\ z \end{bmatrix}^T \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} x, y, z \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \alpha x + \beta y + \gamma z. \quad (3.23)$$

The scalar product takes the character of $\kappa$. For example, if $\kappa(s) \in \mathbb{C}$ is a function of complex frequency $s$, then the scalar product is complex. If $\zeta \in \mathbb{R}$ is real, then the scalar product is real.

**Norm (length) of a vector:** The norm of a vector

$$||e|| \equiv +\sqrt{e \cdot e} \geq 0$$

is defined as the positive square root of the scalar product of the vector with itself. This is a generalization of the length, in any number of dimensions, forcing the sign of the square-root to be non-negative. The length is a concept of Euclidean geometry, and it must always be positive and real. A complex (or negative) length is not physically meaningful. More generally, the Euclidean length of a line is given as the norm of the difference between two real vectors $e_1, e_2 \in \mathbb{R}$

$$||e_1 - e_2||^2 = (e_1 - e_2) \cdot (e_1 - e_2) = (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2 \geq 0.$$

From this formula we see that the norm of the difference of two vectors is simply a compact expression for the Euclidean length. A zero-length vector, such as is a point, is the result of the fact that

$$||x - x||^2 = (x - x) \cdot (x - x),$$

is zero.

**Integral definition of a scalar product:** Up to this point, following Euclid, we have only considered a vector to be a set of elements $\{x_n\} \in \mathbb{R}$, index over $n \in \mathbb{N}$, as defining a linear vector space with scalar product $x \cdot y$, with the scalar product defining the norm or length of the vector $||x|| = \sqrt{x \cdot x}$. Given the scalar product, the norm naturally follows.
At this point an obvious question presents itself: Can we extend our definition of vectors to differentiable functions (i.e., \( f(t) \) and \( g(t) \)), indexed over \( t \in \mathbb{R} \), with coefficients labeled by \( t \in \mathbb{R} \) rather than by \( n \in \mathbb{N} \)? Clearly, if the functions are analytic, there is no obvious reason why this should be a problem, since analytic functions may be represented by a convergent series having Taylor coefficients, thus integrable term by term.

Specifically, under certain conditions, the function \( f(t) \) may be thought of as a vector, defining a normed vector space. This intuitive and somewhat obvious idea is powerful. In this case the scalar product can be defined in terms of the integral

\[
    f(t) \cdot g(t) = \int f(t)g(t)dt
\]

summed over \( t \in \mathbb{R} \), rather than a sum over \( n \in \mathbb{N} \).

This definition of the vector scalar product allows for a significant but straightforward generalization of our vector space, which will turn out to be both useful and an important extension of the concept of a normed vector space. In this space we can define the derivative of a norm with respect to \( t \), which is not possible for the case of the discrete case, indexed over \( n \). The distinction introduces the concept of continuity in the index \( t \), which does not exist for the discrete index \( n \in \mathbb{N} \).

**Pythagorean theorem and the Schwarz inequality:** Regarding Fig. 3.3, suppose we compute the difference between vector \( A \in \mathbb{R} \) and \( \alpha B \in \mathbb{R} \) as \( L = ||A - \alpha B|| \in \mathbb{R} \), where \( \alpha \in \mathbb{R} \) is a scalar that modifies the length of \( B \). We seek the value of \( \alpha \), which we denote as \( \alpha^* \), that minimizes the length of \( L \). From simple geometrical considerations, \( L(\alpha) \) will be minimum when the difference vector is perpendicular to \( B \), as shown in the figure by the dashed line from the tip of \( A \perp B \).

To show this algebraically we write out the expression for \( L(\alpha) \) and take the derivative with respect to \( \alpha \), and set it to zero, which gives the formula for \( \alpha^* \). The argument does not change, but the algebra greatly simplifies, if we normalize \( A, B \) to be unit vectors \( a = A/||A|| \) and \( b = B/||B|| \), which have norm \( = 1 \).

\[
    L^2 = (a - \alpha b) \cdot (a - \alpha b) = 1 - 2\alpha a \cdot b + \alpha^2. \tag{3.25}
\]

Thus the length is shortest \( (L = L_\alpha \), as shown in Fig. 3.3) when

\[
    \frac{d}{d\alpha} L_\alpha^2 = -2a \cdot b + 2\alpha^* = 0.
\]

Solving for \( \alpha^* \) we find \( \alpha^* = a \cdot b \). Since \( L_\alpha > 0 (a \neq b) \), Eq. 3.25 becomes

\[
    1 - 2|a \cdot b|^2 + |a \cdot b|^2 = 1 - |a \cdot b|^2 > 0.
\]

In conclusion \( \cos \theta = |a \cdot b| < 1 \). In terms of \( A, B \) this is \( |A \cdot B| < ||A|| ||B|| \cos \theta \), as shown next to \( B \) in Fig. 3.3. Thus the scalar product between two vectors is their direction cosine. Furthermore, since this forms a right triangle, the Pythagorean theorem must hold. The triangle inequality says that the lengths of the two sides must be greater than the hypotenuse. Note that \( \Theta \in \mathbb{R} \notin \mathbb{C} \).

This derivation is an abbreviated version of a related discussion in Section ?? (p. 117).

**Vector cross (\( \times \)) and wedge (\( \wedge \)) product of two vectors:** The vector product (aka, cross-product) \( A \times B \) and exterior product (aka, wedge-product) \( A \wedge B \) are the second and third types of vector products. As shown in Fig. 3.3,

\[
    C = A \times B = (a_1\hat{x} + a_2\hat{y} + a_3\hat{z}) \times (b_1\hat{x} + b_2\hat{y} + b_3\hat{z}) = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix}
\]

is \( \perp \) to the plane defined by \( A \) and \( B \). The cross product is severely limited to two input vectors \( A \) and \( B \in \mathbb{R}^2 \), taken from three real dimensions (i.e., \( \mathbb{R}^3 \)).
The exterior wedge product generalizes the cross product, since it may be defined in terms of \( \mathbf{A}, \mathbf{B} \in \mathbb{C}^2 \), taken from \( n \) dimensions (\( \mathbb{C}^n \)), with output in \( \mathbb{C} \). Its output is a complex scalar with

\[
\mathbf{A} \wedge \mathbf{B} = -\mathbf{B} \wedge \mathbf{A} = e^{i\theta}
\]

The difference between the two is that the cross product is a vector (typically in \( \mathbb{R} \)) while the wedge product is a signed complex scalar \( \in \mathbb{C} \).

**Example:** If we define \( \mathbf{A} = 3j\hat{x} - 2\hat{y} + 0\hat{z} \) and \( \mathbf{B} = 1\hat{x} + 1\hat{y} + 0\hat{z} \) then the cross product is

1. \[
\mathbf{A} \times \mathbf{B} = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ 3j & -2 & 0 \\ 1 & 1 & 0 \end{vmatrix} = (3j + 2)\hat{z}.
\]

Since \( a_1 \in \mathbb{C} \), this example violates the common assumption that \( \mathbf{A} \in \mathbb{R}^3 \).

2. The wedge product \( \mathbf{A} \wedge \mathbf{B} \) is defined by

\[
\mathbf{A} \wedge \mathbf{B} = \begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = \begin{vmatrix} 3j & 1 \\ -2 & 1 \end{vmatrix} = (3j\hat{x} - 2\hat{y}) \wedge (\hat{x} + \hat{y}) = 3 \cdot 0 \mathbf{x} \wedge \mathbf{x}^0 = 2\hat{y} \wedge \hat{x} + 3j\hat{x} \wedge \hat{y} - 2\hat{y} \wedge \hat{y} = (3j + 2)\hat{x} \wedge \hat{y}
\]

From the above example we see that the absolute value of the wedge product \( |a \wedge b| = ||a \times b|| \), namely

\[
|(a_2\hat{y} + a_3\hat{z}) \wedge (b_2\hat{y} + b_3\hat{z})| = ||(a \times b)||
\]

The wedge product is especially useful because it is zero when the two vectors are co-linear, namely \( \hat{x} \wedge \hat{x} = 0 \) and \( \hat{x} \wedge \hat{y} = 1 \). The advantage of the “wedge” product is that it is valid in \( n > 3 \) dimensions since it is defined for any two vectors, in any number of dimensions. Like the cross product, the magnitude of the wedge product is equal to the area of the trapezoid formed by the two vectors.

**Scalar triple product:** The triple of a third vector \( \mathbf{C} \) with the vector product \( \mathbf{A} \times \mathbf{B} \in \mathbb{R} \) is

\[
\mathbf{C} \cdot (\mathbf{A} \times \mathbf{B}) = \begin{vmatrix} c_1 & c_2 & c_3 \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix} \in \mathbb{R}^3,
\]

which equals the volume of a parallelepiped.

**Impact of Analytic Geometry:** The most obvious impact of analytic geometry was its detailed analysis of the conic sections, using algebra rather than drawings via a compass and ruler. An important example is the composition of the line and circle, a venerable construction, presumably going back to before Diophantus (250CE). Once algebra was invented, the composition could be done using formulas. With this analysis came complex numbers.

The first two mathematicians to appreciate this mixture of Euclid’s geometry and the new algebra were Fermat and Descartes (Stillwell, 2010, p. 111-115); soon Newton contributed to this effort by the addition of physics (e.g., calculations in acoustics, orbits of the planets, and the theory of gravity and light, significant concepts for 1687 (Stillwell, 2010, p. 115-117)).

Given these new methods, many new solutions to problems emerged. The complex roots of polynomials continued to appear, without any obvious physical meaning. Complex numbers seem to have been viewed as more of an inconvenience than a problem. Newton’s solution to this dilemma was to simply ignore the imaginary cases (Stillwell, 2010, p. 119).
3.4.1 Development of Analytic Geometry

Intersection and Gaussian elimination: The first “algebra” (al-jabr) is credited to al-Khwarizmi (830 CE). Its invention advanced the theory of polynomial equations in one variable, Taylor series, and composition versus intersections of curves. The solution of the quadratic equation had been worked out thousands of years earlier, but with algebra a general solution could be defined. The Chinese had found the way to solve several equations in several unknowns, for example, finding the values of the intersection of two circles. With the invention of algebra by al-Khwarizmi, a powerful tool became available to solve the difficult problems.

Composition and Elimination: In algebra there are two contrasting operations on functions: composition and elimination.

Composition: Composition is the merging of functions, by feeding one into the other. If the two functions are \( f, g \) then their composition is indicated by \( f \circ g \), meaning the function \( y = f(x) \) is substituted into the function \( z = g(y) \), giving \( z = g(f(x)) \).

Composition is not limited to linear equations, even though that is where it is most frequently applied. To compose two functions, one must substitute one equation into the other. That requires solving for that substitution variable, which is not always possible in the case of nonlinear equations. However, many tricks are available that may work around this restriction. For example, if one equation is in \( x^2 \) and the other in \( x^3 \) or \( \sqrt{x} \), it may be possible to multiply the first by \( x \) or square the second. The point is that one of the variables must be isolated so that when it is substituted into the other equations, the variable is removed from the mix.

Examples: Let \( y = f(x) = x^2 - 2 \) and \( z = g(y) = y + 1 \). Then

\[
g \circ f = g(f(x)) = (x^2 - 2) + 1 = x^2 - 1.
\]

(3.26)

In general composition does not commute (i.e., \( f \circ g \neq g \circ f \)), as is easily demonstrated. Swapping the order of composition for our example gives

\[
f \circ g = f(g(y)) = z^2 - 2 = (y + 1)^2 - 2 = y^2 + 2y - 1.
\]

(3.27)

Intersection: Complementary to composition is intersection (i.e., decomposition) (Stillwell, 2010, pp. 119,149). For example, the intersection of two lines is defined as the point where they meet. This is not to be confused with finding roots. A polynomial of degree \( N \) has \( N \) roots, but the points where two polynomials intersect has nothing to do with the roots of the polynomials. The intersection is a function (equation) of lower degree, implemented with Gaussian elimination.

Intersection of two lines: Unless they are parallel, two lines meet at a point. In terms of linear algebra this may be written as two linear equations\(^{23}\) (on the left), along with the intersection point \([x_1, x_2]^T\), given by the inverse of the 2x2 set of equations (on the right)

\[
\begin{bmatrix}
a & b \\
c & d
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix}
= \begin{bmatrix}
y_1 \\
y_2
\end{bmatrix}
\]

(3.28)

By substituting the expression for the intersection point \([x_1, x_2]^T\) into the original equation, we see that it satisfies the equations. Thus the equation on the right is the solution to the equation on the left.

---

\(^{23}\)When writing the equation \( Ax = y \) in matrix format, the two equations are \( ax_1 + bx_2 = y_1 \) and \( cx_1 + dx_2 = y_2 \) with unknowns \((x_1, x_2)\), whereas in the original equations \( ay + bx = c \) and \( dy + ex = f \), they were \( y, x \). Thus in matrix format, the names are changed. The first time you see this scrambling of variables, it can be confusing.
Note the structure of the inverse: 1) The diagonal values \((a, d)\) are swapped, 2) the off-diagonal values \((b, c)\) are negated and 3) the \(2 \times 2\) matrix is divided by the determinant \(\Delta = ad - bc\). If \(\Delta = 0\), there is no solution. When the determinant is zero \((\Delta = 0)\), the slopes of the two lines

\[
slope = \frac{dx_2}{dx_1} = \frac{b}{a} = \frac{d}{c}
\]

are equal, thus the lines are parallel. Only if the slopes differ can there be a unique solution.

**Exercise:** Show that the equation on the right is the solution of the equation on the left. **Solution:** By a direct substitution of the right equation into the left equation

\[
\begin{bmatrix} a & b \\ c & d \end{bmatrix} \cdot \frac{1}{\Delta} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} ad - bc & -ab + ab \\ cd - cd & -cb + ad \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} \Delta & 0 \\ 0 & \Delta \end{bmatrix},
\]

which gives the identity matrix.

Algebra will give the solution when geometry cannot. When the two curves fail to intersect on the real plane, the solution still exists, but is complex valued. In such cases, geometry, which only considers the real solutions, fails. For example, when the coefficients \([a, b, c, d]\) are complex, the solution exists, but the determinant can be complex. Thus algebra is much more general than geometry. Geometry fails when the solution has a complex intersection.

A system of linear \(Ax = y\) equations has many interpretations, and one should not be biased by the notation. As engineers we are trained to view \(x\) as the input and \(y\) as the output, in which case then \(y = Ax\) seems natural, much like the functional relation \(y = f(x)\). But what does the linear relation \(x = Ay\) mean, when \(x\) is the input? The obvious answer is that \(y = A^{-1}x\). But when working with systems of equations, there are many uses of equations, and we need to become more flexible in our interpretation. For example \(y = A^2x\) has a useful meaning, and in fact we saw this type of relationship when working with Pell’s equation (p. 61) and the Fibonacci sequence (p. 63). As another example consider

\[
\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} a_{1x} & a_{1y} \\ a_{2x} & a_{2y} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix},
\]

which is reminiscent of a three-dimensional surface \(z = f(x, y)\). We shall find that such generalizations are much more than a curiosity.

**3.4.2 Lec 14: Applications of scalar products**

Another important example of algebraic expressions in mathematics is Hilbert’s generalization of Eq. 1.1, known as the Schwarz inequality, shown in Fig. 3.4. What is special about this generalization is that it proves that when the vertex is 90\(^\circ\), the length of the leg is minimum.

Vectors may be generalized to have \(\infty\) dimensions: \(\mathbf{U}, \mathbf{V} = [v_1, v_2, \cdots, v_\infty]\). The Euclidean inner product (i.e., scalar product) between two such vectors generalizes the finite dimensional case

\[
\mathbf{U} \cdot \mathbf{V} = \sum_{k=1}^{\infty} u_k v_k.
\]

As with the finite case, the norm \(||\mathbf{U}|| = \sqrt{\mathbf{U} \cdot \mathbf{U}} = \sqrt{\sum u_k^2}\) is the scalar product of the vector with itself, defining the length of the infinite component vector. Obviously there is an issue of convergence, if the norm for the vector is to have a finite length.

It is a somewhat arbitrary requirement that \(a, b, c \in \mathbb{R}\) for the Pythagorean theorem (Eq. 1.1). This seems natural enough since the sides are lengths. But, what if they are taken from the complex numbers, as for the lossy vector wave equation, or the lengths of vectors in \(\mathbb{C}^n\)? Then the equation generalizes to

\[
\mathbf{c} \cdot \mathbf{c} = ||\mathbf{c}||^2 = \sum_{k=1}^{n} |c_k|^2,
\]
where \( \|c\|^2 = (c, c) \) is the inner (dot) product of a vector \( c \) with itself, where \( |c_k| \) is the magnitude the complex \( c_k \). As before, \( \|c\| = \sqrt{(c, c)} \) is the norm of vector \( c \), akin to a length.

![Figure 3.4](image)

**Figure 3.4:** The Schwarz inequality is related to the shortest distance (length of a line) between the ends of the two vectors. \( \|U\| = \sqrt{U \cdot U} \) as the scalar product of that vector with itself.

**Schwarz Inequality** The **Schwarz inequality**\(^{24}\) says that the magnitude of the inner product of two vectors is less than or equal to the product of their lengths

\[
|U \cdot V| \leq \|U\| \|V\|.
\]

This may be simplified by normalizing the vectors to have unit length \((\hat{U} = U/\|U\|, \hat{V} = V/\|V\|)\), in which case \(-1 < \hat{U} \cdot \hat{V} \leq 1\). Another simplification is to define the scalar product in terms of the direction cosine

\[
\cos \theta = |\hat{U} \cdot \hat{V}| \leq 1.
\]

A proof of the Schwarz inequality is as follows: From these definitions we may define the minimum difference between the two vectors as the perpendicular from the end of the first to the intersection with the second. As shown in Fig. 3.4, \( U \perp V \) may be found by minimizing the length of the vector difference:

\[
\min_{\alpha} \|V - \alpha U\|^2 = \|V\|^2 + 2\alpha V \cdot U + \alpha^2 \|U\|^2 > 0
\]

\[
0 = \partial_{\alpha} (V - \alpha U) \cdot (V - \alpha U)
\]

\[
= V \cdot U - \alpha^2 \|U\|^2
\]

\[
\therefore \quad \alpha^* = V \cdot U/\|U\|^2.
\]

The **Schwarz inequality** follows:

\[
I_{\text{min}} = \|V - \alpha^* U\|^2 = \|V\|^2 - \frac{|U \cdot V|^2}{\|U\|^2} > 0
\]

\[
0 \leq |U \cdot V| \leq \|U\| \|V\|.
\]

An important example of such a vector space includes the definition of the **Fourier transform**, where we may set

\[
U(\omega) = e^{-j\omega_0 t} \quad V(\omega) = e^{j\omega t} \quad U \cdot V = \int_{-\infty}^{\infty} e^{j\omega t} e^{-j\omega_0 t} \frac{d\omega}{2\pi} = \delta(\omega - \omega_0).
\]

It seems that the Fourier transform is a result that follows from a minimization, unlike the Laplace transform that follows from causal system parameters. This explains the important differences between the two, in terms of their properties (unlike the LT, the FT is not complex analytic). We further explore this topic in Lecture 3.6 (p. 125).

---

\(^{24}\) A simplified derivation is provided in Sect. 3.4 (p. 110).
Lec 15: Gaussian Elimination

The method for finding the intersection of equations is based on the recursive elimination of all the variables but one. This method, known as Gaussian elimination (Appendix C, p. 253), works across a broad range of cases, but may be defined as a systematic algorithm when the equations are linear in the variables. Rarely do we even attempt to solve problems in several variables of degree greater than 1. But Gaussian eliminations may still work in such cases (Stillwell, 2010, p. 90).

In Appendix C.2.1 (p. 259) the inverse of a 2x2 linear system of equations is derived. Even for a 2x2 case, the general solution requires a great deal of algebra. Working out a numeric example of Gaussian elimination is more instructive. For example, suppose we wish to find the intersection of the two equations

\[ \begin{align*}
    x - y &= 3 \\
    2x + y &= 2.
\end{align*} \]

This 2x2 system of equations is so simple that you may immediately visualize the solution: By adding the two equations, \( y \) is eliminated, leaving \( 3x = 5 \). But doing it this way takes advantage of the specific example, and we need a method for larger systems of equations. We need a generalized (algorithmic) approach. This general approach is called Gaussian elimination.

Start by writing the equations in matrix form (note this is not of the form \( Ax = y \))

\[
\begin{bmatrix}
1 & \ -1 \\
2 & \ 1
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix} =
\begin{bmatrix}
3 \\
2
\end{bmatrix}.
\] (3.29)

Next, eliminate the lower left term (\( 2x \)) using a scaled version of the upper left term (\( x \)). Specifically, multiply the first equation by \(-2\), add it to the second equation, replacing the second equation with the result. This gives

\[
\begin{bmatrix}
1 & \ -1 \\
0 & \ 3
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix} =
\begin{bmatrix}
3 \\
2 - 3 \cdot 2 = -4
\end{bmatrix}.
\] (3.30)

Note that the top equation did not change. Once the matrix is “upper triangular” (zero below the diagonal) you have the solution. Starting from the bottom equation, \( y = -4/3 \). Then the upper equation gives \( x - (-4/3) = 3 \), or \( x = 3 - 4/3 = 5/3 \).

In principle, Gaussian elimination is easy, but if you make a calculation mistake along the way, it is very difficult to find your error. The method requires a lot of mental labor, with a high probability of making a mistake. Thus you do not want to apply this method every time. For example, suppose the elements are complex numbers, or polynomials in some other variable such as frequency. Once the coefficients become more complicated, the seemingly trivial problem becomes highly error prone. There is a much better way, that is easily verified, which puts all the numerics at the end, in a single step.

The above operations may be automated by finding a carefully chosen upper-diagonalization matrix \( U \) that does the same operation. For example, let

\[
U = \begin{bmatrix} 1 & 0 \\ -2 & 1 \end{bmatrix}.
\] (3.31)

Multiplying Eq. 3.29 by \( U \), we find

\[
\begin{bmatrix}
1 & \ 0 \\
-2 & \ 1
\end{bmatrix}
\begin{bmatrix}
1 & \ -1 \\
2 & \ 1
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix} =
\begin{bmatrix}
1 & \ -1 \\
0 & \ 3
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix} =
\begin{bmatrix}
3 \\
-4
\end{bmatrix}.
\] (3.32)

thus we obtain Eq. 3.30. At this point we can either back-substitute and obtain the solution, as we did above, or find a matrix \( L \) that finishes the job, by removing elements above the diagonal.

---

Exercise: Show that $\det(U) = \det(UA) = 1$. Solution: Since

$$
\begin{align*}
\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} &= ad - bc,
\end{align*}
$$

and $\det(UA) = \det(U) \cdot \det(A)$, and $\det(U) = 1 - 0 = 1$, the result follows naturally. Common notation is to let $\det(A) = |A|$. In Appendix C.2.1 the inverse of a general 2x2 matrix is summarized in terms of three steps: 1) swap the diagonal elements, 2) reverse the signs of the off-diagonal elements and 3) divide by the determinant $\Delta = ad - bc$. Specifically

$$
\begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{\Delta} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}.
$$

(3.33)

There are very few things that you must memorize, but the inverse of a 2x2 is one of them. It needs to be in your tool-bag, like the quadratic formula.

While it is difficult to compute the inverse matrix from scratch (Appendix C), it takes only a few seconds to verify it (steps 1 and 2)

$$
\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} = \begin{bmatrix} ad - bc & -ab + ab \\ cd - cd & -bc + ad \end{bmatrix} = \begin{bmatrix} \Delta & 0 \\ 0 & \Delta \end{bmatrix}.
$$

(3.34)

Thus dividing by the determinant gives the 2x2 identity matrix. A good strategy, when you don’t trust your memory, is to write down the inverse as best you can, and then verify.

Using the 2x2 matrix inverse on our example (Eq. 3.29), we find

$$
\begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{1 + 2} \begin{bmatrix} 1 & 1 \\ -2 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 5 \\ -6 + 2 \end{bmatrix} = \begin{bmatrix} 5/3 \\ -4/3 \end{bmatrix}.
$$

(3.35)

If you use this method, you will rarely (never) make a mistake, and the solution is easily verified. Either you can check the numbers in the inverse, as was done in Eq. 3.34, or you can substitute the solution back into the original equation.

3.5 Lec 16: Transmission (ABCD) matrix composition method

Figure 3.5: A single LC cell of the LC transmission line (see Fig. I.1 (p. 280). Every cell of any transmission line may be modeled by the ABCD method, as the product of two matrices. For the example shown here, the inductance $L$ of the coil and the capacitance $C$ of capacitor are in units of [henry/m] and [farad/m], thus they depend on length $\Delta x$ [m] that the cell represents. Note the flows are always defined as into the $+$ node.

Matrix composition: Matrix multiplication represents a composition of 2x2 matrices, because the input to the second matrix is the output of the first (this follows from the definition of composition: $f(x) \circ g(x) = f(g(x))$). Thus the ABCD matrix is also known as the transmission matrix method, or occasionally the chain matrix. The general expression for an transmission matrix $T(s)$ is

$$
\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}.
$$

(3.36)
The four coefficients $A(s), B(s), C(s), D(s)$ are all complex functions of the Laplace frequency $s = \sigma + j\omega$ (p. 151). The derivation is repeated in more detail in Section ?? (p. ??).

It is a standard convention to always define the current into the node, but since the input current (on the left) is the same as the output current on the right ($I_2$), hence the negative sign on $I_2$, to meet the convention of current into every node. When transmission matrices are cascaded, all the signs then match.

We have already used 2x2 matrix composition in representing complex numbers (p. 36), and for computing the $gcd(m, n)$ of $m, n \in \mathbb{N}$ (p. 52), Pell’s equation (p. 61) and the Fibonacci sequence (p. 63).

**Definitions of $A, B, C, D$:** The definitions of the four 2-port transfer functions follow trivially from Eq. 3.36:

$$
A(s) = \left. \frac{V_1}{V_2} \right|_{I_2=0}, \quad B(s) = -\left. \frac{V_1}{I_2} \right|_{V_2=0}, \quad C(s) = \left. \frac{I_1}{V_2} \right|_{I_2=0}, \quad D(s) = -\left. \frac{I_1}{I_2} \right|_{V_2=0}.
$$

Each has a physical interpretation, and a corresponding name. Functions $A$ and $C$ are said to be **blocked** because the output current $I_2$ is zero. Functions $B$ and $D$ are said to be **short-circuited** because the output voltage $V_2$ is zero. These two terms (blocked, short-circuited) are very electrical-engineering centric, and should be avoided.

For example, in a mechanical system **blocked** would correspond to an output isometric (no length change) velocity of zero. In mechanics the **isometric force** is defined as the maximum applied force, conditioned on zero velocity (aka, the blocked force). Thus the **short-circuited** force (aka $B$) would correspond to the force when the force is zero, which is nonsense. Thus these engineering-centric terms do not gracefully generalize, so better terminology is needed. Much of this was sorted out by Thévenin26 c1883 (Johnson, 2003) and (Kennelly, 1893).

$A, D$ are called **voltage** (force) and **current** (velocity) **transfer functions**, since they are ratios of voltages and currents, whereas $B, C$ are known as the **transfer admittance** and **transfer admittance**. For example, the unloaded (blocked) ($I_2 = 0$) output voltage $V_2 = I_1/C$, which would correspond to the isometric force in mechanics. In this way each term expresses an output (port 2) in terms of an input (port 1), for a given load condition.

**Exercise:** Explain why $C$ is given as above. **Solution:** Writing out the lower equation gives $I_1 = CV_2 - DI_2$. Setting $I_2 = 0$, we obtain the equation for $C = I_1/V_2|_{I_2=0}$.

Thus the **transfer admittance** $C$ is the input current $I_1$ over the output voltage $V_2$ in the blocked condition $I_2 = 0$. An equivalent relation is the blocked output voltage ($V_2|_{I_2=0}$) over the input current $I_1$

$$
\left. \frac{V_2}{I_1} \right|_{I_2=0} = \frac{1}{C},
$$

which is simply the reciprocal of the transfer admittance $C$ of Eq. 3.37, making it also a transfer impedance. The blocked transfer impedance is denoted the **Thévenin impedance**.

**Exercise:** Can $C = 0$? **Solution:** Yes, if $I_2 = 0$ and $I_1 = I_2, C = 0$. For $C \neq 0$ there needs to be a finite “shunt” impedance across $V_1$.

### 3.5.1 Thévenin parameters of a source:

An important concept in circuit theory is that of the **Thévenin parameters**, the **open-circuit voltage** and the **short-circuit current**, the ratio of which defines the **Thévenin impedance** (Johnson, 2003). The open-circuit voltage is defined as the voltage $V_2$ when the load current $I_2 = 0$, which was shown in the previous exercise to be $V_2/I_1|_{I_2=0} = 1/C$.

---

Exercise: Find the Thévenin source voltage for the circuit of Fig. 3.5. Solution: see discussion below.

Exercise: Show that the Thévenin source impedance is

\[ Z_{\text{Thév}} = \frac{B}{C}. \]

Hint: Use the definitions of \( V_1 = -BI_2|_{V_2=0} \) and \( V_{\text{Thév}} = I_1/C \). Solution: To solve for \( Z_{\text{Thév}} \) write out the definition of the ABCD matrix as two equations, and then solve for the Thévenin impedance, defined as the open-circuit voltage over the short-circuit current.

Exercise: Find the Thévenin source impedance for the circuit of Fig. 3.5. Solution: see discussion below.

Thévenin Voltage: Taking the inverse of Eq. 3.36 and using the definition of the Thévenin voltage

\[
\begin{bmatrix}
V_{\text{Thév}} \\
I_2 = 0
\end{bmatrix} =
\begin{bmatrix}
D(s) & -B(s) \\
-C(s) & A(s)
\end{bmatrix}
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix}.
\]

Note that for a reciprocal system \( \Delta_T = 1 \). Thus

\[ V_{\text{Thév}} = \frac{V_1}{A} = \frac{I_1}{C}. \]

It follows that the Thévenin voltage may be expressed either in terms of a voltage source \( V_1 \) or a current source \( I_1 \). If the source has a known impedance, then \( z_s(s) = V_1/I_1 \) must be specified.

Thévenin Impedance: The Thévenin impedance is the impedance seen looking into port 2, with port 1 shorted (\( V_1 = 0 \))

\[ Z_{\text{Thév}} = \left. \frac{V_2}{I_2} \right|_{V_1=0}. \]

From the upper equation of Eq. 3.36, with \( V_1 = 0 \), we obtain \( AV_2 = BI_2 \), thus

\[ Z_{\text{Thév}} = \frac{B}{C}. \]

Properties of the transmission matrix: The transmission matrix is always constructed from the product of elemental matrices of the form

\[
\begin{bmatrix}
1 & Z(s) \\
0 & 1
\end{bmatrix} \quad \text{or} \quad \begin{bmatrix}
1 & 0 \\
Y(s) & 1
\end{bmatrix}.
\]

Thus for the case of reciprocal systems (P6, p. 132),

\[ \Delta_T = \det \begin{bmatrix}
A(s) & B(s) \\
C(s) & D(s)
\end{bmatrix} = 1, \]

since the determinant of the product of each elemental matrix is 1, the determinant their product is 1. An anti-reciprocal system may be synthesized by the use of a gyrator, and for such cases \( \Delta_T = -1 \).

The eigenvalues and vectors are given in Appendix D (p. 261) and E (p. 265).
3.5.2 Lec 17: The impedance matrix

With a bit of algebra, one may find the impedance matrix in terms of $A, B, C, D$ (Van Valkenburg, 1964a, p. 310)

$$
\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \frac{1}{C} \begin{bmatrix} A & \Delta_T \\ 1 & D \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}.
$$

Note that if $C = 0$, the impedance matrix does not exist.

Definitions of $z_{11}(s), z_{12}(s), z_{21}(s), z_{22}(s)$: The definitions of the matrix elements are easily read off of the equation, as

$$
z_{11} = \frac{V_1}{I_1} \bigg|_{I_3=0}, \quad z_{12} = -\frac{V_1}{I_2} \bigg|_{I_1=0}, \quad z_{21} = \frac{V_2}{I_1} \bigg|_{I_3=0}, \quad z_{22} = -\frac{V_2}{I_2} \bigg|_{I_1=0}.
$$

These definitions follow trivially from Eq. 3.40 and each element has a physical interpretation. For example, the unloaded (i.e., open or isometric) input impedance is $z_{11}(s) = A(s)/C(s)$ while the unloaded transfer impedance is $z_{21}(s) = 1/C(s)$. For reciprocal systems (P6, p. 132) $z_{12} = z_{21}$ since $\Delta_T = 1$. For anti-reciprocal systems, such as dynamic (aka, magnetic) loudspeakers and microphones (Kim and Allen, 2013), $\Delta_T = -1$, thus $z_{21} = -z_{12} = 1/C$. Finally $z_{22}$ is the impedance looking into port 2 with port 1 open/blockaded ($I_1 = 0$).

Exercise: Find the Thévenin impedance in terms of the Transmission matrix elements.

Solution: We showed above that $Z_{\text{Thév}} = B/C$. In terms of the impedance matrix, the Thévenin impedance is the ratio of the unloaded voltage $V_2 = z_{21}I_1 = A/C$, divided by the short circuit current $I_2 = V_1/z_{12} = A/B$. Thus

$$
Z_{\text{Thév}} = \frac{V_2}{I_2} = \frac{A}{B} \frac{B}{C} = \frac{A}{C}.
$$

3.5.3 Lec 18: Network power relations

Impedance is a very general concept, closely tied to the definition of power $P(t)$ (and energy). Power is defined as the product of the effort (force) and the flow (current). As described in Fig. 3.2, these concepts are very general, applying to mechanics, electrical circuits, acoustics, thermal circuits, or any other case where conservation of energy applies. Two basic variables are defined, generalized force and generalized flow, also called conjugate variables. The product of the conjugate variables is the power, and the ratio is the impedance. For example, for the case of voltage and current,

$$
P(t) \equiv \int^t v(t)i(t)dt, \quad Z(s) \equiv \frac{V(\omega)}{I(\omega)}.
$$

3.5.4 Power vs. power series, linear vs. nonlinear

Another place where equations of second degree appear in physical applications is in energy and power calculations. The electrical power is given by the product of the voltage $v(t)$ and current $i(t)$ (or in mechanics as the force times the velocity). For example if we define $P = v(t)i(t)$ to be the power $P$ [watts], then the total energy [joules] at time $t$ is (Van Valkenburg, 1964a, Chapter 14)

$$
E(t) = \int_0^t v(t)i(t)dt.
$$

From this observe that the power is the rate of change of the total energy

$$
P(t) = \frac{d}{dt}E(t),
$$

reminiscent of the fundamental theorem of calculus [Eq. 4.7, (p. 146)].
### 3.5. LECTURE 16: TRANSMISSION (ABCD) MATRIX COMPOSITION METHOD

**Ohm’s law and impedance:** The ratio of voltage over the current is called the *impedance* which has units of [ohms]. For example given a resistor of $R = 10$ [ohms],

\[ v(t) = Ri(t). \]

Namely, 1 [amp] flowing through the resistor would give 10 [volts] across it. Merging the linear relation due to Ohm’s law with the definition of power shows that the instantaneous power in a resistor is quadratic in voltage and current

\[ P(t) = \frac{v(t)^2}{R} = i(t)^2R. \]

(3.42)

Note that Ohm’s law is linear in its relation between voltage and current whereas the power and energy are nonlinear.

Ohm’s law generalizes in a very important way, allowing the impedance (e.g., resistance) to be a linear complex analytic function of complex frequency $s = \sigma + \omega j$ (Kennelly, 1893; Brune, 1931a). Impedance is a fundamental concept in many fields of engineering. For example:

- Newton’s second law $F = ma$ obeys Ohm’s law, with mechanical impedance $Z(s) = sm$.
- Hooke’s law $F = kx$ for a spring is described by a mechanical impedance $Z(s) = k/s$. In mechanics a “resistor” is called a *dash-pot* and its impedance is a positive and real constant.

**Kirchhoff’s laws KCL, KVL:** The laws of electricity and mechanics may be written down using Kirchhoff’s current and voltage laws (KCL, KVL), which lead to linear systems of equations in the currents and voltages (velocities and forces) of the system under study, with complex coefficients having positive real parts.

Points of major confusion are a number of terms that are misused, and overused, in the fields of mathematics, physics and engineering. Some of the most obviously abused terms are *linear/nonlinear, energy, power, power series.* These have multiple meanings, which can, and are, fundamentally in conflict.

**Transfer functions (transfer matrix):** The only method that seems to work, to sort this out, is to cite the relevant physical application, in specific contexts. The most common standard reference is a physical system that has an input $x(t)$ and an output $y(t)$. If the system is linear, then it may be represented by its *impulse response* $h(t)$. In such cases the system equation is

\[ y(t) = h(t) \star x(t) \leftrightarrow Y(\omega) = H(s)|_{\sigma=0} X(\omega); \]

namely, the convolution of the input with the impulse response gives the output. From Fourier analysis this relation may be written in the real frequency domain as a product of the Laplace transform of the impulse response, evaluated on the $\omega j$ axis and the Fourier transform of the input $X(\omega) \leftrightarrow x(t)$ and output $Y(\omega) \leftrightarrow y(t)$.

If the system is nonlinear, then the output is not given by a convolution, and the Fourier and Laplace transforms have no obvious meaning.

The question that must be addressed is why the power is nonlinear, whereas a power series of $H(s)$ is linear: Both have powers of the underlying variables. This is naturally confusing and rarely, if ever, address. The quick answer is that powers of the Laplace frequency $s$ correspond to derivatives, which are linear, whereas the product of the voltage $v(t)$ and current $i(t)$ is nonlinear. The important and interesting question will be addressed in Section 3.7.1 (p. 132), in terms of the system postulates of physical systems.

**What’s going on?** The domain variables must be separated from the codomain variables. In our example, the voltage and current are multiplied together, resulting in a nonlinear output, the power. If the frequency is squared, this is describing the degree of a polynomial. This is not nonlinear because it does not impact the signal output; it characterizes the Laplace transform of the system response.

---

27 In acoustics the pressure is a potential, like voltage. The force per unit area is given by $f = -\nabla p$, thus $F = -\int \nabla p \, dS$. Velocity is analogous to a current. In terms of the velocity potential, the velocity per unit area is $v = -\nabla \phi$.

28 https://en.wikipedia.org/wiki/Impedance_analogy
Table 3.2: The generalized impedance is defined as the ratio of a force over a flow, a concept that also holds in mechanics and acoustics. In mechanics, the ‘force’ is equal to the mechanical force on an element (e.g. a mass, dash-pot, or spring), and the ‘flow’ is the velocity. In acoustics, the ‘force’ is pressure, and the ‘flow’ is the volume velocity or particle velocity of air molecules.

<table>
<thead>
<tr>
<th>Case</th>
<th>Force</th>
<th>Flow</th>
<th>Impedance</th>
<th>units ohms [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>voltage (V)</td>
<td>current (I)</td>
<td>$Z = V/I$</td>
<td></td>
</tr>
<tr>
<td>Mechanics</td>
<td>force (F)</td>
<td>velocity (U)</td>
<td>$Z = F/U$</td>
<td>mechanical [Ω]</td>
</tr>
<tr>
<td>Acoustics</td>
<td>pressure (P)</td>
<td>particle velocity (V)</td>
<td>$Z = P/V$</td>
<td>specific [Ω]</td>
</tr>
<tr>
<td>Acoustics</td>
<td>mean pressure (P)</td>
<td>volume velocity (V)</td>
<td>$Z = P/V$</td>
<td>acoustic [Ω]</td>
</tr>
<tr>
<td>Thermal</td>
<td>temperature (T)</td>
<td>heat-flux (J)</td>
<td>$Z = T/J$</td>
<td>thermal [Ω]</td>
</tr>
</tbody>
</table>

**Ohm’s law:** In general, impedance is defined as the ratio of a force over a flow. For electrical circuits, the voltage is the ‘force’ and the current is the ‘flow.’ Ohm’s law states that the voltage across and the current through a circuit element are related by the impedance of that element (which is typically a function of the Laplace frequency $s = \sigma + \omega j$). For resistors, the voltage over the current is called the resistance, and is a constant (e.g. the simplest case, $V/I = R$). For inductors and capacitors, the impedance depends on the Laplace frequency $s$ [e.g. $V/I = Z(s)$].

As discussed in Fig. 3.2, the impedance concept also holds for mechanics and acoustics. In mechanics, the ‘force’ is equal to the mechanical force on an element (e.g. a mass, dash-pot, or spring), and the ‘flow’ is the velocity. In acoustics, the ‘force’ is pressure, and the ‘flow’ is the volume velocity or particle velocity of air molecules.

In this section we shall derive the method of linear composition of systems, also known as the ABCD transmission matrix method, or in the mathematical literature as the Möbius (bilinear) transformation. Using the method of matrix composition, a linear system of 2x2 matrices can represent a large and important family of networks. By the application of Ohm’s law to the circuit shown in Fig. 3.5, we can model a cascade of such cells.

**Example of the use of the ABCD matrix composition:** In Fig. 3.5 we see the network is composed of a series inductor (mass) having an impedance $Z_l = sL$, and a shunt capacitor (compliance) having an impedance $Z_c = 1/sC$, where $s \in \mathbb{C}$. As determined by Ohm’s law, each impedance is described by a linear relation between the current and the voltage. For the inductive impedance, applying Ohm’s law, we find

$$V_1 - V_2 = Z_l I_1,$$

where $Z_l$ is the complex impedance of the inductor. For the capacitive impedance, applying Ohm’s law we find

$$V_2 = (I_1 + I_2) Z_c,$$

where $Z_c$ is the complex impedance of the capacitor.

Each of these linear impedance relations may be written in matrix form. The series inductor equation gives (note $I_1 = -I_2$)

$$
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix} =
\begin{bmatrix}
1 & Z_l \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
V_2 \\
-I_2
\end{bmatrix},
$$

while the shunt capacitor equation yields (note $V_1 = V_2$)

$$
\begin{bmatrix}
V_2 \\
I_2
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
Y_c & 1
\end{bmatrix}
\begin{bmatrix}
V_3 \\
-I_3
\end{bmatrix},
$$

where $Y_c = 1/Z_c$ is called the admittance.
When the second matrix equation for the shunt admittance (Eq. 3.44) is substituted into the series impedance equation (Eq. 3.43), we find the ABCD matrix \((T_1 \circ T_2)\) for the cell is simply the product of two matrices

\[
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix} =
\begin{bmatrix}
1 & Z_l \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
Y_c & 1
\end{bmatrix}
\begin{bmatrix}
V_3 \\
-I_3
\end{bmatrix} =
\begin{bmatrix}
1 + Z_l Y_c \\
Y_c & 1
\end{bmatrix}
\begin{bmatrix}
V_3 \\
-I_3
\end{bmatrix}.
\] (3.45)

Note that the determinant of the matrix \(\Delta = AD - BC = 1\).

Thus \(A(s) = 1 + Z_L u_c = 1 + s^2 LC\), \(B(s) = Z_l\), \(C(s) = Y_c\) and \(D = 1\). This equation characterizes every possible relation between the input and output voltage and current of the cell.

For example, the ratio of the output to input voltage with the output unloaded \((I_2 = 0)\), known as the voltage divider relation, may be found from the upper equation with \(I_2 = 0\). Writing this out gives

\[
\frac{V_2}{V_1} \bigg|_{I_2=0} = \frac{1}{A(s)} = \frac{1}{1 + Z_l Y_c} = \frac{Z_c}{Z_c + Z_l}.
\]

To derive the formula for the current divider equation, use the lower equation and set \(V_2 = 0\).

\[
\frac{-I_2}{I_1} \bigg|_{V_2=0} = \frac{1}{D} = 1.
\]

### 3.6 Lec 19: Signals: Fourier transforms

Two basic transformations in engineering mathematics are the Fourier and the Laplace transforms, which deal with time–frequency analysis. The best books on this topic is Papoulis (1962).

**Notation:** The Fourier transform takes a time domain signal \(f(t) \in \mathbb{R}\) and transforms it to the frequency domain \(\omega \in \mathbb{R}\), where it is complex \((F(\omega) \in \mathbb{C})\). For the Fourier transform, both the time \(-\infty < t < \infty\) and frequency \(\infty < \omega < \infty\) are strictly real. The relationship between \(f(t)\) and its transform \(F(\omega)\) is indicated by the double arrow symbol

\[
f(t) \leftrightarrow F(\omega).
\]

Since the FT obeys superposition, it is possible to define a FT of a complex time function \(f(t) \in \mathbb{C}, t \in \mathbb{R}\). This is useful in certain engineering applications (i.e., Hilbert envelope, Hilbert transforms). It is accepted in the engineering and physics literature to use the case of the variable to indicate the type of argument. A time function is \(f(t)\), where \(t\) has units of seconds \([s]\) and is in lower case, whereas its Fourier transform, a function of frequency, having units of either hertz \([Hz]\) or radians \([2\pi Hz]\), is written using upper case \(F(\omega)\). This helps the reader parse the type of variable under consideration. This is a helpful piece of notation, but not entirely in agreement with notation used in mathematics.

**Definition of the Fourier transform:** The forward transform takes \(f(t)\) to \(F(\omega)\) while the inverse transform takes \(F(\omega)\) to \(\hat{f}(t)\). The tilde symbol indicates that in general the recovered inverse transform signal can be slightly different from \(f(t)\). We give examples of this in Table 3.3.

\[
F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt
\]

\[
\hat{f}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t} d\omega
\] (3.46)

\[
F(\omega) \leftrightarrow f(t)
\]

\[
\hat{f}(t) \leftrightarrow F(\omega).
\] (3.47)
Table 3.3: Basic (Level I) Fourier transforms. Note \(a > 0 \in \mathbb{R}\) has units \(\text{rad/s}\). To flag this necessary condition, we use \(|a|\) to assure this condition will be met. The other constant \(T_o \in \mathbb{R} [s]\) has no restrictions, other than being real. Complex constants may not appear as the argument to a delta function, since complex numbers do not have the order property.

<table>
<thead>
<tr>
<th>(f(t)) ↔ (F(\omega))</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{\delta}(t)) ↔ (1(\omega))</td>
<td>Dirac</td>
</tr>
<tr>
<td>(1(t) \equiv 1 \forall t \leftrightarrow 2\pi \tilde{\delta}(\omega))</td>
<td>Dirac</td>
</tr>
<tr>
<td>(\text{sgn}(t) = \frac{t}{</td>
<td>t</td>
</tr>
<tr>
<td>(\tilde{u}(t) = \frac{1(t) + \text{sgn}(t)}{2} \leftrightarrow \pi \tilde{\delta}(\omega) + \frac{1}{j\omega} \equiv \tilde{U}(\omega))</td>
<td>step</td>
</tr>
<tr>
<td>(\tilde{\delta}(t - T_o) \leftrightarrow e^{-j\omega T_o})</td>
<td>delay</td>
</tr>
<tr>
<td>(\tilde{\delta}(t - T_o) * f(t) \leftrightarrow F(\omega)e^{-j\omega T_o})</td>
<td>delay</td>
</tr>
<tr>
<td>(\tilde{u}(t)e^{-</td>
<td>a</td>
</tr>
<tr>
<td>(\text{rec}(t) = \frac{1}{T_o} [\tilde{u}(t) - \tilde{u}(t - T_o)] \leftrightarrow \frac{1}{T_o} \left(1 - e^{-j\omega T_o}\right))</td>
<td>pulse</td>
</tr>
<tr>
<td>(\tilde{u}(t) * \tilde{u}(t) \leftrightarrow \tilde{\delta}^2(\omega))</td>
<td>Not defined</td>
</tr>
</tbody>
</table>

Properties of Fourier Transforms:

1. Both time \(t\) and frequency \(\omega\) are real.
2. For the forward transform (time to frequency), the sign of the exponential is negative.
3. The limits on the integrals in both the forward and reverse FTs are \([-\infty, \infty]\).
4. When taking the inverse Fourier transform, the scale factor of \(1/2\pi\) is required to cancel the \(2\pi\) in the differential \(d\omega\).
5. The Fourier step function may be defined by the use of superposition of 1 and \(\text{sgn}(t) = t/|t|\) as

\[
\tilde{u}(t) \equiv \frac{1 + \text{sgn}(t)}{2} = \begin{cases} 
1 & t > 0 \\
1/2 & t = 0 \\
0 & t < 0 
\end{cases}.
\]

Taking the FT of a delayed step function

\[
\tilde{u}(t - T_o) \leftrightarrow \frac{1}{2} \int_{-\infty}^{\infty} [1 - \text{sgn}(t - T_o)] e^{-j\omega t} dt = \pi \delta(\omega) + \frac{e^{-j\omega T_o}}{j\omega}.
\]

Thus the FT of the step function has the term \(\pi \delta(\omega)\) due to the 1 in the definition of the Fourier step. This term introduces a serious flaw with the FT of the step function: While it appears to be causal, it is not.

6. The convolution \(\tilde{u}(t) * \tilde{u}(t)\) is not defined because both \(1 * 1\) and \(\tilde{\delta}^2(\omega)\) do not exist (and cannot be defined).
7. The inverse FT has convergence problems whenever there is a discontinuity in the time response. This we indicate with a hat over the reconstructed time response. The error between the target time function and the reconstructed is zero in the root-mean sense, but not point-wise.

Specifically, at the discontinuity point for the Fourier step function \( t = 0 \), \( \tilde{u}(t) \neq u(t) \), yet \( \int |\tilde{u}(t) - u(t)|^2 dt = 0 \). At the point of the discontinuity the reconstructed function displays Gibbs ringing (it oscillates around the step, hence does not converge at the jump).\(^{29}\) The LT does not exhibit Gibbs ringing.

8. The FT is not always analytic in \( \omega \), as in this example of the step function. The step function cannot be expanded in a Taylor series about \( \omega = 0 \) because \( \tilde{\delta}(\omega) \) is not analytic in \( \omega \).

9. The Fourier \( \delta \) function is denoted \( \tilde{\delta}(t) \), to differentiate it from the Laplace delta function \( \delta(t) \). They differ because the step functions differ, due to the convergence problem described above.

10. One may define

\[
\tilde{u}(t) = \int_{-\infty}^{t} \tilde{\delta}(t) dt,
\]

and define the somewhat questionable notation

\[
\tilde{\delta}(t) = \frac{d}{dt} \tilde{u}(t),
\]

since the Fourier step function is not analytic.

11. The \( \text{rec}(t) \) function is defined as

\[
\text{rec}(t) = \frac{\tilde{u}(t) - \tilde{u}(t - T_o)}{T_o} = \begin{cases} 
0 & t < 0 \\
1/T_o & 0 < t < T_o \\
0 & t > T_o
\end{cases}.
\]

It follows that \( \tilde{\delta}(t) = \lim_{T_o \to 0} \). Like \( \tilde{\delta}(t) \), the \( \text{rec}(t) \) has unit area.

---

**Table 3.4: Summary of key properties of FTs.**

<table>
<thead>
<tr>
<th>FT Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d}{dt} ) v(t) ↔ j( \omega ) V(( \omega ))</td>
<td>deriv</td>
</tr>
<tr>
<td>f(t) \star g(t) ↔ F(( \omega )) G(( \omega ))</td>
<td>conv</td>
</tr>
<tr>
<td>f(t)g(t) ↔ ( \frac{1}{2\pi} ) F(( \omega )) \star G(( \omega ))</td>
<td>conv</td>
</tr>
<tr>
<td>f(at) ↔ ( \frac{1}{a} ) F \left( \frac{\omega}{a} \right)</td>
<td>scaling</td>
</tr>
</tbody>
</table>

---

\(^{29}\)https://en.wikipedia.org/wiki/Gibbs_phenomenon
**Periodic signals:** Besides these two basic types of time–frequency transforms, there are several variants that depend on the symmetry in time and frequency. For example, when the time signal is sampled (discrete in time), the frequency response becomes periodic, leading to the discrete-time Fourier transform (DTFT). When a time response is periodic, the frequency response is sampled (discrete in frequency), leading to the Fourier series. These two symmetries may be simply characterized as periodic in time ⇒ discrete in frequency, and periodic in frequency ⇒ discrete in time. When a function is discrete both in time and frequency, it is necessarily periodic in time and frequency, leading to the discrete Fourier transform (DFT). The DFT is typically computed with an algorithm called the fast Fourier transform (FFT), which can dramatically speed up the calculation when the data is a power of 2 in length.

An important symmetry occurs given functions that are causal (in time) and periodic (in frequency). The best known example is the class of signals that have *z* transforms, which are causal (one-sided in time) discrete-time signals. The harmonic series (Eq. 3.29, p. 89) is the *z*-transform of the discrete-domain.

\[ \omega \]

The two signals (vectors) are orthogonal.

**Exercise:** Consider the discrete time

\[ F(\omega) = f((t))T_o \cdot e^{-j\omega_k t} \]

\[ \equiv \frac{1}{T_o} \int_0^{T_o} f(t)e^{-j\omega_k t} dt, \]

where \( \omega_0 = 2\pi / T_o \), \( f(t) \) has period \( T_o \), i.e., \( f(t) = f(t + nT_o) = e^{j\omega_0 t} \) with \( n \in \mathbb{N} \), and \( \omega_k = k\omega_0 \).

What is the value of the scalar product? **Solution:** Evaluating the scalar product we find

\[ e^{j\omega_0 t} \cdot e^{-j\omega_k t} = \frac{1}{T_o} \int_0^{T_o} e^{j\omega_0 t} e^{-j\omega_k t} dt = \begin{cases} 1 & n = k \\ 0 & n \neq k \end{cases} \]

The two signals (vectors) are orthogonal.

**Exercise:** Consider the discrete time \( F^T \) (DTFT) as a scalar (dot) product (Eq. 3.23, p. 112) between “vectors” \( f((t))T_o \) and \( e^{-j\omega_k t} \)

\[ F((\omega))_{2\pi} = f_n \cdot e^{-j\omega n} \]

\[ \equiv \sum_{n=-\infty}^{\infty} f_n e^{-j\omega n}, \]

where \( \omega_0 = 2\pi / T_o \) and \( \omega_k = k\omega_0 \). If \( f_n = e^{j\omega n} \) what is the value of the scalar product? **Solution:** Evaluating the scalar product we find

\[ e^{j\omega_0 t} \cdot e^{-j\omega_k t} = \frac{1}{T_o} \int_0^{T_o} e^{j\omega_0 t} e^{-j\omega_k t} dt = \frac{1}{T_o} \int_0^{T_o} e^{2\pi j(n-k)t} dt = \begin{cases} 1 & n = k \\ 0 & n \neq k \end{cases} \]

The two signals (vectors) are orthogonal.
3.6.1 Applications to Fourier transforms: Kernel methods

Add discussion of the Poisson Sum formula here (Papoulis, 1962, p. 142).

3.6.2 The characteristic function

Given examples of kernel methods. For example a Maxwellian gas with $10^{23}$ moving molecules, which are smoothed over time with a kernel method.
3.7 Lec 20: Systems: Laplace transforms

The *Laplace transform* takes real signals \( f(t) \in \mathbb{R} \), as a function of real time \( t \in \mathbb{R} \), that are *causal*, i.e., strictly zero for negative time \( f(t) = 0 \) for \( t < 0 \), and transforms them into complex functions \( F(s) \in \mathbb{C} \) of complex frequency \( s = \sigma + \omega j \). As for the Fourier transform, there is the notation \( f(t) \leftrightarrow F(s) \).

When a signal is zero for negative time \( f(t < 0) = 0 \), it is said to be *causal*, and the resulting transform \( F(s) \) is then complex analytic over significant regions of the \( s \)-plane. For a function of time to be causal, time *must* be real \( (t \in \mathbb{R}) \), since if it were complex, it would lose the order property (thus it could not be causal). It is helpful to emphasize the causal nature of \( f(t)u(t) \) by indicating the causal nature, using the Heaviside step function \( u(t) \).

Any restriction on a function (e.g., real, causal, periodic, positive real part, etc.) is called a *symmetry property*. There are many forms of symmetry (Section 3.7.1, p. 132). The concept of symmetry is very general and widely used in both mathematics and physics, where it is more generally known as *group theory*. We shall restrict ourselves to only a few very basic symmetries.

**Definition of the Laplace transform:** The forward and inverse Laplace transforms are

\[
F(s) = \int_{0}^{\infty} f(t)e^{-st} dt \quad f(t) = \frac{1}{2\pi j} \int_{\sigma_{0}+\infty j}^{\sigma_{0}-\infty j} F(s)e^{st} ds \quad (3.48)
\]

\[
F(s) \leftrightarrow f(t) \quad f(t) \leftrightarrow F(s) \quad (3.49)
\]

Here \( s = \sigma + j\omega \in \mathbb{C} \) [2πHz] is the complex Laplace frequency in radians and \( t \in \mathbb{R} \) [s] is the time in seconds.

When dealing with engineering problems it is convenient to separate the *signals* we use from the *systems* that process them. We do this by treating signals, such as a music signal, differently from a system, such as a filter. In general signals may start and end at any time. The concept of causality has no mathematical meaning in signal space. Systems, on the other hand, obey very rigid rules (to assure that they remain physical). These physical restrictions are described in terms of the *network postulates*, which are discussed in Sect. 3.7.1 (p. 132). There is a question as to why postulates are needed, and which ones are the best choices.\(^{30}\) There may be no answers to these questions, but having a set of postulates is a useful way of thinking about physics.\(^{31}\)

As discussed in Section 4.5.2 (p. 175), we must use the Cauchy residue theorem (CRT), requiring closure of the contour \( C \) at \( \omega j \rightarrow \pm j\infty \)

\[
\oint_C = \int_{\sigma_0+j\infty}^{\sigma_0-j\infty} + \int_{\infty} \]

where the path represented by ‘\( \subset \infty \)’ is a semicircle of infinite radius. For a causal, ‘stable’ (e.g. doesn’t “blow up” in time) signal, all of the poles of \( F(s) \) *must* be inside of the Laplace contour, in the left half \( s \)-plane.

![Diagram of a three-element mechanical resonant circuit](https://www.youtube.com/watch?v=JXAfEBbaz_4)

![Diagram of a three-element mechanical resonant circuit](https://www.youtube.com/watch?v=YaUlqXRPMmY)

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\(^{30}\)https://www.youtube.com/watch?v=JXAfEBbaz_4

\(^{31}\)https://www.youtube.com/watch?v=YaUlqXRPMmY
Hooke’s law for a spring states that the force \( f(t) \) is proportional to the displacement \( x(t) \), i.e.,
\[ f(t) = Kx(t) \]
The formula for a dash-pot is \( f(t) = Rv(t) \), and Newton’s famous formula for mass is
\[ f(t) = d[Mv(t)]/dt \]
which for constant \( M \) is \( f(t) = Mdv/dt \).

The equation of motion for the mechanical oscillator in Fig. 4.10 is given by Newton’s second law; the sum of the forces must balance to zero
\[
M\frac{d^2}{dt^2}x(t) + R\frac{d}{dt}x(t) + Kx(t) = f(t).
\]
(3.50)

These three constants, the mass \( M \), resistance \( R \) and stiffness \( K \) (\( \in \mathbb{R} \geq 0 \)) are real and non-negative.
The dynamical variables are the driving force \( f(t) \leftrightarrow F(s) \), the position of the mass \( x(t) \leftrightarrow X(s) \) and its velocity \( v(t) \leftrightarrow V(s) \), with \( v(t) = dx(t)/dt \leftrightarrow V(s) = sX(s) \).

Newton’s second law (c1650) is the mechanical equivalent of Kirchhoff’s (c1850) voltage law (KVL), which states that the sum of the voltages around a loop must be zero. The gradient of the voltage results in a force on a charge (i.e., \( F = qE \)).

Equation 3.50 may be re-expressed in terms of impedances, the ratio of the force to velocity, once it is transformed into the Laplace frequency domain.

**Example:** The divergent series
\[
e^t u(t) = \sum_{0}^{\infty} \frac{1}{n!}t^n \leftrightarrow \frac{1}{s-1}
\]
is a valid description of \( e^t u(t) \), with an unstable pole at \( s = 1 \). For values of \( |x - x_o| < 1 \) (\( x \in \mathbb{R} \)), the analytic function \( P(x) \) is said to have a region of convergence (RoC). For cases where the argument is complex (\( s \in \mathbb{C} \)), this is called the radius of convergence (RoC). We call the region \( |s - s_o| > 1 \) the region of divergence (RoD), and \( |s - s_o| = 0 \), the singular circle. Typically the underlying function \( P(s) \), defined by the series, has a pole on the singular circle for \( s \in \mathbb{C} \). One may isolate such poles by moving the expansion point \( s_o \) until the RoC approaches zero. Outside the circle the Taylor series is divergent and inside it is convergent.

There seems to be a conflict with the time response \( f(t) = e^{st}u(t) \), which has a divergent series (unstable pole). I’m not sure how to explain this conflict, other than to point out that \( t \in \mathbb{R} \); thus, the series expansion of the diverging exponential is real-analytic, not complex analytic. First \( f(t) \) has a Laplace transform with a pole at \( s = 1 \), in agreement with its unstable nature. Second, every analytic function must be single valued. This follows from the fact that each term in Eq. 3.27 is single valued. Third, analytic functions are “smooth” since they may be differentiated an infinite number of times and the series still converges. There can be no jumps or kinks in such functions.

The key idea that every impedance must be complex analytic and \( \geq 0 \) for \( \sigma > 0 \) was first proposed by Otto Brune in his PhD at MIT, supervised by Ernst A. Guillemin, an MIT electrical engineering professor who played an important role in the development of circuit theory and was a student of Arnold Sommerfeld. Other MIT advisers were Norbert Wiener and Vannevar Bush. Brune’s primary, but non-MIT, advisor was W. Cauer, also perhaps a student of Sommerfeld, who was well trained in 19th century German mathematics (Brune, 1931b).

**Summary:** While the definitions of the FT (\( \mathcal{F}T \)) and LT (\( \mathcal{L}T \)) transforms may appear similar, they are not. The key difference is that the time response of the Laplace transform is causal, leading to a complex analytic frequency response. While the frequency response of the Fourier transform is complex, it is not complex analytic since the frequency \( \omega \) is real. Fourier transforms do not have poles. These are not superficial differences.

\[ ^{32}\text{It must be noted that University of Illinois Prof. ‘Mac’ Van Valkenburg was arguably more influential in circuit theory during the same period. Mac’s books are certainly more accessible, but perhaps less widely cited.} \]
The concept of symmetry is helpful in understanding the many different types of time-frequency transforms. Two fundamental types of symmetry are causality and periodicity.

The Fourier transform $\mathcal{F}T$ characterizes the steady-state response while the Laplace transform $\mathcal{L}T$ characterizes both the transient and steady-state response. Given a causal system response $H(s) \leftrightarrow h(t)$ with input $x(t)$, the output is

$$y(t) = h(t) \ast x(t) \leftrightarrow Y(\omega) = H(s)\big|_{s=j\omega} X(\omega).$$

### 3.7.1 Lec 21: Ten system postulates

Solutions of differential equations, such as the wave equation, are conveniently described in terms of mathematical properties, which we present here in terms of 10 network postulates:

(P1) **Causality** (non-causal/acausal): Causal systems respond when acted upon. Virtually all physical systems obey causality. An example of a causal system is an integrator, which has a response of a step function. Filters are also examples of causal systems. Signals represent acausal responses. They do not have a clear beginning or end, such as the sound of the wind or traffic noise. A causal linear system is typically complex analytic. A nonlinear system can be causal, but not complex analytic.

(P2) **Linearity** (nonlinear): Linear systems obey superposition. Two signals $x(t)$ and $y(t)$ are the inputs to a linear system, producing outputs $x'(t)$ and $y'(t)$. When the inputs are presented together as $ax(t) + by(t)$ with weights $a, b \in \mathbb{C}$, the output will be $ax'(t) + by'(t)$. If either $a$ or $b$ is zero, the corresponding signal is removed from the output. **Nonlinear** systems mix the two inputs, thereby producing signals not present in the input. For example, if the inputs to a nonlinear system are two sine waves, the output will contain distortion components, having frequencies not present at the input. An example of a nonlinear system is one that multiplies the two inputs. A second is a diode, which rectifies a signal, letting current flow only in one direction. Most physical systems have some degree of nonlinear response, but this is not always desired. Other systems are designed to be nonlinear, such as the diode example.

(P3) **Passive** (active): An active system has a power source, such as a battery, while a passive system has no power source. While you may consider a transistor amplifier to be active, it is only so when connected to a power source.

(P4) **Real** (complex) time response: Typically systems are “real in, real out.” They do not naturally have complex responses (real and imaginary parts). While a Fourier transform takes real inputs and produces complex outputs, this is not an example of a complex time response. P4 is a characterization of the input signal, not its Fourier transform.

(P5) **Time-invariant** (time varying): For a system to be a time varying system the output must depend on when the input signal starts or stops. If the output, relative to the input, is independent of the starting time, then the system is said to be time-invariant (static).

(P6) **Reciprocal** (non- or anti-reciprocal): In many ways this is the most difficult property to characterize and thus to understand. It is best characterized by the ABCD matrix (Section 3.5, p. 119). If $B = C$, the system is said to be **reciprocal**. If $B = -C$, it is said to be **anti-reciprocal**. The impedance matrix is reciprocal while a loudspeaker is anti-reciprocal and modeled by the gyrator rather than a transformer. Non-reciprocal systems are modeled by gyrators, which may be thought of as transformers which swap the force and flow variables. For example, the input impedance of a gyrator, terminated by an inductor, is a capacitor. For an expanded discussion on reciprocity, see Sect. J, p. 281.
3.7. LECTURE 20: SYSTEMS: LAPLACE TRANSFORMS

(P7) **Reversibility** (non-reversible): If swapping the input and output of a system leaves the system invariant, it is said to be reversible. When \( A = D \), the system is reversible. Note the similarity and differences between reversible and reciprocal.

(P8) **Space-invariant** (space-variant): If a system operates independently as a function of where it physically is in space, then it is space-invariant. When the parameters that characterize the system depend on position, it is space-variant.

(P9) **Deterministic** (random): Given the wave equation, along with the boundary conditions, the system’s solution may be deterministic, or not, depending on its extent. Consider a radar or sonar wave propagating out into uncharted territory. When the wave hits an object, the reflection can return waves that are not predicted, due to unknown objects. This is an example where the boundary condition is not known in advance.

(P10) **Quasi-static** \((ka < 1)\) Quasi-statics follows the Nyquist sampling theorem, for systems that have dimensions that are small compared to the local wavelength. This assumption fails when the frequency is raised (the wavelength becomes short). Thus this is also known as the long-wavelength approximation. Quasi-statics is typically stated as \(ka < 1\), where \(k = 2\pi/\lambda = \omega/c_0\) and \(a\) is the smallest dimension of the system. See p. 230 for a detailed discussion of the role of quasi-statics in acoustic horn wave propagation.

Postulate (P10) is closely related to the Feynman lecture *The “underlying unity” of nature* where Feynman asks: Why do we need to treat the fields as smooth? (Feynman, 1970c, Ch. 12-7) His answer is related to the wavelength of the probing signal relative to the dimensions of the object being probed. This raises the fundamental question: Are Maxwell’s equations a band-limited approximation to reality? Today we have no answers to this question.

https://www.sciencedaily.com/releases/2017/09/170926085958.htm this has the following discussion:

The Lorentz force formula and Maxwell’s equations are two distinct physical laws, yet the two methods yield the same results.

Why the two results coincide was not known. In other words, the flux rule consists of two physically different laws in classical theories. Interestingly, this problem was also a motivation behind the development of the theory of relativity by Albert Einstein. In 1905, Einstein wrote in the opening paragraph of his first paper on relativity theory, “It is known that Maxwell’s electrodynamics — as usually understood at the present time — when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena.” But Einstein’s argument moved away from this problem and formulated special theory of relativity, thus the problem was not solved.

Richard Feynman once described this situation in his famous lecture (The Feynman Lectures on Physics, Vol. II, 1964), “we know of no other place in physics where such a simple and accurate general principle requires for its real understanding an analysis in terms of two different phenomena. Usually such a beautiful generalization is found to stem from a single deep underlying principle. · · · We have to understand the “rule” as the combined effects of two quite separate phenomena.”

Summary discussion of the 10 network postulates: Each postulate has two (or more) categories. For example, (P1) is either causal, non-causal or acausal while (P2) is either linear or non-linear. (P6) and (P9) only apply to 2-port algebraic networks (those having an input and an output). The others apply to both 2– and 1–port networks (e.g., an impedance is a 1-port). An interesting example is the anti-reciprocal transmission matrix of a loudspeaker (Allen, 2019, Lec21).

Related forms of these postulates may be found in the network theory literature (Van Valkenburg, 1964a,b; Ramo et al., 1965). Postulates (P1-P6) were introduced by Carlin and Giordano (1964) and
(P7-P9) were added by Kim et al. (2016). While linearity (P2), passivity (P3), realness (P4) and time-invariance (P5) are independent, causality (P1) is a consequence of linearity (P2) and passivity (P3) (Carlin and Giordano, 1964, p. 5).

### 3.8 Lec 22: Complex analytic mappings (domain-coloring)

One of the most difficult aspects of complex functions of a complex variable is visualizing the mappings from the \( z = x + yj \) to \( w(z) = u + vj \) planes. For example, \( w(z) = \sin(x) \) is trivial when \( z = x + yj \) is real (i.e., \( y = 0 \)), because \( \sin(x) \) is real. Likewise for the case where \( x = 0 \),

\[
\sin(yj) = \frac{e^{-y} - e^y}{2j} = -j\sin(y)
\]

is pure imaginary. However, the more general case

\[
w(z) = \sin(z) \in \mathbb{C}
\]

is not easily visualized. And when \( u(x, y) \) and \( v(x, y) \) are less well known functions, \( w(z) \) can be even more difficult to visualize. For example, if \( w(z) = J_0(z) \) then \( u(x, y), v(x, y) \) are the real and imaginary parts of the Bessel function.

**A software solution:** Fortunately with computer software today, this problem can be solved by adding color to the chart. An Octave/Matlab script\(^3\) `zviz.m` has been used to make the charts shown in Fig. 3.7. Such charts are known as *domain-coloring*\(^4\).

Rather than plotting \( u(x, y) \) and \( v(x, y) \) separately, domain-coloring allows us to display the entire function on one color chart (i.e., colorized plot).

For this visualization we see the complex polar form of \( w(s) = |w|e^{j\varphi} \), rather than the 2x2 (four-dimensional) Cartesian graph \( w(x+yj) = u(x,y) + v(x,y)j \). On the left is the reference condition, the identity mapping \( (w = s) \), and on the right the origin has been shifted to the right and up by \( \sqrt{2} \).

Mathematicians typically use abstract (i.e., non-physical) notation \( w(z) \), where \( w = u + vi \) and \( z = x + yi \). Engineers prefer to think in terms of a physical complex impedance \( Z(s) = R(s) + jX(s) \), having resistance \( R(s) \) and reactance \( X(s) \) [ohms], as a function of the complex Laplace radian frequency \( s = \sigma + \omega j \)[rad], as used, for example, with the Laplace transform (Sect. 3.7, p. 130).

In Fig. 3.7 we use both notations, with \( Z(s) = s \) on the left and \( w(z) = z - \sqrt{j} \) on the right, where we show this color code as a 2x2 dimensional domain-coloring graph. Intensity (dark to light) represents the magnitude of the function, while hue (color) represents the phase, where (see Fig. 3.7) red is 0°, sea-green is 90°, blue-green is 135°, blue is 180°, and violet is −90° (or 270°).\(^5\)

The function \( w = s = |s|e^{2\theta} \) has a dark spot (a zero) at \( s = 0 \), and becomes brighter away from the origin. On the right is \( w(z) = z - \sqrt{j} \), which shifts the zero to \( z = \sqrt{j} \). Thus domain-coloring

\[^{33}\text{http://jontalle.web.engr.illinois.edu/uploads/298/zviz.zip}\]


\[^{35}\text{Colors vary depending on both the display medium and the eye.}\]
gives the full 2x2 complex analytic function mapping \( w(x, y) = u(x, y) + v(x, y)j \), in colorized polar coordinates.

**Visualizing complex functions:** The mapping from \( z = x + iy \) to \( w(z) = u(x, y) + iv(x, y) \) is difficult to visualize because for each point in the domain \( z \), we would like to represent both the magnitude and phase (or real and imaginary parts) of \( w(z) \). A good way to visualize these mappings is to use color (hue) to represent the phase and intensity (dark to light) to represent the magnitude. The Octave/Matlab program \( zviz.m \) has been provided to do this (see Lecture 17 on the class website).

\[
\begin{align*}
\text{Example: } & \text{ Figure 3.8 shows a colorized plot of } \sin\left(\frac{\pi}{2}(z-i)/2\right) \text{ resulting from the Matlab/Octave command } zviz \sin\left(\frac{\pi}{2}(z-i)/2\right). \text{ The abscissa (horizontal axis) is the real } x \text{ axis and the ordinate (vertical axis) is the complex } iy \text{ axis. The graph is offset along the ordinate axis by } 1i, \text{ since the argument } z - i \text{ causes a shift of the sine function by } 1 \text{ in the positive imaginary direction. The visible zeros of } w(z) \text{ appear as dark regions at } (-2, 1), (0, 1), (2, 1). \text{ As a function of } x, w(x + 1j) \text{ oscillates between red (phase is zero degrees), meaning the function is positive and real, and sea-green (phase is } 180^\circ), \text{ meaning the function is negative and real.}
\end{align*}
\]

Along the vertical axis, the function is either a \( \cosh(y) \) or \( \sinh(y) \), depending on \( x \). The intensity becomes lighter as \( |w| \) increases, and white as \( w \to \infty \). The intensity becomes darker as \( |w| \) decreases, and black as \( w \to 0 \).

\[
\begin{align*}
\text{Example: } & \text{ Figure 3.9 shows a domain-color map allowing one to visualize complex mappings by the use of intensity (light/dark) to indicate magnitude, and color (hue) to indicate angle (phase). The white and black lines are the iso-real and iso-imaginary contours of the mapping. Left: This figure shows the domain-color map for the complex mapping from the } z = x + yj \text{ plane to the } w(z) = u + vj = e^{x+iy} \text{ plane, which goes to zero as } x \to -\infty, \text{ causing the domain-color map to become dark for } x < -2. \text{ The white and black lines are always perpendicular because } e^z \text{ is complex analytic everywhere. Right: This shows the principal value of the inverse function } u(x, y) + v((x, y)j = \log(x + y), \text{ which has a zero (dark) at } z = 1, \text{ since there } \log(1) = 0 \text{ (the imaginary part is zero). Note the branch cut from } x = [0, -\infty). \text{ On branches other than the one shown, there are no zeros since the phase } (\angle z = 2\pi n \in \mathbb{Z}) \text{ is not zero. } n \text{ is called the branch index.}
\end{align*}
\]
**Example:** Two additional examples are given in Fig. 3.9 using the notation \( w(z) = u(x,y) + v(x,y)j \) showing the two complex mappings \( w = e^\sigma \) (left) and its inverse \( s = \ln(w) \). The exponential is relatively easy to understand because \( w(s) = |e^{\sigma e^{\omega}}| = e^\sigma \).

The red region is where \( \omega \approx 0 \) in which case \( w \approx e^\sigma \). As \( \sigma \) becomes large and negative, \( w \to 0 \), thus the entire field becomes dark on the left. The field is becoming light on the right where \( w = e^\sigma \to \infty \).

If we let \( \sigma = 0 \) and look along the \( \omega \) axis, we see that the function is changing phase, sea-green (90°) at the top and violet (-90°) at the bottom.

In the right panel note the zero for \( \ln(w) = \ln|w| + \omega j \) at \( w = 1 \). The root of the log function is \( \log(w) = 0 \), \( w_r = 1 \), \( \phi = 0 \), since \( \log(1) = 0 \). More generally, the log of \( w = |w|e^{\phi j} \) is \( s = \ln|w| + \phi j \).

Thus \( s(w) \) can be zero only when the angle of \( w \) is zero.

The \( \ln(w) \) function has a branch cut along the \( \phi = 180 \)° axis. As one crosses over the cut, the phase goes above 180°, and the plane changes to the next sheet of the log function. The only sheet with a zero is the principle value, as shown. For all others, the log function is either increasing or decreasing monotonically, and there is no zero, as seen for sheet 0 (the one showing in Fig. 3.9).

### 3.8.1 Riemann Sphere: 3° extension of chord and tangent method

Once algebra was formulated by c830 CE, mathematicians were able to expand beyond the limits set by geometry on the real plane, and the verbose descriptions of each problem in prose (Stillwell, 2010, p. 93). The geometry of Euclid’s *Elements* had paved the way, but after 2000 years, the addition of the language of algebra changed everything. The analytic function was a key development, heavily used by both Newton and Euler. Also the investigations of Cauchy made important headway with his work on complex variables. Of special note was integration and differentiation in the complex plane of complex analytic functions, which is the topic of stream 3.

It was Riemann, working with Gauss in the final years of Gauss’s life, who made the breakthrough, with the concept of the extended complex plane. This concept was based on the composition of a line with the sphere, similar to the derivation of Euclid’s formula for Pythagorean triplets (Fig. 3.4, p. 98). While the importance of the extended complex plane was unforeseen, it changed analytic mathematics forever, along with the physics it supported. It unified and thus simplified many important integrals, to the extreme. The basic idea is captured by the fundamental theorem of complex integral calculus (Table 4.1, p. 147).

![Riemann Sphere Diagram](image-url)

Figure 3.10: The left panel shows how the real line may be composed with the circle. Each real \( x \) value maps to a corresponding point \( x' \) on the unit circle. The point \( x \to \infty \) maps to the north pole \( N \). This simple idea may be extended with the composition of the complex plane with the unit sphere, thus mapping the plane onto the sphere. As with the circle, the point on the complex plane \( z \to \infty \) maps onto the north pole \( N \). This construction is important because while the plane is open (does not include \( z \to \infty \)), the sphere is analytic at the north pole. Thus the sphere defines the closed extended plane. Figure adapted from Stillwell (2010, pp. 299-300).

The idea is outlined in Fig. 3.10. On the left is a circle and a line. The difference between this case and the derivation of the Pythagorean triplets is that the line starts at the north pole, and ends on the
real \( x \in \mathbb{R} \) axis at point \( x \). At point \( x' \), the line cuts through the circle. Thus the mapping from \( x \) to \( x' \) takes every point on \( \mathbb{R} \) to a point on the circle. For example, the point \( x = 0 \) maps to the south pole (not indicated). To express \( x' \) in terms of \( x \) one must compose the line and the circle, similar to the composition used in Fig. 3.4 (p. 98). The points on the circle, indicated here by \( x' \), require a traditional polar coordinate system, having a unit radius and an angle defined between the radius and a vertical line passing through the north pole. When \( x \to \infty \) the point \( x' \to \infty \), known as the point at infinity. But this idea goes much further, as shown on the right half of Fig. 3.10.

Here the real tangent line is replaced by a tangent complex plane \( z \in \mathbb{C} \), and the complex puncture point \( z' \in \mathbb{C} \), in this case on the complex sphere, called the extended complex plane. This is a natural extension of the chord/tangent method on the left, but with significant consequences. The main difference between the complex plane \( z \) and the extended complex plane, other than the coordinate system, is what happens at the north pole. The point at \( |z| = \infty \) is not defined on the plane, whereas on the sphere, the point at the north pole is simply another point, like every other point on the sphere.

**Open vs. closed sets:** Mathematically the plane is said to be an open set, since the limit \( z \to \infty \) is not defined, whereas on the sphere, the point \( z' \) is a member of a closed set, since the north pole is defined. The distinction between an open and closed set is important, because the closed set allows the function to be complex analytic at the north pole, which it cannot be on the plane (since the point at infinity is not defined).

The \( z \) plane may be replaced with another plane, say the \( w = F(z) \in \mathbb{C} \) plane, where \( w \) is some function \( F \) of \( z \in \mathbb{C} \). For the moment we shall limit ourselves to complex analytic functions of \( z \), namely \( w = F(z) = u(x, y) + v(x, y)j = \sum_{n=0}^{\infty} c_n z^n \).

In summary, given a point \( z = x + yj \) on the open complex plane, we map it to \( w = F(z) \in \mathbb{C} \), the complex \( w = u + vj \) plane, and from there to the closed extended complex plane \( w'(z) \). The point of doing this is that it allows us to allow the function \( w'(z) \) to be analytic at the north pole, meaning it can have a convergent Taylor series at the point at infinity \( z \to \infty \). Since we have not yet defined \( dw(z)/dz \), the concept of a complex Taylor series remains undefined.

### 3.8.2 Bilinear transformation

In mathematics the **bilinear transformation** has special importance because it is linear in its action on both the input and output variables. Since we are engineers we shall stick with the engineering terminology. But if you wish to read about this on the internet, be sure to also search for the mathematical term, Möbius transformation.

When a point on the complex plane \( z = x + yj \) is composed with the bilinear transform \( (a, b, c, d \in \mathbb{C}) \), the result is \( w(z) = u(x, y) + v(x, y)j \)

\[
\begin{align*}
w &= \frac{az + b}{cz + d}. \quad (3.51)
\end{align*}
\]

The transformation from \( z \to w \) is a cascade of four independent compositions:

1. translation \( (w = z + b; \ a = 1, b \in \mathbb{C}, c = 0, d = 1) \),
2. scaling \( (w = |a|z; \ a \in \mathbb{R}, b = 0, c = 0, d = 1) \),
3. rotation \( (w = \frac{a}{|a|}z; \ a \in \mathbb{C}, b = 0, c = 0, d = |a|) \) and
4. inversion \( (w = \frac{1}{z}; \ a = 0, b = 1, c = 1, d = 0) \).

Each of these transformations is a special case of Eq. 3.51, with the inversion the most complicated. I highly recommend a video showing the effect of the bilinear (Möbius) transformation on the plane.\(^{37}\)

\(^{37}\)https://www.youtube.com/watch?v=0zlI8UNr04
The bilinear transformation is the most general way to move the expansion point in a complex analytic expansion. For example, starting from the harmonic series, the bilinear transform gives

\[
\frac{1}{1 - w} = \frac{1}{1 - \frac{az + b}{cz + d}} = \frac{cz + d}{(c - a)z + (d - b)}.
\]

The RoC is transformed from \(|w| < 1\) to \(|(az - b)/(cz - d)| < 1\). An interesting application might be in moving the expansion point until it is on top of the nearest pole, so that the RoC goes to zero. This might be a useful way of finding a pole, for example.

When the extended plane (Riemann sphere) is analytic at \(z = \infty\), one may take the derivatives there, defining the Taylor series with the expansion point at \(\infty\). When the bilinear transformation rotates the Riemann sphere, the point at infinity is translated to a finite point on the complex plane, revealing the analytic nature at infinity. A second way to transform the point at infinity is by the bilinear transformation \(\zeta = 1/z\), mapping a zero (or pole) at \(z = \infty\) to a pole (or zero) at \(\zeta = 0\). Thus this construction of the Riemann sphere and the Möbius (bilinear) transformation allows us to understand the point at infinity, and treat it like any other point. If you felt that you never understood the meaning of the point at \(\infty\) (likely), this should help.
3.8.3 Exercises AE-3

**Topic of this homework:** Visualizing complex functions; Bilinear/Möbius transform; Riemann sphere.

1. **Fundamental theorem of algebra (FTA)**
   - State the fundamental theorem of algebra (FTA).

2. **Algebra with complex variables**
   (a) One can always say that 3 < 4, namely that real numbers have order. One way to view this is to take the difference, and compare to zero, as in 4 − 3 > 0. Here, we will explore how complex variables may be ordered. Define the complex variable \( z = x + iy \) ∈ \( \mathbb{C} \).
   - i. Explain the meaning of \( |z_1| > |z_2| \).
   - ii. If \( x_1, x_2 \in \mathbb{R} \) (are real numbers), define the meaning of \( x_1 > x_2 \). **Hint:** Take the difference.
   - iii. Explain the meaning of \( z_1 > z_2 \).
   - iv. (not graded) If time were complex how might the world be different?

   (b) It is sometimes necessary to consider a function \( w(z) = u + iv \) in terms of the real functions, \( u(x, y) \) and \( v(x, y) \) (e.g. separate the real and imaginary parts). Similarly, we can consider the inverse \( z(w) = x + iy \) where \( x(u, v) \) and \( y(u, v) \) are real functions.
   - i. Find \( u(x, y) \) and \( v(x, y) \) for \( w(z) = 1/z \).
   - ii. Find \( u(x, y) \) and \( v(x, y) \) for \( w(z) = e^z \) with complex constant \( e \in \mathbb{C} \) for the following cases
     - A. \( c = e \)
     - B. \( c = 1 \) (recall that 1 = \( e^{i2\pi k} \) for \( k = 0, 1, 2, \ldots \))
     - iii. \( c = j \). **Hint:** \( j = e^{j\pi} \).
   - iv. Find \( u(x, y) \) for \( w(z) = \sqrt{z} \). **Hint:** Begin with the inverse function \( z = w^2 \).

3. **Möbius transforms and infinity**

   **The bilinear transform:** The **bilinear z transform** is used in signal processing to design a digital (discrete-time) filter \( H(z) \) starting from analog (continuous time) filter design \( H(s) \). The goal of the bilinear transform is to take a function of “analog frequency” \( \omega_a \), where \( \omega_a \in (-\infty, \infty) \), and map it to a finite “digital frequency” range, \( \omega_d \in [-\pi, \pi] \).

   **To do:**
   (a) You are given the analog low-pass filter \( h(t) = e^{-t}u(t) \) which has a frequency response given by
   \[
   H(s) = \frac{1}{s + 1} = \int_0^\infty h(t)e^{-st}dt.
   \]
   Use the bilinear z transform (Eq. ??) to find the discrete time filter \( H(z) \). **Hint:** Use the Matlab/Octave command `help bilinear`. Your answer should be a composition of \( H(s) \) and Eq. ??.
(b) Substitute \( s = j\omega_a \) and \( z = e^{j\omega_d} \) (\( \sigma_a, \sigma_d = 0 \)) into the Eq. ?? to determine the relationship between \( \omega_a, \omega_d \). Express your final result using a tangent function. Hint: Try to form sine and cosine terms! Recall that \( \sin(\omega) = (e^{j\omega} - e^{-j\omega})/2j \) and \( \cos(\omega) = (e^{j\omega} + e^{-j\omega})/2 \).

(c) By hand, draw a graph of the relationship you found the previous part, \( \omega_a = f(\omega_d) \). Make sure to specify the behavior of \( \omega_a \) at \( \omega_d = 0, \pm \pi/2, \pm \pi \).

(d) Explain how this relationship maps the analog frequency \( \omega_a \to \pm \infty \) to a the digital frequency \( \omega_d \).

(e) Draw the \( s \) and \( z \) planes, showing the real parts on the horizontal axes and the imaginary parts on the vertical axes. Mark (e.g. using thick lines) which sets of values are considered when \( \sigma_a, \sigma_d = 0 \).

(f) Geometrically, what is the effect of this Möbius transform? Consider your drawing in the previous part.

4. Probability

Many things in life follow rules we don’t understand, that are not predictable, yet have structure due to some underlying physics. Unlike mathematicians, engineers are taught to learn to deal with such uncertainty, in terms of random processes and probability theory. For many this starts out as a large set of boring incomprehensible definitions, but once you begin to understand it, becomes interesting mathematics. It needs to be in your skin. If you don’t have an intuition for it, either keep working on it, or else find another job. Don’t memorize a bunch of formulae because that won’t work over the long run.

Some view probability as combinatorics. This is wrong. It is much more than that. From my auditory view of speech in noise, probability is about the signal processing of noise and signals (i.e., not combinatorics).

Definitions:

(a) An event is the term to describe an unpredictable outcome.

Example: Measuring the temperature \( T(x,t) \in \mathbb{R} \) with \( x \in \mathbb{R}^3 \) at time \( t \) [s] is an event.

Example: Measuring the temperature every hour gives 24 events per day, with degrees as the units.

Example: The single toss of a coin, resulting in \( \{H,T\} \), is an unpredictable event.

Exercise: What are the units of a coin toss?

Exercise: What are the units of \( H, T \)?

(b) A trial is \( N \) events.

(c) An experiment \( \{M,N\} \) is defined as \( M \) trials of \( N \) events.

(d) Number of events: One must always keep track of the number of events so that one can compute the mean (i.e., average) and the uncertainty of an observable outcome.

(e) The mean of many trials is the average.

(f) A random variable \( X \) is defined as the outcome from an experiment. A random variable rarely has stated units.
Example: Flipping a coin $N = 8$ times defines the number of trials.

$$X \equiv \{H, H, H, T, H, T, T, T\}.$$ 

Exercise: How do you take the mean of something that doesn’t have units?

(g) The Expected value is the mean of $N$ events.

Example: The average temperature is the mean over $N$ events.

Exercise: What is the difference between the mean, expected value and the average?

Exercise: To assign a mean one must define the outcomes by numbers. If we let $H = 1$ and $T = 0$ then the mean is

$$\mu = (1 + 1 + 1 + 0 + 1 + 0 + 0 + 0)/8 = 1/2.$$ 

(h) It is critically important to keep track of the number of events ($N = 8$ in the above example) because $N$ is more important than the actual measured sequence.

(i) It is helpful to think of $N$ as the independent variable and $X$ as the dependent variable. For example, think of $X(N)$ rather than $N(X)$. Concentrate on the fixed $N$, not the random sequence.

Example: To form a trial by flipping a coin $N = 10$ times. We form an experiment by $M$ repeated trials ($M = 1000$).

Problem #4: Basic terminology of experiments

–Q 4.1: What is the mean of a trial, and what is the average over all trials?

–Q 4.2: What is the “expected value” of a random variable $X$?

–Q 4.3: What is the standard deviation about the mean?

–Q 4.4: What is the definition of “information” of a random variable?

–Q 4.5: What is the “entropy” of a random variable?

–Q 4.6: What is the “sampling noise” of a random variable?
Chapter 4

Stream 3a: Scalar (i.e., Ordinary) Differential Equations

Stream 3 is $\infty$, a concept which typically means unbounded (immeasurably large), but in the case of calculus, $\infty$ means infinitesimal (immeasurably small), since taking a limit requires small numbers. Taking a limit means you may never reach the target, a concept that the Greeks called Zeno’s paradox (Stillwell, 2010, p. 76).

When speaking of the class of ordinary (versus vector) differential equations, the term scalar is preferable, since the term “ordinary” is vague, if not a meaningless label. There is a special subset of fundamental theorems for scalar calculus, all of which are about integration, as summarized in Table 4.1 (p. 147), starting with Leibniz’s theorem. These will be discussed below, and more extensively in Lec. 4.2 (p. 146) and Sections 4 (p. 143) and 5 (p. 143).

Chronological history post 16th century

16th
- Bombelli 1526–1572
- Galileo 1564–1642, Kepler 1571–1630, Newton 1642–1727, Principia 1687; Mersenne; Huygens; Pascal; Fermat, Descartes (analytic geometry); and the three Bernoullis (Jakob, Johann & son Daniel)

17th
- Euler 1707–1783 (Student of Johann Bernoulli), d’Alembert 1717–1783, Laprange 1736–1833, Lagrange 1749–1827, Fourier 1768–1830, Gauss 1777–1855, Cauchy 1789–1857,
- Helmholtz 1821–1894, Kelvin 1824–1907, Helmholtz 1821–1894

18th

19th
- Hilbert 1862–1942, Einstein 1879–1955

Following the integral theorems on scalar calculus are those on vector calculus, without which there could be no understanding of Maxwell’s equations. Of these, the fundamental theorem of complex calculus (aka, Helmholtz decomposition), Gauss’s law and Stokes’s theorem form the cornerstone of modern vector field analysis. These theorems allow one to connect the differential (point) and macroscopic (integral) relationships. For example, Maxwell’s equations may be written as either vector differential equations, as shown by Heaviside (along with Gibbs and Hertz), or in integral form. It is helpful to place these two forms side-by-side, to fully appreciate their significance. To understand the differential (microscopic) view, one must understand the integral (macroscopic) view. These are presented in Section 5.5 (p. 218) and Fig. 5.7 (p. 221).

4.1 The beginning of modern mathematics

As outlined in Fig. 4.1, mathematics as we know it today began in the 16th to 18th centuries, arguably starting with Galileo, Descartes, Fermat, Newton, the Bernoulli family, and Euler. Galileo

was formidable, due to his fame, fortune, and his “successful” stance against the powerful Catholic establishment. His creativity in scientific circles was certainly well known due to his many skills and accomplishments. Descartes and Fermat were at the forefront of merging algebra and geometry. While Fermat kept meticulous notebooks, he did not publish, and tended to be secretive. Thus Descartes’ contributions were more widely acknowledged, but not necessarily deeper.

Regarding the development of calculus, much was yet to be done by Newton and Leibniz, using term-by-term integration of functions based on Taylor series representation. This was a powerful technique, but as stated earlier, incomplete because the Taylor series can only represent single-valued functions, within the RoC. But more importantly, Newton (and others) failed to recognize the powerful generalization to complex analytic functions. The first major breakthrough was Newton’s publication of *Principia* (1687), and the second was Riemann (1851), advised by Gauss.

Following Newton’s lead, the secretive and introverted behavior of the typical mathematician dramatically changed with the Bernoulli family (Fig. 4.1). The oldest brother Jacob taught his much younger brother Johann, who then taught his son Daniel. But Johann’s star pupil was Euler. Euler first mastered all the tools and then published, with a prolificacy previously unknown.

**Euler and the circular functions:** The first major task was to understand the family of analytic circular functions, $e^x$, $\sin(x)$, $\cos(x)$, and $\log(x)$, a task begun by the Bernoulli family, but mastered by Euler. Euler sought relations between these many functions, some of which may not be thought of as being related, such as the log and sin functions. The connection that may “easily” be made is through their complex Taylor series representation (Eq. 3.28, p. 87). By the manipulation of the analytic series representations, the relationship between $e^x$, and the $\sin(x)$ and $\cos(x)$, was precisely captured with the relation

$$e^{j\omega} = \cos(\omega) + j\sin(\omega),$$

and its analytic inverse (Greenberg, 1988, p. 1135)

$$\tan^{-1}(z) = \frac{1}{2j} \ln \left( \frac{1j - z}{1j + z} \right).$$

The phase is $\phi(\omega) = \angle z$, from which one may compute the group delay

$$\tau_g(\omega) = -\frac{1}{2\pi} \frac{\partial \phi(\omega)}{\partial \omega}.$$
Exercise: Starting from Eq. 4.1, derive Eq. 4.2. Solution: Let \( z(\omega) = \tan \omega \), then

\[
    z(\omega) = \frac{\sin \omega}{\cos \omega} = \tan(\omega) = -j\frac{e^{j\omega} - e^{-j\omega}}{e^{j\omega} + e^{-j\omega}} = -j\frac{e^{2j\omega} - 1}{e^{2j\omega} + 1}.
\]  

(4.3)

Solving this for \( e^{2j\omega} \) gives

\[
    e^{2j\omega} = \frac{1 + zj}{1 - zj}.
\]  

(4.4)

Taking the square root results in the analytic relationship between \( e^{j\omega} \) and \( j \tan \omega \)

\[
    e^{j\omega} = \pm \sqrt{\frac{1 + zj}{1 - zj}}.
\]

Taking the log, and using the definition of \( \omega(z) = \tan^{-1}(z) \), we obtain Eq. 4.2.

These equations are the basis of transmission lines (TL) and the Smith chart. Here \( z(\omega) \) is the TL’s input impedance and Eq. 4.4 is the reflectance.

![Colorized plots of \( \omega(z) = \tan^{-1}(z) \) and \( \omega(z) = \frac{j}{2}\ln(1 - iz)/(1 + iz) \).](image)

Figure 4.2: Colorized plots of \( \omega(z) = \tan^{-1}(z) \) and \( \omega(z) = \frac{j}{2}\ln(1 - iz)/(1 + iz) \), verifying they are the same complex analytic function.

While many high school students memorize Euler’s relation, it seems unlikely they appreciate the significance of complex analytic functions (Eq. 3.39, p. 92).

**A brief history of complex analytic functions:** Newton famously ignored imaginary numbers, and called them imaginary in a disparaging (pejorative) way. Given Newton’s prominence, his view certainly must have keenly attenuated interest in complex algebra, even though it had been previously quantified by Bombelli in 1525, likely based on his serendipitous finding of Diophantus’s book *Arithmetic* in the Vatican library.

Euler derived his relationships using real power series (i.e., real analytic functions). While Euler was fluent with \( j = \sqrt{-1} \), he did not consider functions to be complex analytic. That concept was first explored by Cauchy almost a century later. The missing link to the concept of complex analytic is the definition of the derivative with respect to the complex argument

\[
    F'(s) = \frac{dF(s)}{ds},
\]  

(4.5)

where \( s = \sigma + \omega j \), without which the complex analytic Taylor coefficients may not be defined.

Euler did not appreciate the role of complex analytic functions because these were first discovered well after his death (1785) by Augustin-Louis Cauchy (1789–1857), by Riemann in 1851.
4.2 Lec 23: Fundamental theorems of scalar calculus

History of the fundamental theorem of scalar calculus: It some sense, the story of calculus begins with the fundamental theorem of calculus (FTC), also known generically as Leibniz’s formula. The simplest integral is the length of a line \( L = \int_0^L dx \). If we label a point on a line as \( x = 0 \) and wish to measure the distance to any other point \( x \), we form the line integral between the two points. If the line is straight, this integral is simply the Euclidean length given by the difference between the two ends (Eq. 3.4, p. 112).

If \( F(\chi) \in \mathbb{R} \) describes a height above the line \( \chi \in \mathbb{R} \), then

\[
 f(x) - f(0) = \int_{x=0}^x F(\chi) d\chi \tag{4.6}
\]

may be viewed as the anti-derivative of \( F(\chi) \). Here \( \chi \) is a dummy variable of integration. Thus the area under \( F(\chi) \) only depends on the difference of the area evaluated at the end points. It makes intuitive sense to view \( f(x) \) as the anti-derivative of \( F(\chi) \).

This property of the area as an integral over an interval, only depending on the end points, has important consequences in physics in terms of conservation of energy, allowing for important generalizations. For example, as long as \( \chi \in \mathbb{R} \), one may let \( F(\chi) \in \mathbb{C} \) with no loss of generality, due to the linear propriety (P1, p. 132) of the integral.

If \( f(x) \) is analytic (Eq. 3.27, p. 87), then

\[
 F(x) = \frac{d}{dx} f(x) \tag{4.7}
\]

is an exact real differential. It follows that \( F(x) \) is analytic. This is known as the fundamental theorem of (real) calculus (FTC). Thus Eq. 4.7 may be viewed as an exact real differential. This is easily shown by evaluating

\[
 \frac{d}{dx} f(x) = \lim_{\delta \to 0} \frac{f(x + \delta) - f(x)}{\delta} = F(x),
\]

starting from the anti-derivative Eq. 4.6. If \( f(x) \) is not analytic then the limit may not exist, so this is a necessary condition.

There are many important variations on this very basic theorem (i.e., Sect. 4, p. 143). For example, the limits could depend on time. Also when taking Fourier transforms, the integrand depends on both time \( t \in \mathbb{R} \) and frequency \( \omega \in \mathbb{R} \) via a complex exponential “kernel” function \( e^{\pm \text{i} \omega t} \in \mathbb{C} \), which is analytic in both \( t \) and \( \omega \).

4.2.1 The fundamental theorems of complex calculus:

The fundamental theorem of complex calculus (FTCC) states (Greenberg, 1988, p. 1197) that for any complex analytic function \( F(s) \in \mathbb{C} \) with \( s = \sigma + \omega \text{j} \in \mathbb{C} \),

\[
 f(s) - f(s_o) = \int_{s_o}^s F(\zeta) d\zeta. \tag{4.8}
\]

Equations 4.6 and 4.8 differ because the path of the integral is complex. Thus the line integral is over \( s \in \mathbb{C} \) rather than a real integral over \( \chi \in \mathbb{R} \). The fundamental theorem of complex calculus (FTCC) states that the integral only depends on the end points, since

\[
 F(s) = \frac{d}{ds} f(s). \tag{4.9}
\]

Comparing exact differentials Eq. 4.5 (FTCC) and Eq. 4.7 (FTC), we see that \( f(s) \in \mathbb{C} \) must be complex analytic, and have a Taylor series in powers in \( s \in \mathbb{C} \). It follows that \( F(s) \) is also complex analytic.
Complex analytic functions: The definition of a complex analytic function $F(s) \in \mathbb{C}$ is that the function may be expanded in a Taylor series (Eq. 3.38, p. 92) about an expansion point $s_0 \in \mathbb{C}$. This definition follows the same logic as the FTC. Thus we need a definition for the coefficients $c_n \in \mathbb{C}$, which most naturally follow from Taylor’s formula

$$c_n = \frac{1}{n!} \frac{d^n F(s)}{ds^n} \bigg|_{s=s_0}. \quad (4.10)$$

The requirement that $F(s)$ have a Taylor series naturally follows by taking derivatives with respect to $s$ at $s_0$. The problem is that both integration and differentiation of functions of complex Laplace frequency $s = \sigma + j\omega$ have not yet been defined. Thus the question is: What does it mean to take the derivative of a function $F(s) \in \mathbb{C}$, $s = \sigma + j\omega \in \mathbb{C}$, with respect to $s$, where $s$ defines a plane rather than a real line? We learned how to form the derivative on the real line. Can the same derivative concept be extended to the complex plane?

The answer is affirmative. The question may be resolved by applying the rules of the real derivative when defining the derivative in the complex plane. However, for the complex case, there is an issue regarding direction. Given any analytic function $F(s)$, is the partial derivative with respect to $\sigma$ different from the partial derivative with respect to $j\omega$? For complex analytic functions, the FTC states that the integral is independent of the path in the $s$ plane. Based on the chain rule, the derivative must also be independent of direction at $s_0$. This directly follows from the FTCC. If the integral of a function of a complex variable is to be independent of the path, the derivative of a function with respect to a complex variable must be independent of the direction. This follows from Taylor’s formula, Eq. 4.10, for the coefficients of the complex analytic formula.

The Cauchy-Riemann conditions: The FTC defines the area as an integral over a real differential $(dx \in \mathbb{R})$, while the FTCC relates an integral over a complex function $F(s) \in \mathbb{C}$, along a complex interval (i.e., path) $(ds \in \mathbb{C})$. For the FTC the area under the curve only depends on the end points of the anti-derivative $f(x)$. But what is the meaning of an “area” along a complex path? The Cauchy-Riemann conditions provide the answer.

Table 4.1: Summary of the fundamental theorems of integral calculus, each of which deals with integration. There are at least two main theorems related to scalar calculus, and three more for vector calculus.

<table>
<thead>
<tr>
<th>Name</th>
<th>Mapping</th>
<th>p.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leibniz (FTC)</td>
<td>$\mathbb{R}^1 \rightarrow \mathbb{R}^0$</td>
<td>146</td>
<td>Area under a real curve</td>
</tr>
<tr>
<td>Cauchy (FTCC)</td>
<td>$\mathbb{C}^1 \rightarrow \mathbb{R}^0$</td>
<td>146</td>
<td>Area under a complex curve</td>
</tr>
<tr>
<td>Cauchy’s theorem</td>
<td>$\mathbb{C}^1 \rightarrow \mathbb{C}^0$</td>
<td>163</td>
<td>Close integral over analytic region is zero</td>
</tr>
<tr>
<td>Cauchy’s integral formula</td>
<td>$\mathbb{C}^1 \rightarrow \mathbb{C}^0$</td>
<td>163</td>
<td>Fundamental theorem of complex integral calculus</td>
</tr>
<tr>
<td>residue theorem</td>
<td>$\mathbb{C}^1 \rightarrow \mathbb{C}^0$</td>
<td>163</td>
<td>Residue integration</td>
</tr>
</tbody>
</table>

4.2.2 Lec 24: Cauchy-Riemann conditions

For the integral of $Z(s) = R(\sigma, \omega) + X(\sigma, \omega)j$ to be independent of the path, the derivative of $Z(s)$ must be independent of the direction of the derivative. As we show next, this leads to a pair of equations known as the Cauchy-Riemann conditions. This is an important generalization of Eq. 1.1 (p. 19), which goes from real integration ($x \in \mathbb{R}$) to complex integration ($s \in \mathbb{C}$) based on lengths, thus on area.

To define

$$\frac{d}{ds} Z(s) = \frac{d}{ds} [R(\sigma, \omega) + jX(\sigma, \omega)],$$

take partial derivatives of $Z(s)$ with respect to $\sigma$ and $j\omega$, and equate them:

$$\frac{\partial Z}{\partial \sigma} = \frac{\partial R}{\partial \sigma} + j\frac{\partial X}{\partial \sigma} = \frac{\partial Z}{\partial j\omega} = \frac{\partial R}{\partial j\omega} + j\frac{\partial X}{\partial j\omega}.$$
This says that a horizontal derivative, with respect to \( \sigma \), is equivalent to a vertical derivative, with respect to \( \omega \). Taking the real and imaginary parts gives the two equations

\[
\begin{align*}
\text{CR-1: } \frac{\partial R(\sigma, \omega)}{\partial \sigma} &= \frac{J \partial X(\sigma, \omega)}{\partial \omega} \\
\text{CR-2: } \frac{\partial R(\sigma, \omega)}{\partial \omega} &= -J \frac{\partial X(\sigma, \omega)}{\partial \sigma},
\end{align*}
\]

(4.11)

known as the Cauchy-Riemann (CR) conditions. The \( J \) cancels in CR-1, but introduces a \( J^2 = -1 \) in CR-2. They may also be written in polar coordinates \((s = re^{j\theta})\) as

\[
\begin{align*}
\frac{\partial R}{\partial r} &= \frac{1}{r} \frac{\partial X}{\partial \theta} \\
\frac{\partial X}{\partial r} &= -\frac{1}{r} \frac{\partial R}{\partial \theta}.
\end{align*}
\]

If you are wondering what would happen if we took a derivative at 45 degrees, then we only need to multiply the function by \( e^{\pi/4} \). But doing so will not change the derivative. Thus we may take the derivative in any direction by multiplying by \( e^{j\theta} \), and the CR conditions will not change.

The CR conditions are necessary conditions that the integral of \( Z(s) \), and thus its derivative, be independent of the path, expressed in terms of conditions on the real and imaginary parts of \( Z \). This is a very strong condition on \( Z(s) \), which follows assuming that \( Z(s) \) may be written as a Taylor series in \( s \):

\[
Z(s) = Z_o + Z_1 s + \frac{1}{2} Z_2 s^2 + \cdots,
\]

(4.12)

where \( Z_n \in \mathbb{C} \) are complex constants given by the Taylor series formula (Eq. 4.10, p. 147). As with the real Taylor series, there is the convergence condition, that \( |s| < 1 \), called the radius of convergence (RoC). This is an important generalization of the region of convergence (RoC) for real \( s = x \).

Every function that may be expressed as a Taylor series in \( s - s_o \) about point \( s_o \in \mathbb{C} \) is said to be complex analytic at \( s_o \). This series, which must be single valued, is said to converge within a radius of convergence (RoC). This highly restrictive condition has significant physical consequences. For example, every impedance function \( Z(s) \) obeys the CR conditions over large regions of the \( s \) plane, including the entire right half-plane (RHP) \((\sigma > 0)\). This condition is summarized by the Brune condition \( \Re\{Z(\sigma > 0)\} \geq 0 \) (Section 4.3, Eq. 4.20, p. 151). When the CR condition is generalized to volume integrals, it is called Green’s theorem, used heavily in the solution of boundary value problems in engineering and physics (Kusse and Westwig, 2010). Sections 4 (p. 143) and 5 (p. 183) depend heavily on these concepts.

We may merge these equations into a pair of second-order equations by taking a second round of partials. Specifically, eliminating the real part \( R(\sigma, \omega) \) of Eq. 4.11 gives

\[
\frac{\partial^2 R(\sigma, \omega)}{\partial \sigma \partial \omega} = \frac{\partial^2 X(\sigma, \omega)}{\partial \omega^2} = -\frac{\partial^2 X(\sigma, \omega)}{\partial \sigma^2},
\]

(4.13)

which may be compactly written as \( \nabla^2 X(\sigma, \omega) = 0 \). Eliminating the imaginary part gives

\[
\frac{\partial^2 X(\sigma, \omega)}{\partial \omega \partial \sigma} = \frac{\partial^2 R(\sigma, \omega)}{\partial \sigma^2} = -\frac{\partial^2 R(\sigma, \omega)}{\partial \omega^2},
\]

(4.14)

which may be written as \( \nabla^2 R(\sigma, \omega) = 0 \).

In summary, for a function \( Z(s) \) to be complex analytic, the derivative \( dZ/ds \) must be independent of direction (path), which requires that the real and imaginary parts of the function obey Laplace’s equation, i.e.,

\[
\text{CR-3: } \nabla^2 R(\sigma, \omega) = 0 \quad \text{and} \quad \text{CR-4: } \nabla^2 X(\sigma, \omega) = 0.
\]

(4.15)

The CR equations are easier to work with because they are first-order, but the physical intuition is best understood by noting two facts (1) the derivative of a complex analytic function is independent of its direction, and (2) the real and imaginary parts of the function both obey Laplace’s equation. Such relationships are known as harmonic functions.\(^2\)

\(^2\)When the function is the ratio of two polynomials, as in the cases of the Brune impedance, they are also related to Möbius transformations, also known as bi-harmonic operators.
As we shall see in the next few lectures, complex analytic functions must be smooth since every analytic function may be differentiated an infinite number of times, within the RoC. The magnitude must attain its maximum and minimum on the boundary. For example, when you stretch a rubber sheet over a jagged frame, the height of the rubber sheet obeys Laplace’s equation. Nowhere can the height of the sheet rise above or below its value at the boundary.

Harmonic functions define conservative fields, which means that energy (like a volume or area) is conserved. The work done in moving a mass from $a$ to $b$ in such a field is conserved. If you return the mass from $b$ back to $a$, the energy is retrieved, and zero net work has been done.

### 4.3 Lec 25: Complex Analytic functions and Brune Impedance

It is rarely stated that the variable that we are integrating over, either $x$ (space) or $t$ (time), is real ($x, t \in \mathbb{R}$), since that fact is implicit, due to the physical nature of the formulation of the integral. But this intuition must be refined once complex numbers are included with $s \in \mathbb{C}$, where $s = \sigma + \omega j$.

That time and space are real variables is more than an assumption: it is a requirement that follows from the real order property. Real numbers have order. For example, if $t = 0$ is now (the present), then $t < 0$ is the past and $t > 0$ is the future. The order property of time and space allows one to order these along a real axis. To have time travel, time and space would need to be complex (they are not), since if the space axis were complex, as in frequency $s$, the order property would be invalid. It follows that if we require order, time and space must be real ($t, x \in \mathbb{R}$). Interestingly, it was shown by d’Alembert (1747) that time and space are related by the pure delay due to the wave speed $c_o$. To obtain a solution to the governing wave equation, which d’Alembert first proposed for sound waves, $x, t \in \mathbb{R}^3$ may be combined as functions of

$$\zeta_{\pm} = t \pm x/c_o,$$

where $c [\text{m/s}]$ is the phase velocity of the waves. The d’Alembert solution to the wave equation, describing waves on a string under tension, is

$$u(x, t) = f(t - x/c_o) + g(t + x/c_o), \quad (4.16)$$

which describes the transverse velocity (or displacement) of two independent waves $f(\zeta_-)$, $g(\zeta_+)$ on the string, which represent forward and backward traveling waves.\(^3\) For example, starting with a string at rest, if one displaces the left end, at $x = 0$, by a step function $u(t)$, then that step displacement will propagate to the right as $u(t - x/c_o)$, arriving at location $x_o [\text{m}]$, at time $x_o/c_o [\text{s}]$. Before this time, the string will not move to the right of the wave-front, at $x_o [\text{m}]$, and after $t_o [\text{s}]$ it will have displacement 1. Since the wave equation obeys superposition (postulate P1, p. 132), it follows that the “plane-wave” eigenfunctions of the wave equation for $x, k \in \mathbb{R}^3$ are given by

$$\psi_{\pm}(x, t) = \delta(t \mp k \cdot x) \leftrightarrow e^{\pm j k \cdot x}, \quad (4.17)$$

where $|k| = 2\pi/|\lambda| = \omega/c_o$ is the wave number, $|\lambda|$ is the wavelength, and $s = \sigma + \omega j$, the Laplace frequency.

When propagation losses are considered, we must replace the wave number $jk$ with a complex analytic vector wave number $k(s) = k_r(s) + jk(s)$, which is denoted as either the complex propagation function, propagation function, or the dispersion relation. The vector complex propagation function is a key generalization of the scalar wave number $k = 2\pi/\lambda$.

Forms of loss include viscosity and radiation. Important examples include acoustic plane waves, electromagnetic wave propagation, antenna theory, and the more complex case of 3D electron wave propagating in crystals (i.e., silicon), where electrons and EM waves are in a state of equilibrium.

\(^3\)d’Alembert’s solution is valid for functions that are not differentiable, such as $\delta(t - c_o x)$.
Electrons and photons are simply different EM states, where $\kappa(\mathbf{x}, s)$ describes the crystal’s dispersion relations as functions of both frequency and direction, famously known as Brillouin zones. Dispersion is a property of the medium such that the wave velocity is a function of frequency and direction, as in silicon.\(^4\) Informed discussions on the history of this topic may be found in Brillouin (1953).

### 4.3.1 Complex impedance functions

Conservation of energy (or power) is a cornerstone of modern physics. It may first have been under consideration by Galileo Galilei (1564-1642) and Marin Mersenne (1588-1648). Today the question is not whether it is true, but why. Specifically, what is the physics behind conservation of energy?

Recall that the power is the product of the force and flow, and impedance is their ratio.

Surprisingly, the answer is straightforward, based on its definition and the properties of impedance.

The total energy $E(t)$ is the integral of the power, since $P(t) = dE/dt$. Thus if we start with all the elements at rest (no currents or voltages), then the energy as a function of time is always positive

$$E(t) = \int_0^t P(t) dt \geq 0,$$

and is simply the total energy applied to the network (Van Valkenburg, 1964a, p. 376). Since the voltage and current are related by either an impedance or an admittance, conservation of energy depends on the property of impedance. From Ohm’s law and P1 (every impedance is causal)

$$v(t) = z(t) \ast i(t) = \int_{\tau=0}^t z(\tau)i(t - \tau)d\tau \leftrightarrow V(s) = Z(s)I(s).$$

**Example:** Let $i(t) = \delta(t)$. Then $|w|^2(\tau) = i(t) \ast i(t) = \delta(\tau)$. Thus

$$I_{xx}(t) = \int_{\tau=0}^t z(\tau)|w|^2(\tau)d\tau = \int_{\tau=0}^t z(\tau)\delta(\tau)d\tau = \int_{0}^t z(\tau)d\tau.$$

The Brune impedance always has the form $z(t) = r_o\delta(t) + \zeta(t)$. The surge impedance is defined as

$$r_o = \int_{0}^{\infty} z(t)dt.$$

The integral of the reactive part ($\zeta(t)$) is always zero, since the reactive part cannot not store energy.

Perhaps easier to visualize is when working in the frequency domain where the total energy, equal to the integral of the real part of the power, is

$$\frac{1}{s} \Re V I = \frac{1}{2s} (V^\ast I + VI^\ast) = \frac{1}{2s} (Z^\ast I^\ast I + ZI^\ast I) = \frac{1}{s} \Re Z(s)|I|^2 \geq 0.$$

Formally this is related to a positive definite operator where the positive resistance forces the definiteness, which is sandwiched between the current.

In conclusion, conservation of energy is totally dependent on the properties of the impedance. Thus one of the most important and obvious applications of complex functions of a complex variable is the impedance function. This seems to be the ultimate example of the FTC, applied to $z(t)$, in the name of conservation of energy.

\(^4\)In case you missed it, I’m suggesting is that photons (propagating waves) and electrons (evanescent waves) are different wave “states.” The difference is the medium, which determines the dispersion relation (Papasimakis et al., 2018).
4.3. LECTURE 25: COMPLEX ANALYTIC FUNCTIONS AND BRUNE IMPEDANCE

Poles and zeros of PR functions must be first degree: We conjecture that this proof also requires that the poles and the zeros of the impedance function be simple (only first degree). Second degree poles would have a reactive “secular” response of the form \( h(t) = t \sin(\omega_k t + \phi)u(t) \), and these terms would not average to zero, depending on the phase, as is required of an impedance. As a result, only single degree poles would be possible.\(^5\) Furthermore, when the impedance is the ratio of two polynomials, where the lower degree polynomial is the derivative of the higher degree one, then the poles and zeros must alternate. This is a well-known property of the Brune impedance that has never been adequately explained except for very special cases (Van Valkenburg, 1964b, p. 104-107). I suspect that no one has ever reported an impedance having second degree poles and zeros as that would be rare impedance. Network analysis books never report 2nd degree poles and zeros in their impedance functions. Nor has there ever been any guidance as to where the poles and zeros might lie in the left-hand plane.

Every impedance must obey conservation of energy (P3): The impedance function \( Z(s) \) has resistance \( R \) and reactance \( X \) as a function of complex frequency \( s = \sigma + j\omega \). From the causality postulate (P1) of Sections 3.7.1 and J (p. 281), \( z(t < 0) = 0 \). Every impedance is defined by a Laplace transform pair

\[
z(t) \leftrightarrow Z(s) = R(\sigma, \omega) + jX(\sigma, \omega),
\]

with \( R, X \in \mathbb{R} \).

According to Postulate P3 (Sect. 3.7.1, p. 132), a system is passive if it does not contain a power source. Drawing power from an impedance violates conservation of energy. This propriety is also called positive-real, which was defined by Brune (1931b,a)

\[
\Re\{Z(s \geq 0)\} \geq 0. \tag{4.20}
\]

Positive-real systems cannot draw more power than is stored in the impedance.\(^6\) The region \( \sigma \leq 0 \) is called the left half s plane (LHP), and the complementary region \( \sigma > 0 \) is called the right half s plane (RHP). According to the Brune condition the real part of every impedance must be non-negative in the RHP. It is easy to construct examples of second-order poles or zeros in the RHP, such that P3 is violated. Thus P3 implies that the impedance may not have more than simple (first-order) poles and zeros, strictly in the LHP. But there is yet more: These poles and zero in the LHP must have order, to meet the minimum phase condition. This minimum phase condition is easily stated

\[
\angle Z(s) < \angle s,
\]

but difficult to prove. There seems to be no proof that second-order poles and zeros (e.g., second-order roots) are not allowed. However such roots would violate a requirement that the poles and zeros must alternate on the \( \sigma = 0 \) axis, which follows from P3. In the complex plane the concept of ‘alternate’ is not defined (complex numbers cannot be ordered). What has been proved (i.e., Foster’s reactance theorem\(^7\)) is that if the poles are on the real or imaginary axis, they must alternate, leading to simple poles and zeros (Van Valkenburg, 1964a). The restriction on poles is sufficient, but not necessary, as \( Z(s) = \frac{1}{\sqrt{s}} \) is a physical realizable (PR) impedance, but is less than a first-degree pole (Kim and Allen, 2013). The corresponding condition in the LHP, and its proof, remains elusive (Van Valkenburg, 1964a).

As an example, a series resistor \( R_o \) and capacitor \( C_o \) have an impedance given by (Table B.2, p. 250)

\[
Z(s) = R_o + \frac{1}{sC_o} \leftrightarrow R_o\delta(t) + \frac{1}{C_o}u(t) = z(t), \tag{4.21}
\]

\(^5\)Secular terms result from second degree poles since \( u(t) \ast u(t) = tu(t) \leftrightarrow 1/s \).

\(^6\)Does this condition hold for the LHP \( \sigma < 0 \)? It does for Eq. 4.22.

\(^7\)https://en.wikipedia.org/wiki/Foster%27s_reactance_theorem
with constants \( R_o, C_o \in \mathbb{R} > 0 \). In mechanics an impedance composed of a dash-pot (damper) and a spring has the same form. A resonant system has an inductor, resistor and a capacitor, with an impedance given by (Table B.1, p. 249)

\[
Z(s) = \frac{sC_o}{1 + sC_oR_o + s^2C_oM_o} \leftrightarrow C_o \frac{d}{dt} \left(c_+ e^{s+t} + c_- e^{s-t}\right) = z(t),
\]

which is a second degree polynomial with two complex resonant frequencies \( s_{\pm} \). When \( R_o > 0 \) these roots are in the left half \( s \) plane, with \( z(t) \leftrightarrow Z(s) \).

Systems (networks) containing many elements, and transmission lines, can be much more complicated, yet still have a simple frequency domain representation. This is the key to understanding how these physical systems work, as will be described below.

**Complex analytic functions:** To solve a differential equation, or integrate a function, Newton used the Taylor series to integrate one term at a time. However, he only used real functions of a real variable, due to the fundamental lack of appreciation of the complex analytic function. This same method is how one finds solutions to scalar differential equations today, but using an approach that makes the solution method less obvious. Rather than working directly with the Taylor series, today we use the complex exponential, since the complex exponential is an eigenfunction of the derivative

\[
\frac{d}{dt} e^{st} = s e^{st}.
\]

Since \( e^{st} \) may be expressed as a Taylor series, having coefficients \( c_n = 1/n! \), in some real sense the modern approach is a compact way of doing what Newton did. Thus every linear constant coefficient differential equation in time may be simply transformed into a polynomial in complex Laplace frequency \( s \), by looking for solutions of the form \( A(s)e^{st} \), transforming the differential equation into a polynomial \( A(s) \) in complex frequency. For example,

\[
\frac{d}{dt} f(t) + af(t) \leftrightarrow (s + a)F(s).
\]

The root of \( A(s) = s_{\pm} + a = 0 \) is the eigenvalue of the differential equation. A powerful tool for understanding the solutions of differential equations, both scalar and vector, is to work in the Laplace frequency domain. The Taylor series has been replaced by \( e^{st} \), transforming Newton’s real Taylor series into the complex exponential eigenfunction. In some sense, these are the same method, since

\[
e^{st} = \sum_{n=0}^{\infty} \frac{(st)^n}{n!}.
\]

(4.23)

Taking the derivative with respect to time gives

\[
\frac{d}{dt} e^{st} = se^{st} = s \sum_{n=0}^{\infty} \frac{(st)^n}{n!},
\]

(4.24)

which is also complex analytic. Thus if the series for \( F(s) \) is valid (i.e., it converges), then its derivative is also valid. This was a very powerful concept, exploited by Newton for real functions of a real variable, and later by Cauchy and Riemann for complex functions of a complex variable. The key question here is: Where does the series fail to converge? If it does not converge, the representation fails. This is the main message behind the FTCC (Eq. 4.8).

The FTCC (Eq. 4.5) is formally the same as the FTC (Eq. 4.7) (Leibniz formula), the key (and significant) difference being that the argument of the integrand \( s \in \mathbb{C} \). Thus this integration is a line integral in the complex plane. One would naturally assume that the value of the integral depends on the path of integration.
But, according to FTCC, it does not. In fact they are clearly distinguishable from the FTC. And the reasoning is the same. If \( F(s) = df(s)/ds \) is complex analytic (i.e., has a power series \( f(s) = \sum_k c_k s^k \), with \( f(s), c_k, s \in \mathbb{C} \)), then it may be integrated, and the integral does not depend on the path. At first blush, this is sort of amazing. The key is that \( F(s) \) and \( f(s) \) must be complex analytic, which means they are differentiable. This all follows from the Taylor series formula Eq. 4.10 (p. 147) for the coefficients of the complex analytic series. For Eq. 4.8 to hold, the derivatives must be independent of the direction, as discussed in Section 4.2.2. The concept of a complex analytic function therefore has eminent consequences, in the form of several key theorems on complex integration discovered by Cauchy (c1820).

The use of the complex Taylor series generalizes the functions it describes, with unpredictable consequences, as nicely shown by the domain coloring diagrams presented in Section 3.8 (p. 134). Cauchy’s tools of complex integration were first exploited in physics by Sommerfeld (1952) to explain the onset transients in waves, as explained in detail in Brillouin (1960, Chap. 3).

Up to 1910, when Sommerfeld first published his results using complex analytic signals and saddle point integration in the complex plane, there was a poor understanding of the implications of the causal wave-front. It would be reasonable to say that his insights changed our understanding of wave propagation, for both light and sound. Sadly this insight has not been fully appreciated, even to this day. If you question my summary, please read Brillouin (1960, Chap. 1).

The full power of the complex analytic function was first appreciated by Bernard Riemann (1826-1866) in his University of Göttingen PhD thesis of 1851, under the tutelage of Carl Friedrich Gauss (1777-1855), and drawing heavily on the work of Cauchy.

The key definition of a complex analytic function is that it has a Taylor series representation over a region of the complex frequency plane \( s = \sigma + j\omega \), that converges in a region of convergence (RoC) about the expansion point, with a radius determined by the nearest pole of the function. A further surprising feature of all analytic functions is that within the RoC, the inverse of that function also has a complex analytic expansion. Thus given \( w(s) \), one may also determine \( s(w) \) to any desired accuracy, critically depending on the RoC.

4.3.2 Lec 26: Multi-valued functions

In the field of mathematics there seems to have been a tug-of-war regarding the basic definition of the concept of a function. The accepted definition today seems to be a single-valued mapping from the domain to the codomain (or range). This makes the discussion of multi-valued functions somewhat tedious. In 1851 Riemann (working with Gauss) seems to have resolved this problem for the natural set of multi-valued functions by introducing the concept of single-valued sheets, delineated by branch-cuts.

Two important examples of multi-valued functions are the circle \( z^2 = x^2 + y^2 \) and \( w = \log(z) \). For example, assuming \( z \) is the radius of the circle, solving for \( y(x) \) gives the multi-valued function

\[
y(x) = \pm \sqrt{z^2 - x^2}.
\]

If we accept the modern definition of a function as the mapping from one set to a second, then \( y(x) \) is not a function, or even two functions. For example, what if \( x > z \)? Or worse, what if \( z = 2j \) with \(|x| < 1|\)?

Riemann’s construction, using branch cuts for multivalued function, resolves all these difficulties (as best I know).

To proceed, we need definitions and classifications of the various types of complex singularities:

1. Poles of degree 1 are called simple poles. Their amplitude is called the residue (e.g. \( \alpha/s \) has residue \( \alpha \)). Simple poles are special (Eq. 4.35, p. 163)\(^8\) as they play a key role in mathematical physics, since their inverse Laplace transform defines a causal eigenfunction.

2. When the numerator and denominator of a rational function have a common root (i.e., factor), that root is said to be removable.

\(^8\)https://en.wikipedia.org/wiki/Pole_(complex_analysis)
3. A singularity that is not (1) removable, (2) a pole or (3) a branch point is called essential.

4. A complex analytic function (except for isolated poles) is called meromorphic. Meromorphic functions can have any number of poles, even an infinite number. The poles need not be simple.

5. A complex analytic function (except for isolated poles), is called meromorphic. Meromorphic functions can have any number of poles, even an infinite number. The poles need not be simple.

6. When the first derivative of a function $Z(s)$ has a simple pole at $a$, then $a$ is said to be a branch point of $Z(s)$. An important example is the logarithmic derivative

$$d \ln(s-a)^{\alpha}/ds = \alpha/(s-a), \quad \alpha \in \mathbb{I}.$$ 

However, the converse does not necessarily hold.

7. I am not clear about the interesting case of an irrational pole ($\alpha \in \mathbb{I}$). In some cases this may be simplified via the logarithmic derivative operation, as mentioned above.

More complex topologies are being researched today, and progress is expected to accelerate due to modern computing technology. It is helpful to identify the physical meaning of these more complex surfaces, to guide us in their interpretation and possible applications.

Branch cuts: Up to this point we have only considered poles of degree $\alpha \in \mathbb{N}$ of the form $1/s^\alpha$. The concept of a branch cut allows one to manipulate (and visualize) multi-valued functions, for which $\alpha \in \mathbb{F}$. This is done by breaking each region into single-valued sheets, as shown in Fig. 4.3 (right). The branch cut is a curve $\in \mathbb{C}$ that separates the various single-valued sheets of a multi-valued function. The concepts of branch cuts, sheets and the extended plane were first devised by Riemann, working with Gauss (1777-1855), as first described in his thesis of 1851. It was these three mathematical and geometrical constructions that provided the deep insight into complex analytic functions, greatly extending the important earlier work of Cauchy (1789-1857) on the calculus of complex analytic functions. For alternative helpful discussion of Riemann sheets and branch cuts, see Boas (1987, Section 29, pp. 221-225) and (Kusse and Westwig, 2010).

Multi-valued functions: The best way to explore the complex mapping from the complex planes $s \to w(s)$ is to master the single valued function $s = w^2(s)$ and its double-valued inverse $w(s) = \sqrt{s}$, the square root function (Fig. 4.3). Single valued functions such as $W(s) = s^2$ are relatively straightforward. Multivalued functions require the concept of a branch cut, defined in the image $(w(s))$ plane, which is a technique to render the multiple values as single valued on each of several sheets, defined by the sheet index in the domain $(s)$ plane, and delineated by a branch cut (in the $w$ plane). The sheets are labeled in the domain $(s)$ plane by a sheet index $k \in \mathbb{Z}$ while branch points and cuts are defined in the image $(w)$ plane (a.k.a., the range). It is important to understand that the path of every branch cut is not unique, and may be moved. However branch points are unique thus not movable.

The multi-valued nature of $w(s) = \sqrt{s}$ is best understood by working with the function in polar coordinates. Let

$$s_k = r e^{\theta_k e^{2\pi k}},$$

where $r = |s|, \theta = \angle s, \in \mathbb{R}$ and $k \in \mathbb{Z}$ is the sheet-index. Furthermore let

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9https://en.wikipedia.org/wiki/Meromorphic_function
10https://en.wikipedia.org/wiki/Meromorphic_function
11https://www.maths.ox.ac.uk/about-us/departmental-art/theory
\[ w = \rho e^{\psi j} = \sqrt{r}e^{\theta j/2}e^{jk}, \quad (4.26) \]

where \( \rho = |w|, \psi \angle w, \in \mathbb{R}. \) The generic Cartesian coordinates are \( s = \sigma + \omega j \) and \( w(s) = u(\sigma, \omega) + v(\sigma, \omega)j. \) For single valued functions such as \( w(s) = s^2 \) (Left) there is no branch cut since \( \psi = 2\theta. \) Note how the red color (\( \theta = 0^\circ \)) appears twice in this mapping. For multi-valued functions a branch-cut is required, typically along the negative \( v(\sigma, \omega) \) axis (i.e, \( \psi = \pi \)) but may be freely distorted, as seen by comparing the right panel of Fig. 4.3 with the right panel of Fig. 4.5.

![Image of complex mapping](https://en.wikipedia.org/wiki/Riemann_surface)

**Figure 4.3:** Here we use Cartesian coordinates in the domain \( s = \sigma + \omega j \) and polar coordinates for the range \( w(\sigma, \omega) = |w|e^{\psi j}. \) The color intensity indicates the magnitude \( |s|, \) with black being \( |s| = 0 \) and bright (eventually white), indicating \( |s| \to \infty. \) **Left:** Mapping: \( w(s) = s^2 \). **Right:** Mapping of the principal branch from \( -s \) to \( w(s) = -\sqrt{-s} \) (i.e., the rotated inverse of \( s^2 \)). This sheet was generated by rotating \( w \) by 180°. The branch cut is on the \( \psi = 0 \) axis, with branch points at \( |w| = 0 \) and \( \infty. \)

![Image of complex mapping](https://en.wikipedia.org/wiki/Riemann_surface)

**Figure 4.4:** Here we show the mapping for the square root function \( z = \pm \sqrt{s} \) which has two single-valued sheets of the \( x \) plane corresponding to the two signs of the square root. The branch cut runs along the real axis, from \( z = 0 \) to \( \infty. \) A more comprehensive explanation is presented in the text. Figure from: [https://en.wikipedia.org/wiki/Riemann_surface](https://en.wikipedia.org/wiki/Riemann_surface)

**Hue:** By studying the output of \( \text{zviz.m} \) (p. 134) we may understand domain-coloring. The domain angles \( \angle s \) go from \(-\pi < \theta < \pi, \) with \( \theta = 0 \) being red and \( \pm \pi \) being green (between yellow and blue). The angle to hue map is shown in the left panel of Fig. 4.5. For the \( w(s) = s^2 \) the \( \angle s \) is expanded by 2, since \( \psi = 2\theta. \) For \( w(s) = \sqrt{s} \) the \( \angle s \) is compressed by a factor of 2, since \( \psi = \theta/2. \) Thus the principle angle \( k = 0, -180^\circ < \theta < 180^\circ \) maps to half the \( w \) plane \( (-90^\circ < \psi < 90^\circ) \) from purple to yellow, while the \( k = 1 \) branch maps to \( 90^\circ < \psi < 270^\circ. \) Note how the panel on the right of Fig. 4.3 matches the right half of \( s \) (purple = -90°, yellow/green = +90°) while the middle panel above comes from the left side of \( s \) (green to purple). The center panel is green at -180°, and purple at +180°, which matches the left panel at \( \pm 180^\circ, \) respectively (i.e., \( e^{\pm j\pi} \)). The principle (i.e., first) Riemann sheet of \( \sqrt{s} \), corresponding to \(-\pi < \theta < \pi \) (i.e., \( k = 0 \)), is shown in the center of Fig. 4.5. This differs from the neighboring sheet \( (k = 1) \), shown on the right. Thus \( w(s) = \sqrt{s} \) is a multi-valued function of \( s, \) having two single-valued sheets.

The principle (i.e., first) Riemann sheet of \( \sqrt{s} \), corresponding to \(-\pi < \theta < \pi \) (i.e., \( k = 0 \)), is shown in the center of Fig. 4.5. This differs from the neighboring sheet \( (k = 1) \), shown on the right. Thus \( w(s) = \sqrt{s} \) is a multi-valued function of \( s, \) having two single-valued sheets.

The location of the branch cut may be moved by rotating the \( z \) coordinate system. For example, \( w(z) = \pm j\sqrt{z} \) and \( w(z) = \pm \sqrt{-z} \) have different branch cuts, as may be easily verified using the Matlab/Octave commands \( j*zviz(z) \) and \( zviz(-z), \) as shown in Fig. 4.5. Since the cut may be
moved, every function is analytic on the branch cut, if a Taylor series is formed on the branch cut, it will describe the function on the two different sheets. Thus the complex analytic series (i.e., the Taylor formula, Eq. 4.10) does not depend on the location of a branch cut, as it only describes the function uniquely (as a single-valued function), valid in its local region of convergence.

The second sheet ($k = 1$) (Fig. 4.5) picks up at $\theta = \pi$ and continues on to $\pi + 2\pi = 3\pi$. The first sheet maps the angle of $w$ (i.e., $\phi = \angle w = \theta/2$) from $-\pi/2 < \phi < \pi/2$ ($w = \sqrt{r}e^{i\phi/2}$). This corresponds to $u = \Re\{w(s)\} > 0$. The second sheet maps $\pi/2 < \psi < 3\pi/2$ (i.e., $90^\circ$ to $270^\circ$), which is $\Im\{w\} = u < 0$. In summary, twice around the $s$ plane is once around the $w(s)$ plane, because the angle is half due to the $\sqrt{s}$. This then describes the multi-valued nature of the square root function.

This concept of analytic inverses becomes important only when the function is multi-valued. For example, if $w(s) = s^2$ then $s(w) = \pm \sqrt{w}$ is multivalued. Riemann dealt with such extensions with the concept of a branch-cut with multiple sheets, labeled by a sheet number. Each sheet describes an analytic function (Taylor series) that converges within some RoC, having a radius out to the nearest pole. Thus Riemann’s branch cuts and sheets explicitly deal with the need to define unique single-valued inverses of multi-valued functions. Since the square root function has two overlapping regions, corresponding to the $\pm$ due to the radical, there must be two connected regions, sort of like mathematical Siamese twins: distinct, yet the same.

Figure 4.3 shows the single-valued function $w(z) = s^2$ (left), and Fig. 4.5 (right) its inverse, the double-valued mapping of $s(w) = \pm \sqrt{w}$.

Branch cuts emanate and terminate at branch points, defined as singularities (poles), that can even have fractional degree, as for example $1/\sqrt{s}$, and terminate at one of the matching roots, which includes the possibility of $\infty$. For example, suppose that in the neighborhood of the pole, at $s_o$, the function is

$$f(s) = \frac{w(s)}{(s - s_o)^k},$$

where $w, s, s_o \in \mathbb{C}$ and $k \in \mathbb{Q}$. When $k = 1$, $s_o = \sigma_o + \omega_o j$ is a first degree “simple pole”, having degree 1 in the $s$ plane, with residue $w(s_o)$. Typically the order and degree are positive integers, but fractional degrees and orders are not uncommon in modern engineering applications (Kirchhoff, 1868; 13This presumes that poles appear in pairs, one of which may be at $\infty$.
14We shall refer to the order of a derivative, or differential equation, and the degree of a polynomial, as commonly used in engineering applications (https://en.wikipedia.org/wiki/Differential_equation#Equation_order).
Lighthill, 1978). Here we shall allow both the degree and order to be fractional ($\in \mathbb{F}$). When $k \in \mathbb{F} \subset \mathbb{R}$ ($k = n/m$) is a real reduced fraction. Namely when $\text{GCD}(n, m) = 1$, $n \perp m$. This defines the degree of a fractional pole. In such cases there must be two sets of branch cuts of degree $n$ and $m$. For example, if $k = 1/2$, the singularity (branch cut) is of degree 1/2, and there are two Riemann sheets, as shown in Fig. 4.3 (p. 155). The analytic inverse of this function is $s = w^2$, as shown in the same figure.

**Fractional-order Bessel function:** An important example is the Bessel function

$$\delta(t) + \frac{1}{t} J_1(t) u(t) \leftrightarrow \sqrt{s^2 + 1},$$

which is related to the solution to the wave equation in two-dimensional cylindrical coordinates (Table B.2, p. 250). Bessel functions are the solutions (i.e., eigenfunctions) of guided acoustic waves in round pipes, or surface waves on the earth (seismic waves), or waves on the surface of a pond (Table 5.2, p. 203).

![Colorized plots of two LT pairs](image)

**Figure 4.6:** Colorized plots of two LT pairs: Left: $\sqrt{\pi/s} \leftrightarrow u(t)/\sqrt{t}$. Right: $\sqrt{s^2 + 1} \leftrightarrow \delta(t) + \frac{1}{t} J_1(t) u(t)$.

It is important to understand that the function is analytic on the branch cut, but not at the branch point. One is free to move the branch cut (at will). It does not need to be on a line: it could be cut in almost any connected manner, such as a spiral. The only rule is that it must start and stop at the matching branch points, or at $\infty$, which must have the same degree.

There are a limited number of possibilities for the degree, $k \in \mathbb{Z}$ or $\in \mathbb{F}$. If the degree is drawn from $\mathbb{R} \not\in \mathbb{F}$, the pole cannot have a residue. According to the definition of the residue, $k \in \mathbb{F}$ will not give a residue. But there remains open the possibility of generalizing the concept of the Riemann integral theorem, to include $k \in \mathbb{F}$. One way to do this is to use the logarithmic derivative which renders fractional poles to simple poles with fractional residues.

If the singularity has an irrational degree ($k \in \mathbb{I}$), the branch cut has the same “irrational degree.” Accordingly there would be an infinite number of Riemann sheets, as in the case of the log function. An example is $k = \pi$, for which

$$F(s) = \frac{1}{s^\pi} = e^{-\log(s)^\pi} = e^{-\pi \log(s)} = e^{-\pi \log(\rho)} e^{-\pi \theta^j},$$

where the domain is expressed in polar coordinates $s = \rho e^{i\theta}$. When $k \in \mathbb{F}$ it may be maximally close (e.g., $k = \pi_{152}/\pi_{153} = \pi_{152}/(\pi_{152} + 2) = 881/883 \approx 0.99883$, or its reciprocal $\approx 1.0023$). The branch cut could be very subtle (it could even go unnoticed), but it would have a significant impact on the function, and on its inverse Laplace transform.

---

15 Since there are no even primes other than $\pi_1 = 2$, the minimum difference is 2. Out of $10^6$ primes, only 5 have a minimum difference of more than $e^{80}$, with these 5 having a uniform distribution on a log scale. Verify $80$. More examples:
Example: Find poles, zeros and residues of $F(s)$.

1. 

   \[ F(s) = \frac{d}{ds} \ln \frac{s + e}{s + \pi}, \]

   **Solution:**

   \[ F(s) = \frac{d}{ds} [\ln(s + e) - \ln(s + \pi)] = \left( \frac{1}{s + e} - \frac{1}{s + \pi} \right) \]

   The poles are at $s_1 = -e$ and $s_2 = -\pi$ with respective residues of $\pm 1$.

2. 

   \[ F(s) = \frac{d}{ds} \ln \frac{(s + 3)e}{(s + j)^{\pi}}, \]

   **Solution:** There is a very important take-home message here regarding the utility of the logarithmic derivative.

3. 

   \[ F(s) = e^{\pi \ln s}, \]

   **Solution:** Add solution.

4. 

   \[ F(s) = \pi^{-s}. \]

   **Solution:** Add solution.

**Multivalued functions:** The two basic functions we review, to answer the questions about multivalued functions and branch cuts, are $w(s) = \sqrt{s}$ and $w(s) = \log(s)$ along with their inverse functions $w(s) = s^2$ and $w(s) = e^s$. For uniformity we shall refer to the **complex abscissa** $(s = \sigma + \omega j)$ and the **complex ordinate** $w(s) = u + v j$. When the complex abscissa and domain are swapped, by taking the inverse of a function, multi-valued functions are a common consequence. For example, $f(t) = \sin(t)$ is single valued, and analytic in $t$, thus has a Taylor series. The inverse function $t(f)$ is multivalued.

The modern terminology is the **domain** and **range**, or alternatively the **co-domain**.

**Log function:** Next we discuss the multi-valued nature of the log function. In this case there are an infinite number of Riemann sheets, not well captured by Fig. 3.9 (p. 135), which only displays the principal sheet. However, if we look at the formula for the log function, the nature is easily discerned. The abscissa $s$ may be defined as multi-valued since

\[ s_k = re^{2\pi kj}e^{\theta j}. \]

Here we have extended the angle of $s$ by $2\pi k$, where $k$ is the sheet index $\in \mathbb{Z}$. Taking the log

\[ \log(s) = \log(r) + (\theta + 2\pi k)j. \]

When $k = 0$ we have the **principal value** sheet, which is zero when $s = 1$. For any other value of $k$, $w(s) \neq 0$, even when $r = 1$, since the angle is not zero, except for the $k = 0$ sheet.

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\[ ^{16}\text{The best way to create confusion is to rename something. The confusion grows geometrically with each renaming. I suspect that everyone who cares knows the terms abscissa and ordinate, and some fraction know the equivalent terms domain and range.} \]
4.3.3 **Exercises DE-I**

**Topic of this homework:** Complex numbers and functions (ordering and algebra); Complex power series; Fundamental theorem of calculus (real and complex); Cauchy-Riemann conditions; Multivalued functions (branch cuts and Riemann sheets)

**Complex Power Series**

In each case derive (e.g. using Taylor’s formula) the power series of \( w(s) \) about \( s = 0 \) and state the ROC of your series. If the power series doesn’t exist, state why! *Hint: In some cases, you can derive the series by relating the function to another function for which you already know the power series at \( s = 0 \).*

**To do:**

1. \( 1/(1 - s) \)
2. \( 1/(1 - s^2) \)
3. \( 1/(1 - s)^2 \)
4. \( 1/(1+s^2). \) *Hint: This series will be very ugly to derive if you try to take the derivatives \( \frac{d^n}{ds^n}[1/(1+s^2)] \). Using the results of our previous homework, you should represent this function as \( w(s) = -0.5i/(s - i) + 0.5i/(s + i) \).*
5. \( 1/s \)
6. \( 1/(1 - |s|^2) \)
7. Consider the function \( w(s) = 1/s \)
   
   (a) Expand this function as a power series about \( s = 1 \). *Hint: Let \( 1/s = 1/(1 - 1 + s) = 1/(1 - (1 - s)) \).*
   
   (b) What is the ROC?
   
   (c) Expand \( w(s) = 1/s \) as a power series in \( s^{-1} = 1/s \) about \( s^{-1} = 1 \).
   
   (d) What is the ROC?
   
   (e) What is the residue of the pole?
8. Consider the function \( w(s) = 1/(2 - s) \)
   
   (a) Expand \( w(s) \) as a power series in \( s^{-1} = 1/s \). State the ROC as a condition on \( |s^{-1}| \). *Hint: Multiply top and bottom by \( s^{-1} \).*
   
   (b) Find the inverse function \( s(w) \). Where are the poles and zeros of \( s(w) \), and where is it analytic?
9. If \( a = 0.1 \) what is the value of
   
   \[
   x = 1 + a + a^2 + a^3 + \cdots?
   \]
   
   Show your work.
10. If \( a = 10 \) what is the value of
    
    \[
    x = 1 + a + a^2 + a^3 + \cdots?
    \]
Two fundamental theorems of calculus

**Fundamental Theorem of Calculus (Leibniz):** According to the Fundamental Theorem of (Real) Calculus (FTC)

\[ F(x) = F(a) + \int_a^x f(\xi) d\xi, \]  
(4.27)

where \( x, a, \xi, F \in \mathbb{R} \). This is an indefinite integral (since the upper limit is unspecified). It follows that

\[ \frac{dF(x)}{dx} = \frac{d}{dx} \int_a^x f(x) dx = f(x). \]

This justifies also calling the indefinite integral the anti-derivative.

For a closed interval \([a, b]\), the FTC is

\[ \int_a^b f(x) dx = F(b) - F(a), \]  
(4.28)

thus the integral is independent of the path from \( x = a \) to \( x = b \).

**Fundamental Theorem of Complex Calculus:** According to the Fundamental Theorem of Complex Calculus (FTCC)

\[ f(z) = f(z_0) + \int_{z_0}^z F(\zeta) d\zeta, \]  
(4.29)

where \( z_0, z, \zeta, F \in \mathbb{C} \). It follows that

\[ \frac{df(z)}{dz} = \frac{d}{dz} \int_{z_0}^z F(\zeta) d\zeta = F(z). \]

**To do:**

- Consider Equation 4.27. What is the condition on \( f(x) \) for which this formula is true?
- Consider Equation 4.38. What is the condition on \( f(z) \) for which this formula is true?
- Perform the following integrals (\( z = x + iy \in \mathbb{C} \)):
  1. \[ I = \int_0^1 + j z dz \]
  2. \[ I = \int_0^1 + j z dz, \] but this time make the path explicit: from 0 to 1, with \( y=0 \), and then to \( y=1 \), with \( x=1 \).
  3. Do your results agree with Equation 4.40?
- Perform the following integrals on the closed path \( C \), which we define to be the unit circle. You should substitute \( z = e^{i\theta} \) and \( dz = ie^{i\theta} d\theta \), and integrate from \([-\pi, \pi]\) to go once around the unit circle.
  1. \[ \int_C z dz \]
  2. \[ \int_C \frac{1}{z} dz \]
  3. Do your results agree with Equation 4.40? If not, do you know why not?
Cauchy-Riemann Equations

For the following problem: \( i = \sqrt{-1} \), \( s = \sigma + i \omega \), and \( F(s) = u(\sigma, \omega) + iv(\sigma, \omega) \).

In class I showed that the integration of a complex analytic function is independent of the path, formally known as the Fundamental theorem of complex calculus. The derivative of \( F(s) \) is defined as

\[
\frac{df}{ds} = \frac{d}{ds} [u(\sigma, \omega) + iv(\sigma, \omega)].
\]

If the integral is independent of the path, then the derivative must also be independent of direction

\[
\frac{df}{ds} = \frac{\partial f}{\partial \sigma} = \frac{\partial f}{\partial \omega}.
\]

1. The Cauchy-Riemann (CR) conditions

\[
\frac{\partial u(\sigma, \omega)}{\partial \sigma} = \frac{\partial v(\sigma, \omega)}{\partial \omega}
\quad \text{and} \quad
\frac{\partial u(\sigma, \omega)}{\partial \omega} = -\frac{\partial v(\sigma, \omega)}{\partial \sigma}
\]

may be used to show where Equation 4.31 holds.

To do:

- Assuming Equation 4.31 is true, use it to derive the CR equations.
- Merge the CR equations to show that \( u \) and \( v \) obey Laplace’s equation (\( \nabla^2 u(\sigma, \omega) = 0 \) and \( \nabla^2 v(\sigma, \omega) = 0 \)). One may conclude that the real and imaginary parts of complex analytic functions must obey these conditions.

2. Apply the CR equations to the following functions. State for which values of \( s = \sigma + i \omega \) the CR conditions do or do not hold (e.g. where the function \( F(s) \) is or is not analytic). Hint: Recall your answers to problem 1.2 of this assignment.

- \( F(s) = e^s \)
- \( F(s) = 1/s \)

Branch cuts and Riemann sheets

1. Consider the function \( |w(z)|^2 = z \). This function can also be written as \( w(z) = \sqrt{z} \). Define \( z = re^{i\theta} \) and \( w(z) = \rho e^{i\theta/2} \).

   - How many Riemann sheets do you need in the domain \( (z) \) and the range \( (w) \) to fully represent this function as single valued?
     Indicate (e.g. using a sketch) how the sheet(s) in the domain map to the sheet(s) in the range.
   - Use \texttt{zviz.m} to plot the positive and negative square roots \( +\sqrt{z} \) and \( -\sqrt{z} \). Describe what you see.
   - Where does \texttt{zviz.m} place the branch cut for this function?
   - Must it necessarily be in this location?

2. Consider the function \( w(z) = \log(z) \). As before define \( z = re^{i\theta} \) and \( w(z) = \rho e^{i\theta} \).

   - Describe with a sketch, and then discuss the branch cut for \( f(z) \).
   - What is the inverse of this function, \( z(f) \)? Does this function have a branch cut (if so, where is it)?
3. Using `zviz.m`, show that

\[
\tan^{-1}(z) = -\frac{j}{2} \log \left(\frac{j - z}{j + z}\right). \tag{4.32}
\]

That is, plot both these function and verify they are the same function.

4. Algebraically justify Eq. 4.2. Hint: Let \( w(z) = \tan^{-1}(z), z(w) = \tan w = \sin w / \cos w \), then solve for \( e^{wj} \).
4.4 LECTURE 27: (WEEK 10) THREE COMPLEX INTEGRATION THEOREMS I

4.4 Lec 27: Three Cauchy integral theorems

4.4.1 Cauchy’s theorems for integration in the complex plane

There are three basic definitions related to Cauchy’s integral formula. They are closely related, and can greatly simplify integration in the complex plane. The choice of names seems unfortunate, if not totally confusing.

1. **Cauchy’s (Integral) Theorem (CIT):**

\[ \oint_C F(s)\,ds = 0, \quad (4.33) \]

if and only if \( F(s) \) is complex analytic inside of a simple closed curve \( C \) (Boas, 1987, p. 45); (Stillwell, 2010, 319). The FTCC (Eq. 4.8) says that the integral only depends on the end points if \( F(s) \) is complex analytic. By closing the path (contour \( C \)) the end points are the same, thus the integral must be zero, as long as \( F(s) \) is complex analytic.

2. **Cauchy’s Integral Formula (CIF):**

\[ \frac{1}{2\pi j} \oint_B \frac{F(s)}{s - s_o}\,ds = \begin{cases} F(s_o), & s_o \in \mathbb{C} < B \text{ (inside)} \\ 0, & s_o \notin \mathbb{C} > B \text{ (outside)} \end{cases}, \quad (4.34) \]

Here \( F(s) \) is required to be analytic everywhere within (and on) the boundary \( B \) of integration (Greenberg, 1988, p. 1200); (Boas, 1987, p. 51); (Stillwell, 2010, p. 220). When the point \( s_o \in \mathbb{C} \) is within the boundary the value \( F(s_o) \in \mathbb{C} \) is the residue of the pole \( s_o \) of \( F(s)/(s - s_o) \). When the point \( s_o \) lies outside the boundary, the integral is zero.

3. **The (Cauchy) Residue Theorem (CRT):** (Greenberg, 1988, p. 1241), (Boas, 1987, p. 73)

\[ \oint_C F(s)\,ds = 2\pi j \sum_{k=1}^{K} c_k = \sum_{k=1}^{K} \oint_{s} \frac{F(s)}{s - s_k}\,ds, \quad (4.35) \]

where the residues \( c_k \in \mathbb{C} \) corresponds to the \( k \)th pole of \( f(s) \) enclosed by the contour \( C \). By the use of Cauchy’s integral formula, the right-most form of the residue theorem is equivalent to the CIF.\(^{17}\)

**How to calculate the residue:** The case of first degree poles has special significance, because the Brune impedance only allows simple poles and zeros, increasing its utility. The residues for simple poles are \( F(s_k) \), which is complex analytic in the neighborhood of the pole, but not at the pole.

Consider the function \( f(s) = F(s)/(s - s_k) \), where we have factored \( f(s) \) to isolate the first-order pole at \( s = s_k \), with \( F(s) \) analytic at \( s_k \). Then the residue of the poles at \( c_k = F(s_k) \). This coefficient is computed by removing the singularity, by placing a zero at the pole frequency, and taking the limit as \( s \to s_k \), namely

\[ c_k = \lim_{s \to s_k} [(s - s_k)F(s)] \quad (4.36) \]


When the pole is an \( N \)th degree, the procedure is much more complicated, and requires taking \( N - 1 \) order derivatives of \( f(s) \), followed by the limit process (Greenberg, 1988, p. 1242). Higher degree poles are rarely encountered; thus, it is good to know that this formula exists, but perhaps it is not worth the effort to memorize it.

\(^{17}\)This theorem is the same as a 2D version of Stokes’s theorem (Boas, 1987).
Summary and examples: These three theorems, all attributed to Cauchy, collectively are related to the fundamental theorems of calculus. Because the names of the three theorems are so similar, they are easily confused.

1. In general it makes no sense (nor is there any need) to integrate through a pole, thus the poles (or other singularities) must not lie on $C$.

2. The Cauchy integral theorem (Eq. 4.33) follows trivially from the fundamental theorem of complex calculus (Eq. 4.8, p. 146), since if the integral is independent of the path, and the path returns to the starting point, the closed integral must be zero. Thus Eq. 4.33 holds when $F(s)$ is complex analytic within $C$.

3. Since the real and imaginary parts of every complex analytic function obey Laplace’s equation (Eq. 4.15, p. 148), it follows that every closed integral over a Laplace field, i.e., one defined by Laplace’s equation, must be zero. In fact this is the property of a conservative system, corresponding to many physical systems. If a closed box has fixed potentials on the walls, with any distribution whatsoever, and a point charge (i.e., an electron) is placed in the box, then a force equal to $F = qE$ is required to move that charge, and thus work is done. However, if the point is returned to its starting location, the net work done is zero.

4. Work is done in charging a capacitor, and energy is stored. However, when the capacitor is discharged, all of the energy is returned to the load.

5. Soap bubbles and rubber sheets on a wire frame obey Laplace’s equation.

6. These are all cases where the fields are Laplacian, thus closed line integrals must be zero. Laplacian fields are commonly observed because they are so basic.

7. We have presented the impedance as the primary example of a complex analytic function. Physically, every impedance has an associated stored energy, and every system having stored energy has an associated impedance. This impedance is usually defined in the frequency $s$ domain, as a force over a flow (i.e., voltage over current). The power $P(t)$ is defined as the force times the flow and the energy $E(t)$ as the time integral of the power

$$E(t) = \int_{-\infty}^{t} P(t) dt,$$

which is similar to Eq. 4.6 (p. 146) [see Section 3.5.3, Eq. 3.42 (p. 123)]. In summary, impedance and power and energy are all fundamentally related.

4.4.2 Lec 28: Cauchy Integral Formula & Residue Theorem

The Cauchy integral formula (Eq. 4.34) is an important extension of the Cauchy integral theorem (Eq. 4.33) in that a pole has been explicitly injected into the integrand at $s = s_0$. If the pole location is outside of the curve $C$, the result of the integral is zero, in keeping with Eq. 4.33. When the pole is inside of $C$, the integrand is no longer complex analytic at the enclosed pole. When this pole is simple, the residue theorem applies. By a manipulation of the contour in Eq. 4.34, the pole can be isolated with a circle around the pole, and then taking the limit, the radius may be taken to zero, in the limit, isolating the pole.

For the related Cauchy residue theorem (Eq. 4.35) the same result holds, except it is assumed that there are $K$ simple poles in the function $F(s)$. This requires the repeated application of Eq. 4.34, $K$ times, so it represents a minor extension of Eq. 4.34. The function $F(s)$ may be written as $f(s)/P_K(s)$, where $f(s)$ is analytic in $C$ and $P_K(s)$ is a polynomial of degree $K$, with all of its roots $s_k \in C$. 

4.5. LECTURE 29: INVERSE LAPLACE TRANSFORM (T < 0): CAUCHY RESIDUE THEOREM

Non-integral degree singularities: The key point is that this theorem applies when \( n \in \mathbb{I} \), including fractions \( n \in \mathbb{F} \), but for these cases the residue is always zero, since by definition, the residue is the amplitude of the \( 1/s \) term (Boas, 1987, p. 73).

Examples:

1. When \( n \in \mathbb{F} \) (e.g., \( n = 2/3 \)), the residue is, by definition, zero.
2. The function \( 1/\sqrt{s} \) has a zero residue (apply the definition of the residue Eq. 4.36).
3. When \( n \neq 1 \in \mathbb{I} \), the residue is, by definition, zero.
4. When \( n = 1 \), the residue is given by Eq. 4.36.
5. This method is necessary when computing the inverse Laplace transform.

4.5 Lec 29: Inverse Laplace transform (t < 0): Cauchy residue theorem

The inverse Laplace transform Eq. 3.49 transforms a function of complex frequency \( F(s) \) and returns a causal function of time \( f(t) \)

\[
f(t) \leftrightarrow F(s),
\]

where \( f(t) = 0 \) for \( t < 0 \). Examples are provided in Table B.2 (p. 250). We next discuss the details of finding the inverse transform by use of the Cauchy residue theorem, and how the causal requirement \( f(t < 0) = 0 \) comes about.

The integrand of the inverse transform is \( F(s)e^{st} \) and the limits of integration are \( -\sigma_o \mp \omega j \). To find the inverse we must close the curve, at infinity, and show that the integral at \( \omega j \to \infty \). There are two ways to close these limits – to the right \( \sigma > 0 \) (RHP), and to the left \( \sigma < 0 \) (LHP) – but there needs to be some logical reason for this choice. That logic is the sign of \( t \). For the integral to converge, the term \( e^{st} \) must go to zero as \( \omega \to \infty \). In terms of the real and imaginary parts of \( s = \sigma + \omega j \), the exponential may be rewritten as \( e^{\sigma t}e^{\omega t} \). Note that both \( t \) and \( \omega \) go to \( \infty \). So it is the interaction between these two limits that determines how we pick the closure, RHP vs. LHP.

Case for causality (t < 0): Let us first consider negative time, including \( t \to -\infty \). If we were to close \( C \) in the left half-plane (\( \sigma < 0 \)), then the product \( \sigma t \) is positive (\( \sigma < 0, t < 0 \), thus \( \sigma t > 0 \)). In this case as \( \omega \to \infty \), the closure integral \( |s| \to \infty \) will diverge. Thus we may not close in the LHP for negative time. If we close in the RHP \( \sigma > 0 \) then the product \( \sigma t < 0 \) and \( e^{\sigma t} \) will go to zero as \( \omega \to \infty \). This then justifies closing the contour, allowing for the use of the Cauchy theorems.

If \( F(s) \) is analytic in the RHP, the FTCC applies, and the resulting \( f(t) \) must be zero, and the inverse Laplace transform must be causal. This argument holds for any \( F(s) \) that is analytic in the RHP (\( \sigma > 0 \)).

Case of unstable poles: An important but subtle point arises: If \( F(s) \) has a pole in the RHP, then the above argument still applies if we pick \( \sigma_o \) to be to the right of the RHP pole. This means that the inverse transform may still be applied to unstable poles (those in the RHP). This explains the need for the \( \sigma_o \) in the limits. If \( F(s) \) has no RHP poles, then \( \sigma_o = 0 \) is adequate, and this factor may be ignored.

Case for zero time (t = 0): When time is zero, the integral does not, in general, converge, leaving \( f(t) \) undefined. This is most clear in the case of the step function \( u(t) \leftrightarrow 1/s \), where the integral may not be closed, because the convergence factor \( e^{st} = 1 \) is lost for \( t = 0 \).

The fact that \( u(t) \) does not exist at \( t = 0 \) explains the Gibbs phenomenon in the inverse Fourier transform. At times where a jump occurs, the derivative of the function does not exist, and thus the time response function is not analytic. The Fourier expansion cannot converge at places where the function
is not analytic. A low-pass filter may be used to smooth the function, but at the cost of temporal resolution. Forcing the function to be analytic at the discontinuity, by smoothing the jumps, is an important computational method.
4.5. LECTURE 29: INVERSE LAPLACE TRANSFORM ($T < 0$): CAUCHY RESIDUE THEOREM

4.5.1 Exercises DE-2

**Topic of this homework:** Cauchy-Riemann conditions; Integration of complex functions; Cauchy’s theorem, integral formula, residue theorem; power series; Riemann sheets and branch cuts; inverse Laplace transforms

**FTCC and integration in the complex plane**

Recall that, according to the Fundamental Theorem of Complex Calculus (FTCC),

$$ f(z) = f(z_0) + \int_{z_0}^{z} F(\zeta) d\zeta, \quad (4.38) $$

where $z_0, z, \zeta, F \in \mathbb{C}$. It follows that

$$ f(z) = \frac{d}{dz} F(z). \quad (4.39) $$

Thus Eq. 4.38 is also known as the *anti-derivative* of $f(z)$.

**To do:**

1. For a closed interval $[a, b]$, the FTCC can be stated as

$$ \int_{a}^{b} F(z) dz = f(b) - f(a), \quad (4.40) $$

meaning that the result of the integral is independent of the path from $x = a$ to $x = b$. What condition(s) on the integrand $f(z)$ is (are) sufficient to assure that Eq. 4.40 holds?

2. For the function $f(z) = c^z$, where $c \in \mathbb{C}$ is an arbitrary complex constant, use the Cauchy-Riemann (CR) equations to show that $f(z)$ is analytic for all $z \in \mathbb{C}$.

3. In the following problems, solve the integral

$$ I = \int_{C} F(z) dz $$

for a given path $C$. In some cases this might be the *definite* integral (Eq. 4.40).

Let the function $F(z) = c^z$, where $c \in \mathbb{C}$ is given for each problem below. *Hint: Can you apply the FTCC?*

- Find the anti-derivative of $F(z)$.
- $c = 1/e = 1/2.7183 \ldots$ where $C$ is $\zeta = 0 \to i \to z$
- $c = 2$ where $C$ is $\zeta = 0 \to (1 + i) \to z$
- $c = i$ where the path $C$ is an inward spiral described by $z(t) = 0.99^t e^{i2\pi t}$ for $t = 0 \to t_0 \to \infty$
- $c = e^{-\tau_0}$ where $\tau_0 > 0$ is a real number, and $C$ is $z = (1 - i\infty) \to (1 + i\infty)$. *Hint: Do you recognize this integral? If you do not recognize the integral, please do not spend a lot of time trying to solve it via the ‘brute force’ method.*
Cauchy’s theorems for integration in the complex plane

There are three basic definitions related to Cauchy’s integral formula. They are all related, and can greatly simplify integration in the complex plane. When a function depends on a complex variable we shall use uppercase notation, consistent with the engineering literature for the Laplace transform.

1. **Cauchy’s (Integral) Theorem** (Stillwell, p. 319; Boas, p. 45)

    \[ \oint_C F(z) \, dz = 0, \]

    if and only if \( F(z) \) is complex-analytic inside of \( C \).

    This is related to the Fundamental Theorem of Complex Calculus (FTCC)

    \[ f(z) = f(a) + \int_a^z F(z) \, dz, \]

    where \( f(z) \) is the anti-derivative of \( F(z) \), namely \( F(z) = \frac{df}{dz} \). The FTCC requires \( F(z) \) to be complex-analytic for all \( z \in \mathbb{C} \). By closing the path (contour \( C \)), Cauchy’s theorem (and the following theorems) allows us to integrate functions that may not be complex-analytic for all \( z \in \mathbb{C} \).

2. **Cauchy’s Integral Formula** (Boas, p. 51; Stillwell, p. 220)

    \[ \frac{1}{2\pi j} \oint_C \frac{F(z)}{z-z_0} \, dz = \begin{cases} F(z_0), & z_0 \in C \text{ (inside)} \\ 0, & z_0 \notin C \text{ (outside)} \end{cases} \]

    Here \( F(z) \) is required to be analytic everywhere within (and on) the contour \( C \). \( F(z_0) \) is called the residue of the pole.

3. **(Cauchy’s) Residue Theorem** (Boas, p. 72)

    \[ \oint_C F(z) \, dz = 2\pi j \sum_{k=1}^K \text{Res}_k, \]

    where \( \text{Res}_k \) are the residues of all poles of \( F(z) \) enclosed by the contour \( C \).

    **How to calculate the residues**: The residues can be rigorously defined as

    \[ \text{Res}_k = \lim_{z \to z_k} [(z - z_k)f(z)]. \]

    This can be related to Cauchy’s integral formula: Consider the function \( F(z) = \frac{w(z)}{(z - z_k)} \), where we have factored \( F(z) \) to isolate the first-order pole at \( z = z_k \). If the remaining factor \( w(z) \) is analytic at \( z_k \), then the residue of the pole at \( z = z_k \) is \( w(z_k) \).

**To do:**

- In one or two brief sentences, describe the relationships between the three theorems:
  - (1) and (2)
  - (1) and (3)
  - (2) and (3)
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- Consider the function with poles at $z = \pm j$

$$F(z) = \frac{1}{1 + z^2} = \frac{1}{(z-j)(z+j)}$$

Apply Cauchy’s theorems to solve the following integrals. **State which theorem(s) you used, and show your work.**

- $\oint_C F(z)\,dz$ where $C$ is a circle centered at $z = 0$ with a radius of $\frac{1}{2}$.
- $\oint_C F(z)\,dz$ where $C$ is a circle centered at $z = j$ with a radius of 1.
- $\oint_C F(z)\,dz$ where $C$ is a circle centered at $z = 0$ with a radius of 2.

**Integration in the complex plane**

In the following questions, you’ll be asked to integrate $F(s) = u(\sigma, \omega) + iv(\sigma, \omega)$ around the contour $C$ for complex $s = \sigma + i\omega$.

$$\oint_C F(s)\,ds.$$

Follow the directions carefully for each question. When asked to state where the function is and is not analytic, you are not required to use the Cauchy-Riemann equations (but you should if you can’t answer the question ‘by inspection’).

**To do:**

1. $F(s) = \frac{1}{s}$
   - State where the function is and is not analytic.
   - Explicitly evaluate the integral when $C$ is the unit circle, defined as $s = e^{i\theta}$, $0 \leq \theta \leq 2\pi$.
   - Evaluate the same integral using Cauchy’s theorem and/or the residue theorem.

2. $F(s) = \frac{1}{s^2}$
   - State where the function is and is not analytic.
   - Explicitly evaluate the integral when $C$ is the unit circle, defined as $s = e^{i\theta}$, $0 \leq \theta \leq 2\pi$.
   - What does your result imply about the residue of the $2^{nd}$ order pole at $s = 0$?

3. $F(s) = e^{st}$
   - State where the function is and is not analytic.
   - Explicitly evaluate the integral when $C$ is the square $(\sigma, \omega) = (1, 1) \rightarrow (-1, 1) \rightarrow (-1, -1) \rightarrow (1, -1) \rightarrow (1, 1)$.
   - Evaluate the same integral using Cauchy’s theorem and/or the residue theorem.

4. $F(s) = \frac{1}{s^{1/2}}$
   - State where the function is and is not analytic.
   - Let $C$ be the unit circle, defined as $s = e^{i\theta}$, $0 \leq \theta \leq 2\pi$. Evaluate the integral using Cauchy’s theorem and/or the residue theorem.
   - Let $C$ be a circle of radius 3, defined as $s = 3e^{i\theta}$, $0 \leq \theta \leq 2\pi$. Evaluate the integral using Cauchy’s theorem and/or the residue theorem.

5. $F(s) = \frac{1}{2\pi j} \left[ e^{st} \right]_{s = \frac{t}{\pi}}^{s = 0}$
• State where the function is and is not analytic.
• Let \( C \) be a circle of radius 3, defined as \( s = 3e^{i\theta}, 0 \leq \theta \leq 2\pi \). Evaluate the integral using Cauchy’s theorem and/or the residue theorem.
• Let \( C \) contain the entire left-half \( s \)-plane. Evaluate the integral using Cauchy’s theorem and/or the residue theorem. Do you recognize this integral?

6. \( F(s) = \pm \frac{1}{\sqrt{s}} \) (e.g. \( F^2 = \frac{1}{s} \))

• State where the function is and is not analytic.
• This function is multivalued. How many Riemann sheets do you need in the domain (\( s \)) and the range (\( f \)) to fully represent this function? Indicate (e.g. using a sketch) how the sheet(s) in the domain map to the sheet(s) in the range.
• Explicitly evaluate the integral

\[
\int_C \frac{1}{\sqrt{z}} \, dz
\]

when \( C \) is the unit circle, defined as \( s = e^{i\theta}, 0 \leq \theta \leq 2\pi \). Is this contour ‘closed’? State why or why not.
• Explicitly evaluate the integral

\[
\int_C \frac{1}{\sqrt{z}} \, dz
\]

when \( C \) is twice around the unit circle, defined as \( s = e^{i\theta}, 0 \leq \theta \leq 4\pi \). Is this contour ‘closed’? State why or why not. Hint: Note that \( \sqrt{e^{i(\theta + 2\pi)}} = \sqrt{e^{2\pi} e^{i\theta}} = e^{i\pi} \sqrt{e^{i\theta}} = -1/\sqrt{e^{i\theta}} \).

• What does your result imply about the residue of the (twice-around \( \frac{1}{2} \) order) pole at \( s = 0 \)?
• Show that the residue is zero (apply the definition of the residue).

A two-port network application for the Laplace transform

The Laplace transform (LT) and inverse Laplace transform (ILT): Recall that the Laplace transform (LT) \( f(t) \leftrightarrow F(s) \)\(^{18}\) of a causal function \( f(t) \) is

\[
F(s) = \int_0^\infty f(t)e^{-st} \, dt,
\]

where \( s = \sigma + j\omega \) is complex frequency\(^{19}\) in [radians] and \( t \) is time in [seconds]. Causal functions and the Laplace transform are particularly useful for describing systems, which have no response until a signal enters the system (e.g. at \( t = 0 \)).

To define the inverse Laplace transform (ILT) we need to understand integration in the complex plane

\[
f(t) = \frac{1}{2\pi j} \int_{\sigma_0 - j\infty}^{\sigma_0 + j\infty} F(s)e^{st} \, ds = \frac{1}{2\pi j} \oint_C F(s)e^{st} \, ds.
\]

The Laplace contour \( C \) actually includes two pieces

\[\oint_C = \int_{\sigma_0 - j\infty}^{\sigma_0 + j\infty} + \int_{C_\infty},\]

\(^{18}\)Many loosely adhere to the convention that the frequency domain uses upper-case [e.g. \( F(s) \)] while the time domain uses lower case [\( f(t) \)].

\(^{19}\)While radians are useful units for calculations, when providing physical insight in discussions of problem solutions, it is easier to work with Hertz, since frequency in [Hz] and time in [s] are mentally more more natural units than radians. The same is true of degrees vs. radians. Boas (p. 10) recommends the use degrees over radians. He gives the example of \( 3\pi/5 \) [radians], which is more easily visualize as \( 108^\circ \).
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where the path represented by ‘$C_\infty$’ is a semicircle of infinite radius with $\sigma \to -\infty$. It is somewhat tricky to do, but it may be proved that the integral over the contour $C_\infty$ goes to zero. For a causal, ‘stable’ (e.g. doesn’t blow up over time) signal, all of the poles of $F(s)$ must be inside of the Laplace contour, in the left-half $s$-plane.

**Transfer functions** Linear, time-invariant systems are described by an ordinary differential equation. For example, consider the first-order linear differential equation

$$a_1 \frac{d}{dt} y(t) = b_1 \frac{d}{dt} x(t) + b_0 x(t). \tag{4.41}$$

This equation describes the relationship between the input ($x(t)$) and output ($y(t)$) of the system. If we define Laplace transforms $y(t) \leftrightarrow Y(s)$ and $x(t) \leftrightarrow X(s)$, then this equation may be written in the frequency domain as

$$a_1 s Y(s) = b_1 s X(s) + b_0 X(s).$$

The **transfer function** for this system is defined as

$$H(s) = \frac{Y(s)}{X(s)} = \frac{b_1 s + b_0}{a_1 s} = \frac{b_1}{a_1} + \frac{b_0}{a_1 s}.$$

In this problem, we will look at the transfer function of a simple two-port network, shown in Figure 4.7. This network is an example of a RC low-pass filter, which acts as a leaky integrator.

![Figure 4.7: This three-element electrical circuit is a system that acts to low-pass filter the signal voltage $V_1(\omega)$, to produce signal $V_2(\omega)$.

To do:

- Use the ABCD method to find the matrix representation of Fig. 4.7.
- Assuming that $I_2 = 0$, find the transfer function $H(s) \equiv V_2/V_1$. From the results of the ABCD matrix you determined above, show that

$$H(s) = \frac{1}{1 + R_1 C s}.$$

- The transfer function $H(s)$ has one pole. Where is the pole? Find the residue of this pole.
- Find $h(t)$, the inverse Laplace transform of $H(s)$.
- Assuming that $V_2 = 0$ find $Y_{12}(s) \equiv I_2/V_1$.
- Find the input impedance to the right-hand side of the system, $Z_{22}(s) \equiv V_2/I_2$ for two cases:
  - $I_1 = 0$
  - $V_1 = 0$
- Compute the determinant of the ABCD matrix. **Hint:** It is always 1.
- Compute the derivative of $H(s) = \frac{V_2}{V_1} \bigg|_{I_2=0}$. 
With the help of a computer

In the following problems, we will look at some of the concepts from this homework using Matlab/Octave. We are using the \texttt{syms} function which requires Matlab’s/Octave’s symbolic math toolbox. Or you may use the EWS lab’s Matlab. Alternative symbolic-math tool, such as Wolfram Alpha.

1. To find the Taylor series expansion about \( s = 0 \) of
   
   \[ F(s) = - \log(1 - s), \]

   first consider the derivative and its Taylor series (about \( s = 0 \))
   
   \[ F'(s) = \frac{1}{1 - s} = \sum_{n=0}^{\infty} s^n. \]

   Then, integrate this series term by term
   
   \[ F(s) = - \log(1 - s) = \int F'(s) \, ds = \sum_{n=0}^{\infty} \frac{s^n}{n}. \]

   Alternatively you may use Matlab/Octave commands:

   ```matlab
   syms s
   taylor(-log(1-s),'order',7)
   ```

   To do:
   
   • Try the above Matlab/Octave commands. Give the first 7 terms of the Taylor series (confirm that Matlab/Octave agrees with the formula derived above).
   
   • What is the inverse Laplace transform of this series? Consider the series term by term.

2. The function \( \frac{1}{\sqrt{z}} \) has a branch point at \( z = 0 \), thus it is singular there.

   • Can you apply Cauchy’s integral theorem when integrating around the unit circle?
   
   • Below is a Matlab/Octave code that computes \( \int_0^{2\pi} \frac{dz}{\sqrt{z}} \) using Matlab’s/Octave’s symbolic analysis package:

   ```matlab
   syms z
   I=int(1/sqrt(z))
   J = int(1/sqrt(z),exp(-j*pi),exp(j*pi))
eval(J)
   ```

   To do: Run this script. What answers do you get for \( I \) and \( J \)?

   • Modify this code to integrate \( f(z) = \frac{1}{z^2} \) \textit{once} around the unit circle. What answers do you get for \( I \) and \( J \)?

3. Bessel functions can describe waves in a cylindrical geometry (e.g. vibrations of a drum head). The Bessel function has a Laplace transform with a branch cut

   \[ J_0(t)u(t) \leftrightarrow \frac{1}{\sqrt{1 + s^2}}. \]

   Draw a hand sketch showing the nature of the branch cut. Hint: Use \texttt{zviz}.

\footnote{https://www.wolframalpha.com/}
To do:

- Try the following Matlab/Octave commands, and then comment on your findings.

```matlab
% Take the inverse LT of 1/sqrt(1+s^2)
syms s
I=ilaplace(1/(sqrt((1+s^2))));
disp(I)

% Find the Taylor series of the LT
T = taylor(1/sqrt(1+s^2),10);
disp(T);

% Verify this
syms t
J=laplace(besselj(0,t));
disp(J);

% Plot the Bessel function
w=0:0.1:10*pi;
b=besselj(0,w);
plot(w/b,
grid on;
```

- When did Friedrich Bessel live? What did he use Bessel functions for?

4. Using `zviz`, for each of the following functions

i. Describe the plot generated by \( zviz S=Z \).

ii. Are the functions defined below legal Brune impedances? (i.e., Do they function obey \( \Re Z(\sigma > 0) \geq 0 \)?) *Hint: Consider the phase (color). Plot `zviz Z` for a reminder of the colormap.*

\[ zviz 1./sqrt(1+S.^2) \]

\[ zviz 1./sqrt(1-S.^2) \]

\[ zviz 1./(1+sqrt(S)) \]

Inverse Laplace transform of the zeta function \( \zeta(s) \)

Take the inverse Laplace transform of \( \zeta_p(s) \leftrightarrow z_p(t) \) (Eq. 3.9, p. 99) and describe the result in words. 

*Hint: Consider the geometric series representation*

\[
\zeta_p(s) = \frac{1}{1 - e^{-sT_p}} = \sum_{k=0}^{\infty} e^{-skT_p},
\]

*for which you can easily look up (or may have memorized) the inverse Laplace transform of each term.*

**Inverse transform of Product of factors:** The time domain version of Eq. 3.8 (p. 99) may be written as the convolution of all the \( z_k(t) \) factors

\[
z(t) = z_2 \ast z_3(t) \ast z_5(t) \ast z_7(t) \cdots \ast z_p(t) \cdots,
\]

where \( \ast \) represents time convolution.

Explain what this means in physical terms. Start with two terms (e.g., \( z_1(t) \ast z_2 \)).
tion that continuation of the infinity of possible continuations, that are not obvious in the frequency domain.

The eigen-modes of that cascaded impedance function.

input admittance of this cascade may be interpreted as an analytic continuation of the transmission line, defined at the ratio of the Laplace transform of the current

\[ \Gamma(s) = e^{-sT_p} \]

\[ \alpha q(n - T_p) + v(t) \]

\[ i(t) = q(t) - (1/\alpha)q(t - T_p) \]

Figure 4.8: This feedback network is described by a time-domain difference equation with delay \( T_p \), has an all-pole transfer function \( \zeta(s) \equiv Q(s)/I(s) \) given by Eq. 4.44, which physically corresponds to a stub of a transmission line, with the input at one end and the output at the other. To describe the \( \zeta(s) \) function we must take \( \alpha = -1 \). A transfer function \( Y(s) = V(s)/I(s) \) that has the same poles as \( \zeta(s) \), but with zeros as given by Eq. 4.45, is the input admittance \( Y(s) = I(s)/V(s) \) of the transmission line, defined at the ratio of the Laplace transform of the current \( i(t) \leftrightarrow I(s) \) over the voltage \( v(t) \leftrightarrow V(s) \).

**Physical interpretation:** Such functions may be generated in the time domain as shown in Fig. 4.8 (p. 174), using a feedback delay of \( T_p \) seconds described by the two equations in the figure with a unity feedback gain \( \alpha = -1 \). Taking the Laplace transform of the system equation we see that the transfer function between the state variable \( q(t) \) and the input \( x(t) \) is given by \( \zeta_p(s) \), which is and all-pole function, since

\[ Q(s) = e^{-sT_p}Q(s) + V(s), \text{ or } \zeta_p(s) \equiv \frac{Q(s)}{V(s)} = \frac{1}{1 - e^{-sT_p}}. \tag{4.44} \]

Closing the feed-forward path gives a second transfer function \( Y(s) = I(s)/V(s) \), namely

\[ Y(s) \equiv \frac{I(s)}{V(s)} = \frac{1 - e^{-sT_p}}{1 + e^{-sT_p}}. \tag{4.45} \]

If we take \( i(t) \) as the current and \( v(t) \) as the voltage at the input to the transmission line, then \( y_p(t) \leftrightarrow \zeta_p(s) \) represents the input impedance at the input to the line. The poles and zeros of the impedance interleave along the \( j\omega \) axis. By a slight modification \( \zeta_p(s) \) may alternatively be written as

\[ Y_p(s) = \frac{e^{sT_p/2} + e^{-sT_p/2}}{e^{sT_p/2} - e^{-sT_p/2}} = j \tan(sT_p/2). \tag{4.46} \]

Every impedance \( Z(s) \) has a corresponding reflectance function given by a Möbius transformation, which may be read off of Eq. 4.45 as

\[ \Gamma(s) \equiv \frac{1 + Z(s)}{1 - Z(s)} = e^{-sT_p} \tag{4.47} \]

since impedance is also related to the round-trip delay \( T_p \) on the line. The inverse Laplace transform of \( \Gamma(s) \) is the round trip delay \( T_p \) on the line

\[ \gamma(t) = \delta(t - T_p) \leftrightarrow e^{-sT_p}. \tag{4.48} \]

In terms of the physics, these transmission line equations are telling us that \( \zeta(s) \) may be decomposed into an infinite cascade of transmission lines (Eq. 4.43), each having a delay given by \( T_p = \ln \pi_p \). The input admittance of this cascade may be interpreted as an analytic continuation of \( \zeta(s) \) which defines the eigen-modes of that cascaded impedance function.

Working in the time domain provides a key insight, as it allows us to parse out the best analytic continuation of the infinity of possible continuations, that are not obvious in the frequency domain. Transforming to the time domain is a form of analytic continuation of \( \zeta(s) \), that depends on the assumption that \( z(t) \) is one-sided in time (causal).
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### 4.5.2 Lec 30: Inverse Laplace transform ($t > 0$)

**Case of $t > 0$:** Next we investigate the convergence of the integral for positive time $t > 0$. In this case we must close the integral in the LHP ($\sigma < 0$) for convergence, so that $st < 0$ ($\sigma \leq 0$ and $t > 0$). When there are poles on the $\omega = 0$ axis, $\sigma_{o} > 0$ assures convergence by keeping the on-axis poles inside the contour. At this point the Cauchy residue theorem (Eq. 4.35) is relevant. If we restrict ourselves to simple poles (as required for a Brune impedance), the residue theorem may be directly applied.

The most simple example is the step function, for which $F(s) = 1/s$ and thus

$$u(t) = \int_{\text{LHP}} e^{st} \frac{ds}{2\pi i} \leftrightarrow 1/s,$$

which is a direct application of the Cauchy residue theorem, Eq. 4.35 (p. 163). The forward transform of $u(t)$ is straightforward, as discussed in Section 3.7 (p. 130). This is true of most if not all of the elementary forward Laplace transforms. In these cases, causality is built into the integral by the limits, so it is not a result, as it must be in the inverse transform. An interesting problem is to prove that $u(t)$ is not defined at $t = 0$.

![Colorized plot of $u(z) = J_{0}(\pi z)$.](image1)

![Colorized plot of $u(t) = \cos(\pi(t+jy))$.](image2)

**Figure 4.9:** Left: Colorized plot of $u(z) = J_{0}(\pi z)$. The first zero is at 2.405, and thus appears at $0.7655 = 2.405/\pi$, somewhat larger than the root of $\cos(\pi/2)$. Right: Note the similarity to $u(z) = \sin(z)$. The LT’s have similar characteristics, as documented in Table B.2 (p. 250).

The inverse Laplace transform of $F(s) = 1/(s + 1)$ has a residue of 1 at $s = -1$, thus that is the only contribution to the integral. More demanding cases are Laplace transform pairs

$$\frac{1}{\sqrt{t}} u(t) \leftrightarrow \sqrt{\pi/s} \quad \text{and} \quad J_{0}(t) u(t) \leftrightarrow \frac{1}{\sqrt{s^{2}+1}},$$

and more on p. 250. Many of these are easily proved in the forward direction, but are much more difficult in the inverse direction, due to the properties at $t = 0$, unless of course the residue theorem (Eq. 4.35, p. 163) is invoked. The last LT-pair helps us understand the basic nature of the Bessel functions $J_{0}(z)$ and $H_{1}^{(1)}(z^{2})$, with a branch cut along the negative axis (Allen, 2019).

The form $\sqrt{s}$ is called a semi-inductor (Kim and Allen, 2013), also known as the skin effect in EM theory. The form $1/\sqrt{s}$ is a semi-capacitor.

**Some open questions:** Without the use of the CRT (Eq. 4.35) it is difficult to see how to evaluate the inverse Laplace transform of $1/s$ directly. For example, how does one show that the above integral is zero for negative time (or that it is 1 for positive time)? The CRT neatly solves this difficult problem by the convergence of the integral for negative and positive time. Clearly the continuity of the integral at $\omega \to \infty$ plays an important role. Perhaps the Riemann sphere plays a role in this that has not yet been explored.
4.5.3 **Lec 31: Properties of the LT (e.g., Linearity, convolution, time-shift, modulation, etc.)**

As shown in the table of Laplace transforms, there are integral (i.e., integration, not integer) relationships, or properties, that are helpful to identify. The first of these is a definition, not a property:

\[ f(t) \leftrightarrow F(s). \]

When taking the LT, the time response is given in lower case (e.g., \( f(t) \)) and the frequency domain transform is denoted in upper case (e.g., \( F(s) \)). It is required, but not always explicitly specified, that \( f(t < 0) = 0 \), that is, the time function must be **causal** (P1: Section 3.7.1).

**Linearity:** A key property so basic that it is almost forgotten, is the linearity property of the LT, summarized in P2 of Section 3.7.1 (p. 132).

**Convolution property:** One of the most basic and useful properties is that the product of two LTs in frequency results in convolution in time

\[ f(t) \ast g(t) = \int_0^t f(\tau)g(t - \tau)d\tau \leftrightarrow F(s)G(s), \]

where we use the \( \ast \) operator as a shorthand for the convolution of two time functions.

A key application of convolution is filtering, which takes many forms. The most basic filter is the moving average, the moving sum of data samples, normalized by the number of samples. Such a filter has very poor performance. It also introduces a delay of half the length of the average, which may or may not constitute a problem, depending on the application. Another important example is a low-pass filter that removes high-frequency noise, or a notch filter that removes line-noise (i.e., 60 [Hz] in the US, and its 2nd and 3rd harmonics, 120 and 180 [Hz]). Such noise is typically a result of poor grounding and ground loops. It is better to solve the problem at its root than to remove it with a notch filter. Still, filters are very important in engineering.

By taking the LT of the convolution we can derive this relationship:

\[
\int_0^{\infty} [f(t) \ast g(t)]e^{-st}dt = \int_0^{\infty} \left[ \int_0^{t} f(\tau)g(t - \tau)d\tau \right] e^{-st}dt
= \int_0^t f(\tau) \left[ \int_{t=0}^{\infty} g(t' - \tau)e^{-s't}d\tau \right] d\tau
= \int_0^t f(\tau) \left[ e^{-s\tau} \int_{t'=0}^{\infty} g(t')e^{-s't'}dt' \right] d\tau
= G(s) \int_0^t f(\tau)e^{-s\tau}d\tau
= G(s)F(s).
\]

We first encountered this relationship in Section ?? (p. ??) in the context of multiplying polynomials, which was the same as convolving their coefficients. Hopefully the parallel is obvious. In the case of polynomials, the convolution was discrete in the coefficients, and here it is continuous in time. But the relationships are the same.

**Time-shift property:** When a function is time-shifted by time \( T_o \), the LT is modified by \( e^{sT_o} \), leading to the property

\[ f(t - T_o) \leftrightarrow e^{-sT_o} F(s). \]

This is easily shown by applying the definition of the LT to a delayed time function.
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**Time derivative:** The key to the eigenfunction analysis provided by the LT is the transformation of a time derivative on a time function, that is,
\[
\frac{d}{dt} f(t) \leftrightarrow s F(s).
\]
Here $s$ is the eigenvalue corresponding to the time derivative of $e^{st}$. Given the definition of the derivative of $e^{st}$ with respect to time, this definition seems trivial. Yet that definition was not obvious to Euler. It needed to be extended to the space of complex analytic function $e^{st}$, which did not happen until at least Riemann (1851).

*Given a differential equation of order $K$, the LT results in a polynomial in $s$, of degree $K$. It follows that this LT property is the cornerstone of why the LT is so important to scalar differential equations, as it was to the early analysis of Pell’s equation and the Fibonacci sequence, as presented in earlier chapters.*

This property was first uncovered by Euler. It is not clear if he fully appreciated its significance, but by the time of his death, it certainly would have been clear to him. Who first coined the terms *eigenvalue* and *eigenfunction*? The word *eigen* is a German word meaning *of one*.

**Initial and final value theorems:** There are much more subtle relations between $f(t)$ and $F(s)$ that characterize $f(0^+)$ and $f(t \to \infty)$. While these properties can be very important in certain applications, they are beyond the scope of the present treatment. These relate to so-called initial value theorems. If the system under investigation has potential energy at $t = 0$, then the voltage (velocity) need not be zero for negative time. An example is a charged capacitor or a moving mass. These are important situations, but better explored in a more in-depth treatment.

### 4.5.4 Solving differential equations: Method of Frobenius

Many differential equations may be solved by assuming a power series (i.e., Taylor series) solution of the form
\[
y(x) = x^r \sum_{n=0}^{\infty} c_n x^n \quad (4.49)
\]
with coefficients $c_n \in \mathbb{C}$. The *method of Frobenius* is quite general (Greenberg, 1988, p. 193).

**Example:** When a solution of this form is substituted into the differential equation, a recursion relation in the coefficients results. For example, if the equation is
\[
y''(x) = \lambda^2 y(x)
\]
the recursion is $c_n = c_{n-1}/n$. The resulting equation is
\[
y(x) = e^{\lambda x} = x^0 \sum_{n=0}^{\infty} \frac{1}{n!} x^n,
\]
namely $c_n = 1/n!$, thus $nc_n = 1/(n - 1)! = c_{n-1}$.

**Exercise:** Find the recursion relation for Bessel’s equation of order $\nu$
\[
x^2 y''(x) + xy'(x) + (x^2 - \nu^2)y(x) = 0.
\]

**Solution:** If we assume a complex analytic solution of the form Eq. 4.49, we find the Bessel recursion relation for coefficients $c_k$ to be
\[
c_k = -\frac{1}{k(k + 2\nu)} c_{k-2}
\]
(Greenberg, 1988, p. 231).
4.5.5 Exercises DE-3

Laplace transforms

Given a Laplace transform (LT) pair \( f(t) \leftrightarrow F(s) \), the frequency domain will always be upper-case [e.g. \( F(s) \)] and the time domain lower case \([f(t)] \) and causal (i.e., \( f(t < 0) = 0 \)). The definition of the forward transform \((f \rightarrow F(s))\) is

\[
F(s) = \int_{0}^{\infty} f(t) e^{-st} dt, \]

where \( s = \sigma + j\omega \) is the complex Laplace frequency in [radians] and \( t \) is time in [seconds].

The inverse Laplace transform (LT\(^{-1}\)), \( F(s) \rightarrow f(t) \) is defined as

\[
f(t) = \frac{1}{2\pi j} \int_{\sigma_0-j\infty}^{\sigma_0+j\infty} F(s) e^{st} ds = \frac{1}{2\pi j} \oint_{C} F(s) e^{st} ds
\]

with \( \sigma_0 > 0 \in \mathbb{R} \) is a positive constant.

As discussed in the lecture notes (Section 1.4.7, p. 72) we may use the Cauchy Residue Theorem (CRT), to evaluate the \( LT^{-1} \), by requiring closure of the contour \( C \) at \( \omega j \rightarrow \pm j\infty \)

\[
\oint_{C} = \int_{\sigma_0-j\infty}^{\sigma_0+j\infty} + \int_{C_{\infty}},
\]

where the path represented by ‘\( C_{\infty} \)’ is a semicircle of infinite radius. For a causal, ‘stable’ (e.g. doesn’t “blow up” in time) signal, all of the poles of \( F(s) \) must be inside of the Laplace contour, in the full (closed) left-half \( s \)-plane \((\sigma \leq 0)\).

![Figure 4.10: Three-element mechanical resonant circuit consisting of a spring, mass and dash-pot (e.g., viscous fluid).](image)

Hooke’s law for a spring states that the force \( f(t) \) is proportional to the displacement \( x(t) \), i.e., \( f(t) = K x(t) \). The formula for a dash-pot is \( f(t) = R v(t) \), and Newton’s famous formula for mass is \( f(t) = d[M v(t)]/dt \), which for constant \( M \) is \( f(t) = M dv/dt \).

The equation of motion for the mechanical oscillator in Fig. 4.10 is given by Newton’s second law; the sum of the forces must balance to zero

\[
M \frac{d^2 x(t)}{dt^2} + R \frac{dx(t)}{dt} + K x(t) = f(t).
\]

These three constants – the mass \( M \), resistance \( R \) and stiffness \( K \) – are all real and positive. The dynamical variables are the driving force \( f(t) \leftrightarrow F(s) \), the position of the mass \( x(t) \leftrightarrow X(s) \) and its velocity \( v(t) \leftrightarrow V(s) \), with \( v(t) = dx(t)/dt \leftrightarrow V(s) = sX(s) \).
4.5. LECTURE 29: INVERSE LAPLACE TRANSFORM (T < 0): CAUCHY RESIDUE THEOREM

Brune Impedance

A Brune impedance is defined as the ratio of the force \( F(s) \) over the flow \( V(s) \), and may be expressed in residue form as

\[
Z(s) = c_0 + \sum_{k=1}^{K} \frac{c_k}{s - s_k} = \frac{N(s)}{D(s)} \tag{4.51}
\]

with

\[
D(s) = \prod_{k=1}^{K} (s - s_k) \quad \text{and} \quad c_k = \lim_{s \to s_k} (s - s_k)D(s) = \prod_{n'=1}^{K-1} (s - s_n).
\]

The prime on index \( n' \) means that \( n = k \) is not included in the product.

To do:

1. Find the Laplace transform (\( \mathcal{L}T \)) of the three force relations in terms of the force \( F(s) \) and the velocity \( V(s) \), along with the electrical equivalent impedance:
   
   (a) Hooke's Law \( f(t) = Kx(t) \).
   
   (b) Dash-pot resistance \( f(t) = Rv(t) \).
   
   (c) Newton's Law for Mass \( f(t) = Md\frac{dv(t)}{dt} \).

2. Take the Laplace transform (\( \mathcal{L}T \)) of Eq. 3.50, and find the total impedance \( Z(s) \) of the mechanical circuit.

3. What are \( N(s) \) and \( D(s) \) (e.g. Eq. 4.51)?

4. Assume that \( M = R = K = 1 \), find the residue form of the admittance \( Y(s) = 1/Z(s) \) (e.g. Eq. 4.51) in terms of the roots \( s_{\pm} \). You may check your answer with the Matlab's \texttt{residue} command.

5. By applying the CRT, find the inverse Laplace transform (\( \mathcal{L}T^{-1} \)). Use the residue form of the expression that you derived in the previous exercise.

\[ \begin{array}{cccc}
\text{\textcolor{red}{f}_1} & \text{\textcolor{red}{M}} & \text{\textcolor{red}{K}} & \text{\textcolor{red}{f}_2} \\
\text{\textcolor{red}{v}_1} & \frac{1}{2}M & \text{\textcolor{red}{C}} & \text{\textcolor{red}{v}_2} \\
\text{\textcolor{red}{f}_3} & \text{\textcolor{red}{M}} & \text{\textcolor{red}{K}} & \text{\textcolor{red}{f}_4} \\
\text{\textcolor{red}{v}_3} & \text{\textcolor{red}{v}_4} & \frac{1}{2}M \\
\end{array} \]

Figure 4.11: Depiction of a train consisting of cars, treated as a mass \( M \) and linkages, treated as springs of stiffness \( K \) or compliance \( C = 1/K \). Below it is the electrical equivalent circuit, for comparison. The mass is modeled as an inductor and the springs as capacitors to ground. The velocity is analogous to a current and the force \( f_n(t) \) to the voltage \( v_n(t) \). The train may be accurately modeled as a transmission line (TL), since the equivalent electrical circuit is a lumped model of a TL.

Disc this in Book-Supplement for constant and variable mass and compliance Make \( \Delta \) small such that HOTs may be ignored. Apply Nyquest thm, with two cells per wavelength.
Transfer functions

In this problem, we will look at the transfer function of a two-port network, shown in Fig. 4.11. We wish to model the dynamics of a freight-train having \(N\) such cars. The model of the train consists of masses connected by springs.

The velocity transfer function for this system is defined as the ratio of the output to the input velocity. Consider the engine on the left pulling the train at velocity \(V_1\) and each car responding with a velocity of \(V_n\). Then

\[
H(s) = \frac{V_N(s)}{V_1(s)}
\]

is the frequency domain ratio of the last car having velocity \(V_N\) to \(V_1\), the velocity of the engine, at the left most spring (i.e., coupler).

To do: Use the ABCD method to find the matrix representation of Fig. 4.11. Consistent with the figure, break the model into cells each consisting of three elements: a series inductor representing half the mass \((L = M/2)\), a shunt capacitor representing the spring \((C = 1/K)\), and another series inductor representing half the mass \((L = M/2)\). Each cell is symmetric, making the model a cascade of identical cells (P7, p. 133).

At each node define the force \(f_n(t) \leftrightarrow F_n(\omega)\) and the velocity \(v_n(t) \leftrightarrow V_n(\omega)\) at junction \(n\).

1. Write the ABCD matrix \(T\) for a single cell, composed of series mass \(M/2\), shunt compliance \(C\) and series mass \(M/2\), that relates the input node 1 to node 2, where

\[
\begin{bmatrix}
F_1 \\
V_1
\end{bmatrix} = T
\begin{bmatrix}
F_2(\omega) \\
-V_2(\omega)
\end{bmatrix}.
\]

Note that here the mechanical force \(F\) is analogous to electrical voltage, and the mechanical velocity \(V\) is analogous to electrical current.

Solution:

\[
T = \begin{bmatrix}
1 & sM/2 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
sC & 1
\end{bmatrix}
\begin{bmatrix}
1 & sM/2 \\
0 & 1
\end{bmatrix}
\approx
\begin{bmatrix}
1 + s^2MC/2 & (sM)(1 + s^2MC/4) \\
sC & 1 + s^2MC/2
\end{bmatrix}
\]

Defining the wave velocity

\[
c_o = \frac{1}{\sqrt{MC}} < \omega_c/2 < \omega_c\sqrt{2}/2,
\]

and the wave delay \(T_o\), the wavelength \(\lambda = c_o/f\), and the the distance between cars as \(\Delta_o = c_oT_o\), we may define the Nyquist sampling rate as approximation Eq. 4.52b follows when \(\omega < \omega_c\).

Solution: Such a system is a transmission line having a wave speed of \(c_o = 1/\sqrt{MC}\) and the characteristic impedance of \(r_o = \sqrt{MC}\). Each cell, composed of 2 masses connected by one spring, is taken to have a length \(\Delta\).

We wish to find the Nyquist frequency \(f_c\) such that the wavelength \(\lambda > n\Delta\), where \(\Delta\) is the cell length. Using the formula for the wavelength in terms of the wave velocity and frequency we find

\[
\lambda = c_o/f_c = n\Delta.
\]
Nyquist sampling requires \( n > 2 \). For Nyquist sampling \((n > 2)\), we conclude that

\[
f_c < \frac{c_0}{2\Delta} = \frac{1}{2\Delta\sqrt{MC}}.
\]

If we wish to have the system be accurate for a given frequency we must make \( \Delta \) smaller, while keeping the velocity constant. Thus the characteristic resistance \( r_o \) will change as \( f_c \to \infty \) and \( \Delta \to 0 \). We can either let \( M \to \infty \) and \( C \to 0 \) with their product constant, or the other way around. In one case \( r_o \to \infty \) and in the other it goes to 0.

From Appendix E this matrix has eigenvalues

\[
\lambda_{\pm} = 1 \mp 2s/s_c \approx e^{\pm sT_c}.
\]

The eigenvectors are

\[
E_{\pm} = \begin{bmatrix} \mp \sqrt{M/C} \\ 1 \end{bmatrix},
\]

with the characteristic impedance defined as \( r_o = \sqrt{M/C} \).

2. Assuming that \( N = 2 \) and that \( F_3 = 0 \) (two mass problem), find the transfer function \( H(s) \equiv V_2/V_1 \). From the results of the \( T \) matrix you determined above, find

\[
H_{21}(s) = \frac{V_2}{V_1} \bigg|_{F_2=0}
\]

**Solution:** From the lower equation we see that \( V_1 = sCF_2 - (s^2MC/2 + 1)V_2 \). Recall that \( F_2 = 0 \), thus

\[
\begin{aligned}
\frac{V_2}{V_1} &= \frac{-1}{s^2MC/2 + 1} = \left( \frac{c_+}{s - s_+} + \frac{c_-}{s - s_-} \right), \\
\end{aligned}
\]

with complex eigenfrequencies \( s_{\pm} = \pm j\sqrt{\frac{2}{MC}} = \pm \sqrt{2} s_c \) and complex residues \( c_{\pm} = \pm j/\sqrt{2MC} = \pm s_c/\sqrt{2} \).

3. Find \( h_{21}(t) \), the inverse Laplace transform of \( H_{21}(s) \). **Solution:**

\[
h(t) = \oint_{s_0-j\infty}^{s_0+j\infty} \frac{e^{st}}{s^2MC/2 + 1} \frac{ds}{2\pi j} = c_+ e^{-s_+t}u(t) + c_- e^{-s_-t}u(t).
\]

The integral follows from the CRT. The poles are at \( s_{\pm} = \pm j\sqrt{\frac{2}{MC}} \) and the residues are \( c_{\pm} = \pm j/\sqrt{2MC} \).

4. What is the input impedance \( Z_2 = F_2/V_2 \) if \( F_3 = -r_0V_3 \)? **Solution:** Starting from \( T \) calculated above, find \( Z_2 \)

\[
Z_2(s) = \frac{F_2}{V_2} = \frac{F_3}{-V_3} = \frac{-(1 + s^2CM/2)r_0V_3 - sM(1 + s^2CM/4)V_3}{-sCr_0V_3 - (1 + s^2CM/2)V_3}
\]

5. Simplify the expression for \( Z_2 \) with \( N \to \infty \) by defining the characteristic impedance as \( r_0 = \sqrt{M/C} \) and again assuming that: 1) \( F_3 = -r_0V_3 \) (i.e., \( -V_3 \) cancels), 2) \( |s/s_c| \to 0 \) (Nyquist approximation).
**Solution:** Applying the Nyquist approximation (i.e., \( s/s_c \to 0 \))

\[
Z_2(s) = \frac{r_o(1 + s^2CM/2) + sM(1 + s^2CM/4)}{r_osC + (1 + s^2CM/2)} \\
\approx \frac{r_o + sM}{1 + r_osC} = \frac{MC}{1 + r_osC} \\
= \frac{r_o}{M + r_os/s_c} \\
\approx r_o + sM \\
= r_o.
\]

This shows that below the cutoff frequency (Nyquist approximation), the system approximates a transmission line terminated in its characteristic impedance.

6. State the ABCD matrix relationship between the first and \( N \)th node, in terms of the cell matrix.

**Solution:**

\[
\begin{bmatrix} F_1 \\ V_1 \end{bmatrix} = T^N \begin{bmatrix} F_N(\omega) \\ -V_N(\omega) \end{bmatrix}
\]

7. Given a \( T \) (ABCD) transmission matrix, the eigenvalues are and vectors are given in Appendix F, p. 269, repeated here.

**Eigenvalues:**

\[
\lambda_+ = \frac{1}{2} \left( (A + D) - \sqrt{(A - D)^2 + 4BC} \right), \quad \lambda_- = \frac{1}{2} \left( (A + D) + \sqrt{(A - D)^2 + 4BC} \right)
\]

Due to symmetry, \( A = D \), this simplifies to \( \lambda_\pm = A \mp \sqrt{BC} \) so that the eigenmatrix is

\[
\Lambda = \begin{bmatrix} A - \sqrt{BC} & 0 \\ 0 & A + \sqrt{BC} \end{bmatrix}
\]

**Eigenvectors:** The eigenvectors simplifying even more

\[
\begin{bmatrix} E_+ \\ E_- \end{bmatrix} = \frac{1}{\mp \sqrt{B/C}} \begin{bmatrix} (A - D) \mp \sqrt{(A - D)^2 + 4BC} \\ 1 \end{bmatrix} = \begin{bmatrix} \pm \sqrt{B/C} \\ 1 \end{bmatrix}
\]

**Eigenmatrix:**

\[
E = \begin{bmatrix} -\sqrt{B/C} & 1/\sqrt{B/C} \\ 1 & 1 \end{bmatrix}, \quad E^{-1} = \frac{1}{2} \begin{bmatrix} -\sqrt{B/C} & 1 \\ 1 & 1 \end{bmatrix}
\]

**To do:** What is the velocity transfer function \( H_{N1} = \frac{V_N}{V_1} \)? Hint: Use an eigenmatrix diagonalization, as we did for the Pell equation (Appendix C).

**Solution:**

\[
\begin{bmatrix} F_1 \\ V_1 \end{bmatrix} = T^N \begin{bmatrix} F_N(\omega) \\ -V_N(\omega) \end{bmatrix}
\]

along with the eigenvalue expansion

\[
T^N = EA^NE^{-1} = E \begin{bmatrix} \lambda_+^N & 0 \\ 0 & \lambda_-^N \end{bmatrix} E^{-1}.
\]
Chapter 5

Vector Calculus (Stream 3b)

5.1 Lec 32: Properties of Fields and potentials

Before we can define the vector operations \( \nabla(), \nabla \cdot (), \nabla \times (), \nabla^2() \), we must define the objects they operate on: scalar and vector fields. The word field has two very different meanings: a mathematical one, which defines an algebraic structure, and a physical one, discussed next.

Ultimately we wish to integrate in \( \mathbb{R}^3 \), \( \mathbb{R}^n \) and \( \mathbb{C}^n \). Integration is quantified by several fundamental theorems of calculus, each about integration (Section 4.2, p. 146-147).

**Scalar fields:** We use the term scalar field interchangeably with analytic in a connected region of the spatial vector \( x = [x, y, z]^T \in \mathbb{R}^3 \). In mathematics, functions that are piece-wise differentiable are called smooth, which is distinct from analytic. Every analytic function may be written as a single valued and infinitely differentiable power series. A smooth function has at least one or more derivatives, but need not be analytic.

**Example:** The function \( f(t) = tu(t) \) is smooth and has one smooth derivative

\[
\frac{d}{dt} tu(t) = u(t) + t\delta(t), \quad \frac{d^2}{dt^2} tu(t) = \frac{d}{dt} u(t) = \delta(t),
\]

but does not have a second derivative at \( t = 0 \). Thus \( tu(t) \) is not analytic at \( t = 0 \). However it has a Laplace transform \( F(s) \leftrightarrow f(t) \)

\[
u(t) = u(t) \ast u(t) \leftrightarrow \frac{1}{s^2}
\]

with a second-order pole at \( s = 0 \) with residue 1. Thus the Laplace transform is analytic everywhere, except at its second-order pole. If we let \( \zeta = 1/s \), \( F(\zeta) = \zeta^2 \) is analytic on the open disk \( |\zeta| < \infty \).

**Example:** The outbound eigenfunction of the lossy scalar wave equation in spherical coordinates (i.e, the spherical Bessel function) is

\[
g(r, t) = \frac{e^{st - \kappa(s)r}}{r},
\]

where \( g(r, t) \) is the pressure, \( \kappa(s) = (s + \beta_o \sqrt{s})/c_o \) is the complex wave number (Eq. K.1, p. 287), \( c_o \) is the speed of sound and \( r = \sqrt{\bar{x} \cdot \bar{x}} \). If we ignore viscous and thermal losses, \( \beta_o = 0 \) (Mason, 1928).

Note that \( \ln g(r) = st - \kappa(s)r - \ln r \) is analytic everywhere except at \( r = 0 \), yet is double-valued due to \( \sqrt{\bar{x}} \), forcing a branch cut, as required to fully describe it in the complex \( s \) plane.

---

Initially we will limit the definition to an analytic surface $S(x)$, as shown in Fig. 5.1, having height $z(x, y) \in \mathbb{R}$, as a function of $x, y \in \mathbb{R}^2$ (a plane)

$$z(x, y, t) = \phi(x, y, t),$$

where $z(x, y, t)$ describes a surface that is analytic in $x$. We may allow the field to optionally be a single-valued function of time $t \in \mathbb{R}$, since that is the nature of the solutions of the equations we wish to solve.

For example picture the smooth single-valued potential a height $z$ (e.g., constant temperature at height $z$) shown in Fig. 5.1, having isoclines (lines on a surface with constant slope).

Vector fields: A vector field\(^3\) is composed of three scalar fields. For example, the electric field used in Maxwell’s equations $E(x, t) = [E_x, E_y, E_z]^T$ [V/m] has three components, each of which is a scalar field. When the magnetic flux vector $B(x)$ is static (P5, p. 132), the potential $\phi(x)$ [V] uniquely defines $E(x, t)$ via the gradient.

$$E(x, t) = -\nabla \phi(x, t). \quad [\text{V/m}] \quad (5.1)$$

The electric force on a charge $q$ is $F = qE$, thus $E$ is proportional to the force, and when the medium is conductive, the current density (a flow) is $J = \sigma E \quad [\text{A/m}^2]$.

Example: Suppose we are given the vector field in $\mathbb{R}^3$

$$A(x) = [\phi(x), \psi(x), \theta(x)]^T, \quad [\text{Wb/m}]$$

where each of the three functions is a scalar field. For example, $A(x) = [x, xy, xyz]^T$ is a legal vector field (the components are analytic in $x$).

Taking an example from Maxwell’s equations, the magnetic flux vector is given by\(^4\)

$$B(x, t) = \nabla \times A(x, t). \quad [\text{Wb/m}^2] \quad (5.2)$$

We shall see that this is always true because the magnetic charge $\nabla \cdot B(x, t)$ is always 0. This assumes in-vacuo conditions.

To verify that a field is a potential, check out the units [V, A, °C]. However, a proper mathematical definition is that the potential must be an analytic function of $x$ and $t$, so that one may operate on it with $\nabla()$ and $\nabla \times ()$. The divergence of a scalar field is not a legal operation.

A helpful discussion of vector potentials, with extensive examples, may be found in Feynman (1970c, p. 14-1 to 14.3). If you need to master vector potentials, read Feynman (1970c, Ch. 14.1).

\(^3\)https://en.wikipedia.org/wiki/Vector_field

\(^4\)Perhaps this might be generalized by replacing $A$ by $A - \dot{D}$ where $D = \epsilon(x, t)E(x, t)$. 
Scalar potentials: The above discussion shows the utility of potentials for defining vector fields (e.g., Eqs. 5.1 and 5.2). The distinction between a potential and a scalar field is that potentials have units, and thus have a physical meaning. Scalar potentials (i.e., voltage $\phi(x, t)$ [V], temperature $T(x, t)$ [$^\circ$C] and pressure $p(x, t)$ [Pascals]) are examples of physical scalar fields. All potentials are composed of scalar fields, but not all scalar fields are potentials.

Example: The $\hat{y}$ component of $E$, $E_y(x, t) = \hat{y} \cdot E(x, t)$ [V/m], is not a potential. While $\nabla E_y$ is mathematically defined, as the gradient of one component of a vector field, it has no physical meaning (as best I know).

Example: The step function $u(t) \leftrightarrow 1/s$ is not analytic at time $t = 0$. In the Laplace frequency domain, $1/s$ is not complex analytic at $s = 0$, due to the pole.

Vector potentials: Vector potentials, like scalar potentials, are vector fields with physically meaningful units. They are more complicated than scalar potentials because they are composed of three scalar fields. This follows from the fundamental theorem of vector calculus, i.e., Helmholtz’s decomposition theorem.

Since we find it useful to analyze problems using voltage, and then take the gradient to find the electric field $E(x, t)$, the same logic and utility holds when using the vector potential, to determine the magnetic field $B(x, t)$ (Feynman, 1970d). When operating on a scalar potential we use a gradient, whereas for the vector potential, we must operate with the curl. In Eq. 5.1 we assumed that the magnetic flux vector $B(x)$ was static, thus $E(x, t)$ is the gradient of the time-dependent voltage $\phi(x, t)$. However, when the magnetic field is dynamic (not static), Eq. 5.1 is not valid due to magnetic induction: A voltage induced into a loop of wire is proportional to the time-varying flux cutting across that loop of wire. This is known as the Ampère-Maxwell law. In the static case the induced voltage is zero.

Example: Next we explore the potentials in quantifying Maxwell’s equations. When the magnetic field is time-varying, Eq. 5.1 must be extended to include both the scalar $\phi(x, t)$ and vector potentials $A(x, t)$

\[
E(x, t) = -\nabla \phi(x, t) - \frac{\partial A(x, t)}{\partial t}, \quad [\text{V/m}] \tag{5.3}
\]

\[
B(x, t) = \nabla \times A(x, t) \left[ + \frac{\partial D(x, t)}{\partial t} \right] \quad [\text{Wb/m}^2] \tag{5.4}
\]

(Sommerfeld, 1952, p. 146); (Feynman, 1970b, p. 18-10). If the permittivity is inhomogeneous, $A(x, t)$ would also need to be extended to include the gradient of the potential. If we add to $A(x, \omega)$ an additional displacement current $sD(x, \omega)$, it would have no effect because $\nabla \times D = \epsilon_0 \nabla \times \nabla \phi - 0$. However, if $\epsilon(x, \omega)$ were inhomogeneous, $\nabla \times [\epsilon(x, \omega) \nabla \phi(x, \omega)]$ would not be zero.

5.1.1 Lec 33: Gradient $\nabla$, divergence $\nabla \cdot$, curl $\nabla \times$, and Laplacian $\nabla^2$

Three key vector differential operators are required for understanding linear partial differential equations, such as the wave and diffusion equations. All of these begin with the $\nabla$ operator:

\[
\nabla = \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z}.
\]

The official name of this operator is nabla. It has three basic uses: 1) the gradient of a scalar field, the 2) divergence of a vector field, and 3) the curl of a vector field. The shorthand notation $\nabla \phi(x, t) = (\hat{x} \partial_x + \hat{y} \partial_y + \hat{z} \partial_z)\phi(x, t)$ is convenient.
Table 5.1: The three vector operators manipulate scalar and vector fields, as indicated. The gradient converts scalar fields into vector fields. The divergence maps vector fields to scalar fields. The curl maps vector fields to vector fields. Second-order operators (christened, DoG, GoD, etc.) are mnemonics defined in Sect. 5.5.5 (p. 222).

<table>
<thead>
<tr>
<th>Name</th>
<th>Input</th>
<th>Output</th>
<th>Operator</th>
<th>Mnemonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>Scalar</td>
<td>Vector</td>
<td>(\nabla())</td>
<td>(\text{grad})</td>
</tr>
<tr>
<td>Divergence</td>
<td>Vector</td>
<td>Scalar</td>
<td>(\nabla \cdot ())</td>
<td>(\text{div})</td>
</tr>
<tr>
<td>Curl</td>
<td>Vector</td>
<td>Vector</td>
<td>(\nabla \times ())</td>
<td>(\text{curl})</td>
</tr>
<tr>
<td>Laplacian</td>
<td>Scalar</td>
<td>Scalar</td>
<td>(\nabla \cdot \nabla = \nabla^2())</td>
<td>DoG</td>
</tr>
<tr>
<td>Vector Laplacian</td>
<td>Vector</td>
<td>Vector</td>
<td>(\nabla \cdot \nabla = \nabla^2())</td>
<td>GoD</td>
</tr>
</tbody>
</table>

**Gradient:** As shown in Fig. 5.1 (p. 184) the gradient transforms a complex scalar field \(\phi(x, s) \in \mathbb{C}\) into a vector field \((\mathbb{C}^3)\)

\[
\nabla \phi(x, s) = \left( \hat{x} \frac{\partial \phi}{\partial x} + \hat{y} \frac{\partial \phi}{\partial y} + \hat{z} \frac{\partial \phi}{\partial z} \right) \phi(x, s)
\]

The gradient may also be factored into a unit vector \(\hat{n}\), as defined in Fig. 5.1, defining the direction of the gradient, and the gradient’s length \(||\nabla()||\), defined in terms of the norm of the gradient. Thus the gradient of \(\phi(x)\) may be written in “polar coordinates” as \(\nabla \Phi(x) = ||\nabla \Phi|| \hat{n}\), thus defining \(\hat{n} = \frac{\nabla(\Phi(x))}{||\nabla \Phi||}\).

Important examples of the use of the gradient include the electric field vector \(E(x) = -\nabla \phi(x)\) [V/m], the gradient of a voltage [V], and the force density \(f(x) = -\nabla \rho(x)\) [N/m], the gradient of a pressure [Pa].

**Example:** Consider the paraboloid \(z = 1 - (x^2 + y^2)\) as the potential, with iso-potential circles of constant \(z\) that have radius of zero at \(z = 1\), and unit radius at \(z = 0\). The negative gradient

\[
E(x) = -\nabla z(x, y) = 2(x\hat{x} + y\hat{y} + 0\hat{z})
\]

is \(\perp\) to the circles of constant radius (constant \(z\)), and thus points in the direction of the radius.

If one were free-fall skiing this surface, they would be the first one down the hill. Normally skiers try to stay close to the iso-clines (not in the direction of the gradient), so they can stay in control. If you ski an iso-cline, you must walk, since there is no pull due to gravity.

**Divergence:** The divergence of a vector field results in a scalar field. For example, the divergence of the electric field flux vector \(D(x)\) [Col/m^2] equals the scalar field charge density \(\rho(x)\) [Col/m^3]

\[
\nabla \cdot D(x) \equiv \left( \hat{x} \frac{\partial}{\partial x} + \hat{y} \frac{\partial}{\partial y} + \hat{z} \frac{\partial}{\partial z} \right) \cdot D(x) = \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z} = \rho(x).
\]  

(5.5)

Thus it is analogous to the scalar (dot) product (e.g., \(A \cdot B\)) between two vectors.

When working with guided waves (narrow tubes of flux) having rigid walls that block flow, such that the diameter is small compared with the wavelength (P10, p. 133), the divergence simplifies to

\[
\nabla \cdot D(x) = \nabla_r D_r = \frac{1}{A(r)} \frac{\partial}{\partial r} A(r) D_r(r),
\]  

(5.6)

where \(r\) is the distance down the horn (range variable), \(A(r)\) is the area of the iso-response surface as a function of range \(r\), and \(D_r(r)\) is the radial component of vector \(D\) as a function of range \(r\). For
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example, in spherical coordinates the area \( A(r) = A_0 r^2 \) is proportional to the square of the range Table 5.2 (p. 203). This expression reduces to the radial component of the divergence of \( D(x) \) in spherical coordinates. In cylindrical coordinates \( A(r) = A_0 r \), and in rectangular coordinates the area \( A = \pi r_0^2 \) is independent of the range \( r \).

**Properties of the divergence:** The divergence is a direct measure of the net flux of the vector field. A vector field is said to be **incompressible** if the divergence of that field is zero. It is therefore **compressible** when the divergence is non-zero (e.g., \( \nabla \cdot D(x, s) = \rho(x, s) \)).

**Example:** Compared to air, water is considered to be incompressible. The stiffness of a fluid (i.e., the bulk modulus) is a measure of its compressibility. At very low frequencies air may be treated as incompressible (just like water), since as \( s \to 0 \), 
\[
-\nabla \cdot \mathbf{u}(x, s) = \frac{s}{\eta_0 P_0} \mathcal{P}(x, s) \to 0.
\]

The definition of compressible depends on the wavelength in the medium, so the terms must be used with some awareness of the frequencies being used in the analysis.

**Curl:** The curl transforms a complex vector field \( \mathbf{H}(x, s) \in \mathbb{C}^3 \) into a complex vector field \( \mathbf{C}(x, s) \in \mathbb{C}^2 \) \([\text{A/m}^2]\).

**Example:** The curl of the magnetic intensity \( \mathbf{H}(x, s) \) vector, in the frequency domain, is equal to the vector current density \( \mathbf{C}(x, s) \):
\[
\nabla \times \mathbf{H}(x, s) \equiv \begin{vmatrix}
\hat{x} & \hat{y} & \hat{z} \\
\partial_x & \partial_y & \partial_z \\
H_x & H_y & H_z
\end{vmatrix} = \mathbf{C}(x, s). \quad [\text{A/m}^2] \tag{5.7}
\]

The notation \( \left| \cdot \right| \) indicates the determinant (Appendix C.1, p. 255), \( \partial_z \) is shorthand for \( \partial/\partial x \) and \( \mathbf{H} = [H_x, H_y, H_z]^T \).

The curl and the divergence are both key when writing out Maxwell’s four equations. Without a full understanding of these two differential operators (\( \nabla, \nabla \times \)), there is little hope of understanding Maxwell’s basic results, the most important equations of mathematical physics, and the starting point for Einstein’s relativity theories. Some will say that quantum mechanics falls outside the realm of MEs, but this is at least open to debate.

The curl is a measure of the rotation of a vector field. For the case of water, it would correspond to the angular momentum, such as in a whirlpool, or with wind, a tornado. A spinning top is another excellent example, given a spinning solid body. While a top (aka gyroscope) must fall over if not spinning, once it is spinning, it can stably stand on its pointed tip. These systems are stable due to conservation of angular momentum: Once something is spinning, it will continue to spin.

**Example:** When \( \mathbf{H} = -y \hat{x} + x \hat{y} + 0 \hat{z} \), \( \nabla \times \mathbf{H} = 2 \hat{z} \), and thus has a constant rotation; when \( \mathbf{H} = 0 \hat{x} + 0 \hat{y} + z^2 \hat{z} \), \( \nabla \times \mathbf{H} = 0 \) has a curl of zero, and thus is **irrotational.** There are simple rules that precisely govern when a vector field is rotational versus irrotational, and compressible versus incompressible. These classes are dictated by Helmholtz’s theorem, the fundamental theorem of vector calculus (FTVC: Eq. 5.77, p. 229).

**Laplacian:** The Laplacian \( (\nabla^2 \equiv \nabla \cdot \nabla) \) is
\[
\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2},
\tag{5.8}
\]
and takes a scalar field onto a scalar field.

---

https://www.youtube.com/watch?v=ElLl6gzNhFE
Example: Starting from a scalar field, the gradient produces a vector, which is then operated on by the divergence to take the output of the gradient back to a scalar field. One of the classic cases is the Laplacian of a voltage field. The gradient of the scalar voltage \( \Phi(x) \) [V] results in the electric field vector \( \mathbf{E} \)

\[
\mathbf{E}(x) = [E_x(x), E_y(x), E_z(x)]^T = -\nabla \Phi(x), \quad [\text{V/m}]
\]

which in free space is proportional to the electric flux \( \mathbf{D} = \varepsilon_0 \mathbf{E} \) [C/m\(^2\)], the divergence of which gives the charge density \( \rho(x) \) [C/m\(^3\)]. Here \( \varepsilon_0 \) [F/m] is the vacuum permittivity, which is \( \approx 8.8542 \times 10^{-12} \) [F/m].

Example: The simplest example of a scalar field is the voltage between two very large (think \( \infty \)) conducting parallel planes, or plates (large so that we may ignore the edge effects). In this case the voltage varies linearly (the voltage is complex analytic) between the two plates. For example

\[
V(x, y, z) = V_o(1 - x)
\]

(5.9)
is a scalar field. At \( x = 0 \) the voltage is \( V_o \) and at \( x = 1 \) the voltage is zero. Between 0 and 1 the voltage varies linearly. Thus \( V(x, y, z) \) defines a scalar field.

If the same setup is used, but the two plates are \( 1 \times 1 \) [cm\(^2\)], with a 1 [mm] air gap, there will be a small “fringe” effect at the boundary that will (slightly) modify the ideal fields. This effect can be made small by changing the air gap to area ratio, so that the sides do not significantly impact the capacitor’s value.

Example: A second classic example is an acoustic pressure field \( \varphi(x, t) \) [Pa], which defines a vector force density \( \mathbf{f}(x, t) = -\nabla \varphi(x, t) \) [N/m\(^2\)] (Eq. 5.23, p. 198). When this force density [N/m\(^2\)] is integrated over an area, the net radial force [N] is

\[
F_r = -\int_S \nabla \varphi(x) ||dS||, \quad [\text{N}]
\]

(5.10)

An inflated balloon with a static internal pressure of 3 [atm], in an ambient pressure of 1 [atm] (sea level), forms a sphere due to the elastic nature of the rubber, which acts as a stretched spring under tension. The net force on the surface of the balloon is its area times the pressure drop of 2 atm across the surface. Thus the static pressure is

\[
\varphi(x) = 3u(r_o - r) + 1, \quad [\text{Pa}]
\]

where \( u(r) \) is a step function of the radius \( r = ||x|| > 0 \), centered at the center of the balloon, having radius \( r_o \).

Taking the gradient gives the negative\(^7\) of the radial force density (i.e., perpendicular to the surface of the balloon)

\[
-f_r(r) = \nabla \varphi(x) = \frac{\partial}{\partial r} 3u(r_o - r) + 1 = -2\delta(r_o - r). \quad [\text{Pa}]
\]

This equation describes a static pressure that is 1 [atm] (10\(^5\) [Pa]) outside the balloon and 3 [atm] inside. The net positive force density is the negative of the gradient of the static pressure.

Taking the divergence of this radial force gives the Laplacian of the scalar pressure field

\[
\nabla^2 \varphi(x) = \nabla \cdot \nabla \varphi(x) = -\nabla \cdot \mathbf{f}(x).
\]

\(^7\)The force is pointing out, stretching the balloon.
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5.1.2 Laplacian operator in \(N\) dimensions

In general it may be shown that in \(N = 1, 2, 3\) dimensions (Sommerfeld, 1949, p. 227)

\[
\nabla_r^2 \mathcal{P} = \frac{1}{r^{N-1}} \frac{\partial}{\partial r} \left( r^{N-1} \frac{\partial \mathcal{P}}{\partial r} \right).
\]

(5.11)

For each value of \(N\), the area \(A(r) = A_0 r^{N-1}\). This will turn out to be useful when working with the Laplacian in 1, 2, and 3 dimensions. This naturally follows from the Webster Horn Equation (Eq. 5.28, p. 199).

Example: When \(N = 3\) (i.e., spherical geometry)

\[
\nabla_r^2 \mathcal{P} = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial \mathcal{P}}{\partial r}
\]

(5.12)

\[
= \frac{1}{r} \frac{\partial^2}{\partial r^2} r \mathcal{P}
\]

(5.13)

resulting in the general d’Alembert solutions (Eq. 4.16 p. 149) for the spherical wave equation

\[
\mathcal{P}^{\pm}(r, s) = \frac{1}{r} e^{\mp \kappa(s) r}
\]

for the spherical geometry.

Exercise: Prove this last result by expanding Eq. 5.12, 5.13 using the chain rule. Solution: Expanding Eq. 5.12:

\[
\frac{1}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial \mathcal{P}}{\partial r} = \frac{1}{r^2} \left( 2r + r^2 \frac{\partial}{\partial r} \right) \frac{\partial \mathcal{P}}{\partial r}
\]

\[
= \frac{2}{r} \mathcal{P}_r + \mathcal{P}_{rr}.
\]

Expanding Eq. 5.13:

\[
\frac{1}{r} \frac{\partial}{\partial r} r \mathcal{P} = \frac{1}{r} \frac{\partial}{\partial r} \left( \mathcal{P} + r \mathcal{P}_r \right)
\]

\[
= \frac{1}{r} \left( \mathcal{P}_r + \mathcal{P} + r \mathcal{P}_{rr} \right)
\]

\[
= \frac{2}{r} \mathcal{P}_r + \mathcal{P}_{rr}.
\]

Summary: The radial component of the Laplacian in spherical coordinates (Eq. 5.12), simplifies to

\[
\nabla_r^2 \varphi(x) = \frac{1}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial \varphi(x)}{\partial r} = \frac{1}{r} \frac{\partial^2}{\partial r^2} r \varphi(x).
\]

Since \(\nabla^2 = \nabla \cdot \nabla\), it follows that the net force \(f(x) = [F_r, 0, 0]^T\), (Eq. 5.10) in spherical coordinates, has a radial component \(F_r\) and angular components of zero. Thus the force across a balloon may be approximated by a delta function across the thin sheet of stretched rubber.
Example: The previous example may be extended in an interesting way to the case of a rigid hose, a rigid tube, terminated on the right in an elastic medium (the above example of a balloon), for example an automobile tire. On the far left let’s assume there is a pump injecting the fluid into the hose. Consider two different fluids: air and water. Air may be treated as a compressible fluid, whereas water is incompressible. However, such a classification is a relative, being determined by the relative compliance of the balloon (i.e., tire) at the relatively rigid pump and hose.

This is a special case of a more general situation: When the fluid is treated as incompressible (rigid) the speed of sound becomes infinite, and the wave equation is not the best describing equation, and the motion is best approximated using Laplace’s equation. This is the transition from short to long wavelengths, from wave propagation, with delay, to quasi-statics, having no apparent delay.

This example may be modeled as either an electrical or mechanical system. If we take the electrical analog, the pump is a current source, injecting charge \( Q \) into the hose, which being rigid cannot expand (has a fixed volume). The hose may be modeled as a resistor, and the tire as a capacitor \( C \), which fills with charge as it is delivered via the resistor, from the pump. A capacitor obeys the same law as a spring \( F = KV \), or in electrical terms, \( Q = CV \). Here \( V \) is the voltage, which acts as a force \( F \), \( Q \) is the charge, which acts like the mass of the fluid. The charge is conserved, just as the mass of the fluid is conserved, meaning they cannot be created or destroyed. The flow of the fluid is called the flux, which is the general term for the mass or charge current. The two equations may be rewritten directly in terms of the force \( F \), \( V \) and flow, as an electrical current \( I = dQ/dt \) of mass flux \( J = dM/dt \), giving two impedance relations:

\[
I = \frac{d}{dt} CV \quad \text{(A)}
\]

and

\[
J = \frac{d}{dt} CF \quad \text{[kgm/m²]}.
\]

It is common to treat the stiffness of the balloon, which acts as a spring with compliance \( C \) (stiffness \( K = 1/C \)), in which case the equations reduce to the same equation, in terms of an impedance \( Z \), typically defined in the frequency domain as the ratio of the generalized force over the generalized flow

\[
Z(s) = \frac{1}{sC} \quad \text{[ohms]}
\]

In the case of the mechanical system \( Z_{\text{mech}}(s) \equiv F/J \), and for the electrical system \( Z_{\text{elec}}(s) \equiv V/I \). It is conventional to use the unit [ohms] when working with any impedance. It is convenient to use a uniform terminology for different physical situations and forms of impedance, greatly simplifying the notation.

While the two systems are very different in their physical realization, they are mathematically equivalent, forming a perfect analog. The formula for the impedance is typically expressed in the Laplace frequency domain, which of course is the Laplace transform of the time variables. In the frequency domain Ohm’s law becomes Eq. 5.15 for the case of a spring and Eq. 5.14 for the capacitor.

The final solution of this system is solved in the frequency domain. The impedance seen by the source is the sum of the resistance \( R \) added to the impedance of the load, giving

\[
Z = R + \frac{1}{sC}
\]

The solution is simply the relation between the force and the flow, as determined by the action of the source on the load \( Z(s) \). The final answer is given in terms of the voltage across the compliance in terms of the voltage \( V_c \) (or current \( I_c \)) due to the source. Once the algebra is done, in the frequency domain, the voltage across the compliance \( V_c \) divided by the voltage of the source is given as

\[
\frac{V_c}{V_{\text{source}}} = \frac{R}{R + 1/sC}
\]

Thus the problem reduces to some algebra in the frequency domain. The time domain response is found by taking the inverse Laplace transform, which in this case has a simple pole at \( s_p = 1/RC \).
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Cauchy’s residue formula gives the final answer, which describes how the voltage across the compliance builds exponentially with time, from zero to the final value. Given the voltage, the current may also be computed as a function of time. This then represents the entire process of either blowing up a balloon, or charging a capacitor, the difference being only the physical notation, as the math is identical.

Note that the differential equation is first-order in time, which in frequency means the impedance has a single pole. This means that the equation for the charging of a capacitor, or pumping up a balloon, describes a diffusion process. If we had taken the impedance of the mass of the fluid in the hose into account, we would have a lumped-parameter model of the wave equation, with a second-order system. This is mathematically the same as the homework assignment DE-3 about train cars (masses) connected together by springs (Fig. 4.11, p. 179, of Sect. 4.5.5, p. 180).

Example: The voltage

\[
\phi(x, t) = e^{-\kappa \cdot x} u(t - x/c) \leftrightarrow \frac{1}{s} e^{-\kappa \cdot x} \quad [V]
\] (5.16)

is an important case since it represents one of d’Alembert’s two solutions (Eq. 4.16, p. 149) of the wave equation (Eq. 3.4, p. 73), as well as an eigenfunction of the gradient operator \( \nabla \). From the definition of the scalar (dot) product of two vectors (Fig. 3.3, p. 112),

\[
\kappa \cdot x = \kappa_x x + \kappa_y y + \kappa_z z = ||\kappa|| \cdot ||x|| \cos \theta_{kx},
\]

where \( ||\kappa|| = \sqrt{\kappa_x^2 + \kappa_y^2 + \kappa_z^2} \) and \( ||x|| = \sqrt{x^2 + y^2 + z^2} \) are the lengths of vectors \( \kappa \), and \( x \) and \( \theta_{kx} \) is the angle between them. As before, \( s = \sigma + \omega j \) is the Laplace frequency.

To keep things simple let \( \kappa = [\kappa_x, 0, 0]^T \) so that \( \kappa \cdot x = \kappa_x x \hat{x} \). We shall soon see that \( ||\kappa|| = 2\pi / \lambda \) follows from the basic relationship between a wave’s radian frequency \( \omega = 2\pi f \) and its wavelength \( \lambda \)

\[
\omega \lambda = c_0.
\] (5.17)

As frequency increases, the wavelength becomes shorter. This key relationship may have been first researched by Galileo (c.1564), followed by (c.1627) Mersenne\(^8\) (Fig. 1.2, p. 22).

Exercise: Show that Eq. 5.16 is an eigenfunction of the gradient operator \( \nabla \). Solution: Taking the gradient of \( \phi(x, t) \) gives

\[
\nabla e^{-\kappa \cdot x} u(t) = -\nabla \kappa \cdot x e^{-\kappa \cdot x} u(t) = -\kappa e^{-\kappa \cdot x} u(t),
\]

or in terms of \( \phi(x, t) \)

\[
\nabla \phi(x, t) = -\kappa \phi(x, t) \leftrightarrow -\frac{s}{c} e^{-\kappa \cdot x}.
\]

Thus \( \phi(x, t) \) is an eigenfunction of \( \nabla \), having the vector eigenvalue \( \kappa \). As before, \( \nabla \phi \) is proportional to the current since \( \phi \) is a voltage, and the ratio, i.e., the eigenvalue, may be thought of as a mass, analogous to the impedance of a mass (or inductor). In general the units provide the physical interpretation of the eigenvalues and their spectra. A famous example is the Rydberg spectrum of the hydrogen atom.

Exercise: Compute \( \hat{n} \) for \( \phi(x, s) \) as given by Eq. 5.16. Solution: \( \hat{n} = \kappa / ||\kappa|| \). This represents a unit vector in the direction of the current.

\(^8\)http://www-history.mcs.st-and.ac.uk/Biographies/Mersenne.html

“In the early 1620s, Mersenne listed Galileo among the innovators in natural philosophy whose views should be rejected. However, by the early 1630s, less than a decade later, Mersenne had become one of Galileo’s most ardent supporters.”

CHAPTER 5. STREAM 3B: VECTOR CALCULUS (10 LECTURES)

Exercise: If the sign of $\kappa$ is negative, what are the eigenvectors and eigenvalues of $\nabla \phi(x,t)$? Solution:

\[ \nabla e^{-\kappa x} u(t) = -\kappa \cdot \nabla (x) e^{-\kappa x} u(t) \]
\[ = -\kappa e^{-\kappa x} u(t). \]

Nothing changes other than the sign of $\kappa$. Physically this means the wave is traveling in the opposite direction, corresponding to the forward and retrograde d’Alembert waves.

Prior to this section, we have only considered the Taylor series in one variable, such as for polynomials $P_N(x), x \in \mathbb{R}$ (Sect. 3.1, Eq.3.7 p. 74) and $P_N(s), s \in \mathbb{C}$ (Sect. 4.2.2, Eq.3.38 p. 92). The generalization from real to complex analytic functions led to the Laplace transform, and the hosts of integration theorems (FTCC, Cauchy I, II, III). What is in store when we generalize from one spatial variable ($\mathbb{R}$) to three ($\mathbb{R}^3$)?

Exercise: If $E(x,t) = E_\hat{x} \hat{x}$, express $E(x,t)$ in terms of the voltage potential $\phi(x,t)$ [V]. Solution: The electric field strength may be found from the voltage as

\[ E(x,t) = -\nabla \phi(x,t) = -\hat{x} \frac{\partial}{\partial x} \phi(x,t) \text{ [V/m].} \]

Exercise: Find the velocity $v(t)$ of an electron in a field $E$. Solution: From Newton’s 2nd law, $-qE = m_e \ddot{v}(t)$ [Nt], where $m_e$ is the mass of the electron. Thus we must solve this first-order differential equation to find $v(t)$. This is easily done in the frequency domain $v(t) \leftrightarrow V(\omega)$.

Role of Potentials: Note that the scalar fields (e.g., temperature, pressure, voltage) are all scalar potentials, summarized in Fig. 3.2 (p. 124). In each case the gradient of the potential results in a vector field, just as in the electric case above (Eq. 5.1).

It is important to understand the physical meaning of the gradient of a potential, which is typically a generalized force (electric field, acoustic force density, temperature flux), which in turn generates a flow (current, velocity, heat flux). The ratio of the gradient over the flow determines the impedance.

1. Example 1: The voltage drop across a resistor causes a current to flow, as described by Ohm’s law. Taking the difference in voltage between two points is a crude form of gradient when the frequency $f$ [Hz] is low, such that the wavelength is much larger than the distance between the two points. This is the essence of the quasi-static approximation P10 (133).

2. Example 2: The gradient of the pressure gives rise to a force density in the fluid medium (air, water, oil, etc.), which causes a flow (volume velocity vector) in the medium.

3. Example 3: The gradient of the temperature also causes a flow of heat, which is proportional to the thermal resistance, given Ohm’s law for heat (Feynman, 1970c, p. 3-7).\[9\]

4. Example 4: Nernst potential: When a solution contains charged ions, it is called an electro-chemical Nernst potential $N(x,t)$.\[10\] This electro-chemical field is similar to a voltage or temperature field, the gradient of which defines a virtual force on the charged ions.

Thus in the above examples there is a potential, the gradient of which is a force, which when applied to the medium (an impedance) causes a flow (flux or current) proportional to that impedance, due to the medium. This is a very general set of concepts, worthy of some thought. In every case there is a force and a flow. The product of the force and flow is a power, while the ratio may be modeled using 2x2 ABCD impedance matrices (Eq. 3.36, p. 119).

\[https://en.wikipedia.org/wiki/Thermal_conduction\#Fourier%27s_law\]

\[https://en.wikipedia.org/wiki/Nernst_equation\]
Exercise: Show that the integral of Eq. 5.1 is an anti-derivative. Solution: The solution uses the definition of the anti-derivative, defined by the FTC (Eq. 4.7, p. 146):

\[
\phi(x,t) - \phi(x_o,t) = \int_{x_o}^{x} E(x,t) \cdot dx
\]

\[
= -\int_{x_o}^{x} \nabla \phi(x,t) \cdot dx
\]

\[
= -\int_{x_o}^{x} \left( \hat{x} \frac{\partial \phi}{\partial x} + \hat{y} \frac{\partial \phi}{\partial y} + \hat{z} \frac{\partial \phi}{\partial z} \right) \phi(x,t) \cdot dx
\]

\[
= -\int_{x_o}^{x} \frac{\partial \phi}{\partial x} dx - \int_{y_o}^{y} \frac{\partial \phi}{\partial y} dy - \int_{z_o}^{z} \frac{\partial \phi}{\partial z} dz
\]

\[
= - \int_{x_o}^{x} d\phi(x,t)
\]

\[
= -\left( \phi(x,t) - \phi(x_o,t) \right).
\]

This may be verified by taking the gradient of both sides

\[
\nabla \phi(x,t) - \nabla \phi(x_o,t) = -\nabla \int_{x_o}^{x} E(x,t) \cdot dx = E(x,t).
\]

Applying the FTC (Eq. 4.7, p. 146), the anti-derivative must be \( \phi(x,t) = E_x x \hat{x} + 0 \hat{y} + 0 \hat{z} \). This very same point is made by Feynman (1970c, p. 4-1, Eq. 4.28).

Given that the force on a charge is proportional to the gradient of the potential, from the above exercise showing that the integral of the gradient only depends on the end points, the work done in moving a charge only depends on the limits of the integral, which is the definition of a conservative field, but which only holds in the ideal case where \( E \) is determined by Eq. 5.1, i.e., the medium has no friction (i.e., there are no other forces on the charge).

The conservative field: An important question is: “When is a field conservative?” A field is conservative when the work done by the motion is independent of the path of motion. Thus the conservative field is related to the FTC, which states that the integral of the work only depends on the limits of the integral, which is the definition of a conservative field, but which only holds in the ideal case where \( E \) is determined by Eq. 5.1, i.e., the medium has no friction (i.e., there are no other forces on the charge).

A more complete answer must await the introduction of the fundamental theorem of vector calculus, discussed in Sect. 5.5.5 (Eq. 5.77, p. 229). A few specific examples provide insight:

Example: The gradient of a scalar potential, such as the voltage (Eq. 5.1), defines the electric field, which drives a current (flow) across a resistor (impedance). When the impedance is infinite, the flow will be zero, leading to zero power dissipation. When the impedance is lossless, the system is conservative.

Example: At audible frequencies the viscosity of air is quite small and thus, for simplicity, it may be taken as zero. However, when the wavelength is small (e.g., at 100 [kHz] \( \lambda = c_o / f = 345 / 10^5 = 3.45 \) [mm]) the lossless assumption breaks down, resulting in a significant propagation loss. When the viscosity is taken into account, the field is lossy, thus the field is no longer conservative.

Example: If a temperature field is a time-varying constant (i.e., \( T(x,t) = T_o(t) \)), there is no “heat flux,” since \( \nabla T_o(t) = 0 \). When there is no heat flux (i.e., flux, or flow), there is no heat power, since the power is the product of the force times the flow.

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11 https://en.wikipedia.org/wiki/Laminar_flow#Examples
Example: The force of gravity is given by the gradient of Newton’s gravitational potential (Eq. 3.1, p. 72)

\[ F = -\nabla r \phi_N(r) = -\frac{\partial}{\partial r} \frac{1}{r} = \frac{1}{r^2}. \]

Historically speaking \( \phi_N(r) \) was the first conservative field, used to explain the elliptic orbits of the planets around the sun. Galileo’s law says that bodies fall with constant acceleration, giving rise to a parabolic path and a time of fall proportional to \( t^2 \). This behavior of falling objects directly follows from Galileo’s potential

\[ \phi_G(r) = \frac{1}{r - r_o} = \frac{-r_o}{1 - r/r_o \ r < r_o} = -r_o\left(1 - \frac{r}{r_o} + \frac{(r/r_o)^2}{2} + \cdots \right) \approx -r_o - r, \]

which given the large radius \( r_o \) of the earth, and the small distance of the object from the surface of the earth \( r - r_o \), is equal to the distance above the ground. Thus Galileo’s law says that the force a falling body sees is constant

\[ F_G = -\nabla r \phi_G(r) = 1. \]

This can be decorated with constants to account for the actual size of the force of gravity.

Example: Galileo discovered that the height of a falling object is

\[ r(t) = \frac{1}{2} m G_o (t - t_o)^2, \]

where \( m \) is the object’s mass and \( G_o \) is the gravitational constant for the earth at its surface \( r_o \). Show that \( r(t) \) directly follows from the potential \( \phi_G = r_o - r \). This formula holds if you toss a ball into the air, or if you drop it from a high place. Solution: Given Galileo’s potential \( \phi_G(r) = m G_o (r_o - r) \), show that the force is constant, thus that \( \ddot{r}(t) = m G_o \). Given Galileo’s formula for the height \( r(t) \), the velocity is \( v(t) = \dot{r}(t) = m G_o t \), and the acceleration is \( \ddot{r}(t) = m G_o \).

Example: Find the time that it takes to fall from a distance \( r = L \). Namely, solve \( r(t) = L \) for the time the object takes to fall the distance \( L \). Solution: Setting \( t_o = 0 \) gives \( t^2 = 2L/m G_o \). Thus the time to fall is \( T(L) = \sqrt{2L/m G_o} \).

5.2 Lec 34: Partial differential equations and field evolution:

There are three main classes of partial differential equations (PDEs): elliptic, parabolic, and hyperbolic, distinguished by the order of the time derivative. These categories seem to have little mathematical utility (the categories appear as labels).

The Laplacian \( \nabla^2 \): In the most important case the space operator is the Laplacian \( \nabla^2 \), the definition of which depends on the dimensionality of the waves, that is, the coordinate system being used. We first discussed the Laplacian as a 2D operator in Section 4.2.2 (p. 147), when we studied complex analytic functions, and again in Section 5.1.1 (p. 185). An expression for \( \nabla^2 \) for 1, 2 and 3 dimensions was provided as Eq. 5.11 (p. 189). In 3D rectangular coordinates it is defined as (see p. 235)

\[ \nabla^2 T(x) = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) T(x). \] (5.18)

The Laplacian operator is ubiquitous in mathematical physics, starting with simple complex analytic functions (Laplace’s equation) and progressing to Poisson’s equation, the diffusion equation, and finally the wave equation. Only the wave equation expresses delay. The diffusion equation “wave” has an instantaneous spread (the effective “wave” velocity is infinite, i.e., it’s not a wave).

Examples of elliptic, parabolic and hyperbolic equations are:

1. Laplace’s equation
Example:
\[ \nabla^2 \Phi(x) = 0, \]
which describes, for example, the voltage inside a closed chamber with various voltages on the walls, or the steady state temperature within a closed container, given a specified temperature distribution on the walls. There is no dynamics to the potential, even when it is changing, since the potential instantaneously follows the potential at the walls.

2. **Poisson’s equation:** In the steady state the diffusion equation degenerates to either Poisson’s or Laplace’s equation, which are classified as *elliptic equations* (second-order in space, zero-order in time). Like the diffusion equation, the evolution has a wave velocity that is functionally infinite.

Example:
\[ \nabla^2 \Phi(x, t) = \rho(x, t), \]
which holds for gravitational fields, or the voltage around a charge.

3. **Fourier diffusion equation:** Equation 5.21 describes the evolution of the scalar temperature \( T(x, t) \) (a scalar potential), gradients of solution concentrations (i.e., ink in water) and Brownian motion. Diffusion is first-order in time, which is categorized as *parabolic* (first-order in time, second-order in space). When these equations are Laplace transformed, diffusion has a single real root, resulting in a real solution (e.g., \( T \in \mathbb{R} \)). There is no wave-front for the case of the diffusion equation. As soon as the source is turned on, the field is non-zero at every point in the bounded container.

Example:
\[ \nabla^2 T(x, t), = D_o \frac{\partial T(x, t)}{\partial t} \leftrightarrow s D_o T(x, s), \]
which describes, for example, the temperature \( T(x, t) \leftrightarrow T(x, \omega) \), as proposed by Fourier in 1822, or the diffusion of two miscible liquids (Fick, 1855) and Brownian motion (Einstein, 1905). The diffusion equation is not a wave equation since the temperature wave front propagates instantaneously.

4. **Wave equations:**

(a) **scalar wave equations** (Eq. 3.3) describe the evolution of a scalar potential field such as pressure \( \rho(x, t) \) (sound), or the displacement of a string or membrane under tension. The wave equation is second-order in time. When transformed into the frequency domain, the solution has pairs of complex conjugate roots, leading to two real solutions (i.e, \( \rho(x, t \in \mathbb{R})\)). The wave equation is classified as *hyperbolic* (second-order in time and space).

(b) **vector wave equations** Maxwell’s equations describe the propagation of the vector electric \( E(x, t) \) and \( H(x, t) \) fields, along with the electric \( D(x, t) \) and magnetic \( B(x, t) \) flux.

Historically the wave equation was seen to be related to several other important partial differential equations, as the theory evolved, resulting in the following:

Each of these three equations has properties that may be simply explained, and visualized, for \( N = 1, 2, 3 \) geometries, and all contain the Laplacian \( \nabla^2(\cdot) = \nabla \cdot \nabla(\cdot) \) (p. 189).

**Solution evolution:** The partial differential equation defines the “evolution” of the scalar field (pressure \( \rho(x, t) \)) and temperature \( T(x, t) \), or vector field \( (E, D, B, H) \), as functions of space \( x \) and time \( t \). There are two basic categories of field evolution, *diffusion* and *propagation*. 
1. **Diffusion**: The simplest and easiest PDE example, easily visualized, is a static\(^{12}\) (time invariant) scalar temperature field \(T(x) \, [°C]\). Just like an impedance or admittance, a field has regions where it is analytic, and for the same reasons, \(T(x, t)\) satisfies Laplace’s equation

\[
\nabla^2 T(x, t) = 0.
\]

Since there is no current when the field is static, such systems are lossless, and thus are conservative.

When \(T(x, t)\) depends on time (is not static), it is described by the **diffusion equation**

\[
\nabla^2 T(x, t) = \kappa \frac{\partial}{\partial t} T(x, t), \tag{5.21}
\]

a rule for how \(T(x, t)\) evolves with time from its initial state \(T(x, 0)\). Constant \(\kappa\) is called the **thermal conductivity** which depends on the properties of the fluid in the container, with \(s\kappa\) being the admittance per unit area. The conductivity is a measure of how the heat gradients induce heat currents \(J = \kappa \nabla T\), analogous to Ohm’s law for electricity.

Note that if \(T(x, \infty)\) reaches **steady state** \(J = 0\) as \(t \to \infty\), it evolves into a static state, thus \(\nabla^2 T = 0\). This depends on what is happening at the boundaries. When the wall temperature of a container is a function of time, then so will the internal temperature continue to change, but with a delay that depends on the thermal conductivity \(\kappa\).

Such a system is analogous to an electrical resistor-capacitor series circuit, connected to a battery. For example: the wall temperature (voltage across the battery) represents the potential driving the system. The thermal conductivity \(\kappa\) (the electrical resistor) is likewise analogous. The fluid (the electrical capacitor) is being heated (charged) by the heat (charge) flux. In all cases Ohm’s law defines the ratio of the potential (voltage) and the flux (current). How this happens can only be understood once the solution to the equations has been established.

2. **Propagation**: Pressure and electromagnetic waves are described by a scalar potential (pressure) (Eq. 3.3, p. 72) and a vector potential (electromagnets) (Eq. 5.72, p. 227), resulting in scalar and vector wave equations.

All these partial differential equations, scalar and vector wave equations, and the diffusion equation, depend on the Laplacian \(\nabla^2\), which we first saw with the Cauchy-Riemann conditions (Eq. 4.15, p. 148).

**The vector Taylor series**: Next we shall expand the concept of the one-dimensional Taylor series, a function of one variable, to \(x \in \mathbb{R}^3\). Just as we generalized the derivative with respect to the real frequency variable \(\omega \in \mathbb{R}\) to the complex analytic frequency \(s = \sigma + \omega j \in \mathbb{C}\), here we generalize the derivative with respect to \(x \in \mathbb{R}\), to the vector \(x \in \mathbb{R}^3\).

Since the scalar field is analytic in \(x\), it is a perfect place to start. Assuming we have carefully defined the Taylor series 3.28 (p. 87) in one and two (Eq. 4.12, p. 148) variables, the Taylor series of \(f(x)\) in \(x = 0 \in \mathbb{R}^3\) may be defined as

\[
\begin{align*}
\begin{bmatrix} x \end{bmatrix} + \begin{bmatrix} \delta x \end{bmatrix} &= \begin{bmatrix} x \end{bmatrix} + \nabla f(x) \cdot \begin{bmatrix} \delta x \end{bmatrix} + \sum_{k=1}^{3} \sum_{l=1}^{3} \frac{\partial^2 f(x)}{\partial x_k \partial x_l} \delta x_k \delta x_l + \text{HOT}. \tag{5.22}
\end{align*}
\]

From this definition it is clear that the gradient is the generalization of the second term in the 1D Taylor series expansion.

\(^{12}\)Postulate (P3), p. 132.
Summary: For every potential $\phi(x, t)$ there exists a force density $f(x, t) = -\nabla \phi(x, t)$, proportional to the potentials, which drives a generalized flow $u(x, t)$. If the normal component of the force and flow are averaged over a surface, the mean-force and volume-flow (i.e., volume-velocity for the acoustic case) are defined. In such cases the impedance is the net force through the surface force over the net flow, and Gauss’s law and quasi-statics (P10, p. 133) come into play (Feynman, 1970a). We call this the generalized impedance.

Assuming linearity (P2, p. 132), the product of the force and flow is the power, and the ratio (force/flow) is an impedance (Fig. 3.2, p. 124). This impedance statement is called either Ohm’s law, Kirchhoff’s laws, Laplace’s law, or Newton’s laws. In the simplest of cases, they are all linearized (proportional) complex relationships between a force and a flow. Very few impedance relationships are inherently linear over a large range of force or current, but for physically useful levels, they can be treated as linear. Nonlinear interactions require a more sophisticated approach, typically involving numerical methods.

In electrical circuits it is common to define a zero potential ground point that all voltages use as the referenced potential. The ground is a useful convention, as a simplifying rule, but it obscures the physics, and obscures the fact that the voltage is not the force. Rather, the force is the voltage difference, referenced to the ground, which is defined as zero volts. This results in abstracting away (i.e., hiding) the difference in voltage. It seems misleading (more precisely it is wrong) to state Ohm’s law as the voltage over the current, since Ohm’s law actually says that the voltage difference (i.e., voltage gradient) over the current defines an impedance (Kennelly, 1893).

When one measures the voltage between two points, it is a crude approximation to the gradient, based on the quasistatic approximation (P10). The pressure is also a potential, the gradient of which is a force density, which drives the volume-velocity (flow).

In Sect. 5.5.5 (p. 222) we introduce the fundamental theorem of vector calculus (aka Helmholtz’ decomposition theorem), which generalizes Ohm’s law to include circulation (e.g., angular momentum, vorticity and the related EM magnetic effects). To understand these generalizations in flow one needs to understand compressible and rotational fields, complex analytic functions, and a lot more history of mathematical-physics (Table 5.3, p. 224).

Note that it is the difference in the potential (i.e., voltage, temperature, pressure) that is proportional to the flux. This can be viewed as a major simplification of the gradient relationship, justified by the quasi-static assumption P10 (p. 133).

The roots of the impedance are related to the eigenmodes of the system equations.

5.3 Lec 35: Scalar Wave Equations (Acoustics)

In this section we discuss the general solution to the wave equation. The wave equation has two forms: scalar waves (acoustics) and vector waves (electromagnetics). These have an important mathematical distinction but a similar solution space, one scalar and the other vector. To understand the differences we start with the scalar wave equation.

The scalar wave equation: A good starting point for understanding PDEs is to explore the scalar wave equation (Eq. 3.3, p. 72). Thus, we shall limit our analysis to acoustics, the classic case of scalar waves. Acoustic wave propagation was first analyzed mathematically by Isaac Newton (electricity had yet to be discovered) in his famous book Principia (1687), in which he first calculated the speed of sound based on the conservation of mass and momentum.

Early history: The study of wave propagation begins at least as early as Huygens (ca. 1678), followed soon after (ca. 1687) by Sir Isaac Newton’s calculation of the speed of sound (Pierce, 1981, p. 15). The acoustic variables are the pressure

$$p(x, t) \leftrightarrow P(x, \omega)$$
Figure 5.2: Experimental setup showing a large pipe on the left terminating the wall containing a small hole with a balloon, shown in green. At time $t = 0$ the balloon is pricked and a pressure pulse is released. The baffle on the left represents a semi-infinite long tube having a large radius compared to the horn input diameter $2a$, such that the acoustic admittance looking to the left ($A/\rho \omega$, with $A \to \infty$) is very large compared to the horn’s throat admittance (Eq. 5.47). At time $T$ the outbound pressure pulse $p(r; T) = \delta(t - x/c_o)/r$ has reached a radius $x = r - r_o = c_o T$ where $r = x$ is the location of the source at the throat of the horn and $r_o$ is measured from the vertex. At the throat of the horn $V_+/A_+ = V_-/A_-$. There is an important generalization of the problem of lossless plane-wave propagation in 1-dimensional (1D) uniform tubes known as transmission line theory. By allowing the area $A(r)$ of the horn to vary along the range axis $r$ (the direction of wave propagation), as depicted in Fig. 5.2 for the conical horn (i.e., $A(r) = A_0 (r/r_o)^2$), general solutions to the wave equation may be explored. Classic applications of horns include vocal tract acoustics, loudspeaker design, cochlear mechanics, the hydrogen atom, and cases having wave propagation in periodic media (Brillouin, 1953).

and the particle velocity

$$u(\vec{x}, t) \leftrightarrow U(\vec{x}, \omega).$$

To obtain a wave, one must include two basic components: the stiffness of air, and its mass. These two equations shall be denoted (1) Newton’s 2nd law ($F = ma$) and (2) Hooke’s law ($F = \kappa x$), respectively. In vector form these equations are (1) Euler’s equation (i.e., conservation of momentum density)

$$-\nabla p(\vec{x}, t) = \rho_o \frac{\partial}{\partial t} \vec{u}(\vec{x}, t) \leftrightarrow \rho_o \omega \vec{U}(\vec{x}, s), \tag{5.23}$$

which assumes the time-average density $\rho_o$ to be independent of time and position $x$, and (2) the continuity equation (i.e., conservation of mass density)

$$-\nabla \cdot \vec{u}(\vec{x}, t) = \frac{1}{\eta_o \rho_o} \frac{\partial}{\partial t} p(\vec{x}, t) \leftrightarrow \frac{s}{\eta_o \rho_o} P(\vec{x}, s) \tag{5.24}$$

(Pierce, 1981; Morse, 1948, p. 295). Here $P_o = 10^5$ [Pa] is the barometric pressure, $\eta_o P_o$ is the dynamic (adiabatic) stiffness, with $\eta_o = 1.4$. Combining Eqs. 5.23 and 5.24 (removing $\vec{u}(\vec{x}, t)$) results in the 3-dimensional (3D) scalar pressure wave equation

$$\nabla^2 p(\vec{x}, t) = \frac{1}{c_o^2} \frac{\partial^2}{\partial t^2} p(\vec{x}, t) \leftrightarrow \frac{s^2}{c_o^2} P(\vec{x}, s) \tag{5.25}$$

with $c_o = \sqrt{\eta_o P_o/\rho_o}$ being the sound velocity. Because the merged equations describe the pressure, which is a scalar field, this is an example of the scalar wave equation.

Exercise: Show that Eqs. 5.23 and 5.24 can be reduced to Eq. 5.25. Solution: Taking the divergence of Eq. 5.23 gives

$$-\nabla \cdot \nabla p(\vec{x}, t) = \rho_o \frac{\partial}{\partial t} \nabla \cdot \vec{u}(\vec{x}, t). \tag{5.26}$$

Note that $\nabla \cdot \nabla = \nabla^2$ (p. 235). Next, substituting Eq. 5.24 into the above relation results in the scalar wave equation Eq. 5.25, since $c_o = \sqrt{\eta_o P_o/\rho_o}$.

5.3.1 Lec 36: The Webster horn equation

There is an important generalization of the problem of lossless plane-wave propagation in 1-dimensional (1D) uniform tubes known as transmission line theory. By allowing the area $A(r)$ of the horn to vary along the range axis $r$ (the direction of wave propagation), as depicted in Fig. 5.2 for the conical horn (i.e., $A(r) = A_0 (r/r_o)^2$), general solutions to the wave equation may be explored. Classic applications of horns include vocal tract acoustics, loudspeaker design, cochlear mechanics, the hydrogen atom, and cases having wave propagation in periodic media (Brillouin, 1953).
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For the 1D scalar wave equation (guided waves, aka, acoustic horns), the Webster Laplacian is

$$\nabla_r^2 \varphi(r, t) = \frac{1}{A(r)} \frac{\partial}{\partial r} \left[ A(r) \frac{\partial}{\partial r} \right] \varphi(r, t). \quad (5.27)$$

The Webster Laplacian is based on the quasi-static approximation (P10: p. 132) which requires that the frequency lie below the critical value $f_c = c_o/2d$, namely that a half wavelength be greater than the horn diameter $d$ (i.e., $d < \lambda/2$).\(^{13}\) For the case of the adult human ear canal, $d = 7.5 \text{ [mm]}$, $f_c = (343/2 \cdot 7.5) \times 10^{-3} \approx 22.87 [\text{kHz}]$.

The term on the right of Eq. 5.27, which is identical to Eq. 5.11 (p. 189), is also the Laplacian for thin tubes (e.g., rectangular, spherical, and cylindrical coordinates). Thus the Webster horn “wave” equation is

$$\frac{1}{A(r)} \frac{\partial}{\partial r} \left[ A(r) \frac{\partial}{\partial r} \right] \varphi(r, t) = \frac{1}{c_o^2} \frac{\partial^2}{\partial t^2} \varphi(r, t) \leftrightarrow \frac{s^2}{c_o^2} \mathcal{P}(r, s), \quad (5.28)$$

where $\varphi(r, t) \leftrightarrow \mathcal{P}(r, s)$ is the acoustic pressure in Pascals [Pa] (Hanna and Slepian, 1924; Mawardi, 1949; Morse, 1948; Olson (1947, p. 101); Pierce (1981, p. 360). Extensive experimental analyses for various types of horns (conical, exponential, parabolic) along with a review of horn theory may be found in Goldsmith and Minton (1924).

The limits of the Webster horn equation: It is commonly stated that the Webster horn equation (WHEN) is fundamentally limited and thus is an approximation that only applies to frequencies much lower than $f_c$. However, in all these discussions it is assumed that the area function $A(r)$ is the horn’s cross-sectional area, not the area of the iso-pressure wave-front (Morse, 1948; Shaw, 1970; Pierce, 1981).

In the next section it is shown that this “limitation” may be avoided (subject to the $f < f_c$ quasi-static limit (P10, p. 133)), making the Webster horn theory an “exact” solution for the lowest-order “plane-wave” eigenfunction. The nature of the quasi-static approximation is that it “ignores” higher-order evanescent modes, which are naturally small since they are in cutoff (evanescent modes do not propagate) (Hahn, 1941; Karal, 1953). This is the same approximation that is required to define an impedance, since every eigenmode defines an impedance (Miles, 1948).

To apply this theory, the acoustic variables (eigenfunctions) are redefined for the average pressure and its corresponding volume velocity, each defined on the iso-pressure wave-front boundary (Webster, 1919; Hanna and Slepian, 1924). The resulting acoustic impedance is then the ratio of the average pressure over the volume velocity. This approximation is valid up to the frequency where the first cross mode begins to propagate ($f > f_c$), which may be estimated from the roots of the Bessel eigenfunctions (Morse, 1948). Perhaps it should be noted that these ideas, which come from acoustics, apply equally well to electromagnetics, or any other wave phenomena described by eigenfunctions.

The best known examples of wave propagation are electrical and acoustic transmission lines. Such systems are loosely referred to as the telegraph or telephone equations, referring back to the early days of their discovery (Heaviside, 1892; Campbell, 1903b; Brillouin, 1953; Feynman, 1970a). In acoustics, wave-guides are known as horns, such as the horn connected to the first phonographs from around the turn of the century (Webster, 1919). Thus the names reflect the historical development, to a time when the mathematics and the applications were running in close parallel.

\(^{13}\)This condition may be written several ways, the most common being $ka < 1$, where $k = 2\pi/\lambda$ and $a$ is the horn radius. This may be expressed in terms of the diameter as $\frac{2\pi \cdot d}{\lambda} < 1$, or $d < \lambda/\pi < \lambda/2$. Thus $d < \lambda/2$ may be a more precise metric by the factor $\pi/2 \approx 1.6$. This is called the half-wavelength assumption, a synonym for the quasi-static approximation.
Figure 5.3: Derivation of horn equation using Gauss’s law: The divergence of the velocity $\nabla \cdot \mathbf{u}$, within $\delta x$, shown as the filled shaded region, is integrated over the enclosed volume. Next the divergence theorem is applied, transforming the integral to a surface integral normal to the surface of propagation. This results in the difference of the two volume velocities $\delta \nu = \nu(x + \delta x) - \nu(x) = [\mathbf{u}(x + \delta x) \cdot \mathbf{A}(x + \delta x) - \mathbf{u}(x) \cdot \mathbf{A}(x)]$. The flow is always perpendicular to the iso-pressure contours.

**Conservation of momentum:** The first step is an integration of the normal component of Eq. 5.23 (p. 198) over the iso-pressure surface $S$, defined by $\nabla p = 0$

$$-\int_S \nabla p(\mathbf{x},t) \cdot d\mathbf{A} = \frac{\rho_o}{\partial t} \int_S \mathbf{u}(\mathbf{x},t) \cdot d\mathbf{A}. $$

The average pressure $\bar{\rho}(\mathbf{x},t)$ is defined by dividing by the total area

$$\bar{\rho}(\mathbf{x},t) \equiv \frac{1}{A(\mathbf{x})} \int_S p(\mathbf{x},t) \hat{n} \cdot d\mathbf{A}. \tag{5.29}$$

From the definition of the gradient operator

$$\nabla p = \frac{\partial p}{\partial x} \hat{n}, \tag{5.30}$$

where $\hat{n}$ is a unit vector perpendicular to the iso-pressure surface $S$. Thus the left side of Eq. 5.23 reduces to $\partial \bar{\rho}(\mathbf{x},t)/\partial x$.

The integral on the right side defines the volume velocity

$$\nu(\mathbf{x},t) \equiv \int_S \mathbf{u}(\mathbf{x},t) \cdot d\mathbf{A}. \tag{5.31}$$

Thus the integral form of Eq. 5.23 becomes

$$-\frac{\partial}{\partial x} \bar{\rho}(\mathbf{x},t) = \frac{\rho_o}{A(\mathbf{x})} \frac{\partial}{\partial t} \nu(\mathbf{x},t) \leftrightarrow \mathcal{F}(x,s) \mathcal{V}, \tag{5.32}$$

where

$$\mathcal{F}(s,x) = s \rho_o/A(x) = s M(x) \tag{5.33}$$

and $M(x) = \rho_o/A(x)$ [kgm/m$^5$] is the per-unit-length mass density of air.

**Conservation of mass:** Integrating Eq. 5.24 (p. 198) over the volume $V$ gives

$$-\int_V \nabla \cdot \mathbf{u} \, dV = \frac{1}{\eta_o \rho_o} \frac{\partial}{\partial t} \int_V p(\mathbf{x},t) \, dV. $$

The volume $V$ is defined by two iso-pressure surfaces between $x$ and $x + \delta x$ (green region of Fig. 5.3).

On the right-hand side we use the definition of the average pressure (i.e., Eq. 5.29), integrated over the volume $dV$.

Applying Gauss’s law to the left-hand side, and using the definition of $\bar{\rho}$ (on the right), in the limit $\delta x \to 0$, gives

$$\frac{\partial \nu}{\partial x} = \frac{A(x)}{\eta_o \rho_o} \frac{\partial \bar{\rho}}{\partial t} \leftrightarrow -\mathcal{F}(x,s) \mathcal{P}(x,s) \tag{5.34}$$

As shown in Fig. 5.3, we convert the divergence into the difference between two volume velocities, namely $\nu(x + \delta x) - \nu(x)$, and $\partial \nu/\partial x$ as the limit of this difference over $\delta x$, as $\delta x \to 0$. 

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14 As shown in Fig. 5.3, we convert the divergence into the difference between two volume velocities, namely $\nu(x + \delta x) - \nu(x)$, and $\partial \nu/\partial x$ as the limit of this difference over $\delta x$, as $\delta x \to 0$. 

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where

\[ \mathcal{Y}(s,x) = sA(x)/\eta_o P_o = sC(x). \]

\[ C(x) = A(x)/\eta_o P_o \text{ m}^4/\text{N} \]

is the per-unit-length compliance of the air. Equations 5.32 and 5.34 accurately characterize the Webster plane-wave mode up to the frequency where the higher-order eigenmodes begin to propagate (i.e., \( f > f_c \)).

**Speed of sound** \( c_o \): In terms of \( M(x) \) and \( C(x) \), the speed of sound and the acoustic admittance are

\[ c_o = \sqrt{\frac{\text{stiffness}}{\text{mass}}} = \frac{1}{\sqrt{C(x)M(x)}} = \frac{\eta_o P_o}{\rho_o}. \] (5.35)

**Characteristic admittance** \( \mathcal{Y}(x) \): Since the horn equation (Eq. 5.28) is second-order, it has pressure eigenfunction solutions \( P^+ \) and \( P^- \) and their corresponding velocity eigenfunctions \( V^+ \) and \( V^- \), related through Eq. 5.32, which defines the characteristic admittance \( \mathcal{Y}(x) \)

\[ \mathcal{Y}(x) = \frac{1}{\sqrt{\text{stiffness} \cdot \text{mass}}} = \sqrt{\frac{C(x)}{M(x)}} = \frac{A(x)}{\rho_o c_o} = \frac{V^+}{P^+} = \frac{V^-}{P^-}. \] (5.36)

(Campbell, 1903a, 1910, 1922). The characteristic impedance \( Z(x) = 1/\mathcal{Y}(x) \). Based on physical requirements, the admittance must be positive, since only the positive square root is allowed. Note that once the pressure eigenfunctions are determined, the corresponding velocity is given by Eq. 5.32, and then the admittance is given by the ratio of the two. It follows that the characteristic admittance is given by the logarithmic derivative of the pressure eigenfunctions.

**Propagation function** \( \kappa(s) \): The eigenfunctions of the wave equation are

\[ P(x,s) = e^{\pm \kappa(s)x} e^{\text{st}} \]

where \( \kappa(s) = \sqrt{\mathcal{Y}(x,s)\mathcal{Y}(x,s)} = \sqrt{sMsC} \). From the above definitions

\[ \kappa(s) = \sqrt{s\rho_o sA(x)/\eta_o P_o} = \frac{s}{c_o}. \]

Thus \( \kappa(s) \) and \( s \) are the eigenvalues of the differential operations \( \partial/\partial x \) and \( \partial/\partial t \) operating on the pressure \( P(x,s) \).

One must be careful when defining the area \( A(x) \): The area is not the cross-sectional area of the horn, rather it is the wave-front area.

5.3.2 Matrix formulation of WHEN

Newton’s laws of conservation of momentum (Eq. 5.23) and mass (Eq. 5.24) are modern versions of Newton’s starting point for calculating the horn lowest-order plane-wave eigenmode wave speed. Following the derivation of the acoustic equations for the average pressure \( P(r,\omega) \) and the volume velocity (Eqs. 5.32, 5.34), the equations may be expressed as the 2x2 matrix

\[ \frac{d}{dr} \begin{bmatrix} P(r,\omega) \\ V(r,\omega) \end{bmatrix} = \begin{bmatrix} 0 & sM(r) \\ sC(r) & 0 \end{bmatrix} \begin{bmatrix} P(r,\omega) \\ V(r,\omega) \end{bmatrix}. \] (5.37)

Here \( M(r) = \rho_o/A(r) \) and \( C(r) = A(r)/\eta_o P_o \) are the unit-length mass and compliance of the horn (Ramo et al., 1965, p. 213). The product of \( P(r,\omega) \) and \( V(r,\omega) \) define the acoustic power while their ratio defines an impedance (Pierce, 1981, p. 37-41).
To obtain the Webster horn pressure equation Eq. 5.28 (p. 199) from Eq. 5.37, take the partial derivative of the top equation

\[
-\frac{\partial^2 P}{\partial r^2} = s \frac{\partial M(r)}{\partial r} V + s M(r) \frac{\partial V}{\partial r},
\]

and use the lower equation to remove \( \frac{\partial V}{\partial r} \)

\[
\frac{\partial^2 P}{\partial r^2} + s \frac{\partial M(r)}{\partial r} V = s^2 M(r) C(r) P = \frac{s^2}{c_o^2} P.
\]

Then use the upper equation a second time to remove \( V \)

\[
\frac{\partial^2 P}{\partial r^2} + \frac{1}{A(r)} \frac{\partial A(r)}{\partial r} \frac{\partial P}{\partial r} = \frac{s^2}{c_o^2} P(r, s).
\] (5.38)

By use of the chain rule, equations of this form may be directly integrated

\[
\nabla_r P = \frac{1}{A(r)} \frac{\partial}{\partial r} \left[ A(r) \frac{\partial}{\partial r} P(r, s) \right] = \frac{\partial}{\partial r^2} P(r, s) + \frac{1}{A(r)} \frac{\partial A(r)}{\partial r} P_r(r, s).
\] (5.39)

This is equivalent to integration by parts, with integration factor \( A(r) \). Above we may replace \( s^2/c_o^2 \) everywhere by \( \kappa(s) \).

Merging Eqs. 5.38 and 5.39 results in the Webster horn equation (Eq. 5.28, p. 199):

\[
\frac{1}{A(r)} \frac{\partial}{\partial r} A(r) \frac{\partial}{\partial r} P(r, s) = \frac{s^2}{c_o^2} P(r, s).
\]

Equations having this integrated form are known as Sturm-Liouville equations. This important class of differential equations follows from the use of separation of variables on the Laplacian, in any (i.e., every) separable coordinate system (Morse and Feshbach, 1953, Ch. 5.1, p. 494-523).

Summary: Applying Gauss’s law to the 3D wave equation (Eq. 5.25, p. 198) results in a 1D Webster horn equation (WHEN, Eq. 5.28, p. 199), which is a non-singular Sturm-Liouville equation, where the area function is the integration factor \( A(r) \).

Thus Eqs. 5.25 and 5.37 are equivalent to the WHEN (Eq. 5.28).

5.4 Lec 37: d’Alembert’s eigenvector superposition principle

Since the Webster horn equation is second-order in time, it has two unique pressure eigenfunctions \( P^+(r, s) \) and \( P^-(r, s) \). The general solution may always be written as the superposition of pressure eigenfunctions, with amplitudes determined by the boundary conditions.

Based on d’Alembert’s superposition principle, the pressure \( P \) and volume velocity \( V \) may be decomposed in terms of the pressure eigenfunctions \( P^+ \) and \( P^- \)

\[
\begin{bmatrix} P(r, \omega) \\ V(r, \omega) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \mathcal{Y}(r) & -\mathcal{Y}(r) \end{bmatrix} \begin{bmatrix} P^+(r, \omega) \\ P^-(r, \omega) \end{bmatrix}
\] (5.40)

where \( \mathcal{Y} = A(r)/\rho_o \omega c_o = 1/Z \). This equation has several important applications.

15 The Webster horn equation is also related to Schrödinger’s equation, the cornerstone of quantum mechanics (Sect. 5.3.1, p. ??).
5.4. LECTURE 37: D’ALEMBERT’S SUPERPOSITION PRINCIPLE

Table 5.2: Table of horns and their properties for \( N = 1, 2 \) or 3 dimensions, along with the exponential horn (EXP). In this table the horn’s range variable is \( \xi \) [m], having area \( A(\xi) \) [m²], diameter \( \xi_o = \sqrt{A(\xi_o)}/4\pi \) [m]. \( F(r) \) is the coefficient on \( P_e, \kappa(s) \equiv s/c_o \), where \( c_o \) is the speed of sound and \( s = \sigma + \omega j \) is the Laplace frequency. The range variable \( \xi \) may be rendered dimensionless (see Fig. 5.4) by normalizing it as \( r \equiv (\xi - \xi_o)/(L - \xi_o) \). The horn’s range variable \( T \) is the negative sign. Eigenfunctions \( H^\pm(\xi, s) \) are the horn having poles and zeros at \( r = 0 \) to 1. The horn’s eigenfunctions are \( P^\pm(\xi, \omega) \leftrightarrow \phi^\pm(\xi, t) \). When \( \pm \) is indicated, the outbound solution corresponds to the negative sign. Eigenfunctions \( H^\pm(\xi, s) \) are outbound and inbound Hankel functions. The last column is the radiation admittance normalized by the characteristic admittance \( Y(r) = A(r)/\rho_o c_o \).

<table>
<thead>
<tr>
<th>( N )</th>
<th>Name</th>
<th>Area/( A_o )</th>
<th>( F(r) )</th>
<th>( \mathcal{P}^\pm(r, s) )</th>
<th>( \phi^\pm(r, t) )</th>
<th>( Y^\pm_{rad}/Y^\pm )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D</td>
<td>uniform</td>
<td>1</td>
<td>1</td>
<td>( e^{\pm \kappa(s)r} )</td>
<td>( -1 )</td>
<td>( \delta(t + r/c_o) )</td>
</tr>
<tr>
<td>2D</td>
<td>parabolic</td>
<td>( \sqrt{r/r_o} )</td>
<td>( r/r_o )</td>
<td>1/( r )</td>
<td>( H_o^\pm(-j\kappa r) )</td>
<td>( -r )</td>
</tr>
<tr>
<td>3D</td>
<td>conical</td>
<td>( r )</td>
<td>( r^2 )</td>
<td>2/( r )</td>
<td>( e^{\pm \kappa(s)r} )</td>
<td>( -\delta(t) \pm \frac{c_o}{r} u(t) )</td>
</tr>
<tr>
<td>EXP</td>
<td>exponential</td>
<td>( e^{mr} )</td>
<td>( e^{2mr} )</td>
<td>( 2m )</td>
<td>( e^{-m(\pm \sqrt{m^2 + \omega^2})r} )</td>
<td>( 1 \pm \frac{c_o}{sr} )</td>
</tr>
</tbody>
</table>

**Generalized admittance/impedance:** The generalized admittance\(^{16} \) \( Y_{in}(r, s) \) looking into the horn is

\[
Y_{in}(r, s) = \frac{Y(r, \omega)}{\mathcal{P}(r, \omega)} = \frac{Y^+ - Y^-}{\mathcal{P}^+ + \mathcal{P}^-} = \frac{Y^+ - Y^-}{\mathcal{P}^+ + \mathcal{P}^-} (1 - \frac{Y^+}{\mathcal{P}^+} + \frac{Y^-}{\mathcal{P}^-}) = \frac{Y(r, \omega)}{1 - \Gamma(r, s)} = \frac{Y(r, \omega)}{1 + \Gamma(r, s)}.
\] (5.41)

Here we have factored out the forward traveling eigenfunction \( Y^+ \) and \( \mathcal{P}^+ \), and re-expressed \( Y_{in} \) in terms of two ratios, the characteristic admittance \( Y(r) \) (Eq. 5.36) and the reflectance \( \Gamma(r, s) \). \( Y_{in}(s) \) depends on the entire horn, and in the case of a finite length horn \( s \) depends on the terminating admittance. When the horn is terminated, reflections occur, resulting in the horn having poles and zeros at frequencies \( s_k \in \mathbb{C} \), where \( \Gamma(r, s_k) = \pm 1 \).

The reflectance is defined as

\[
\Gamma(r, s) = \frac{Y^-(r, \omega)}{Y^+(r, \omega)} = \frac{\mathcal{P}^-(r, \omega)}{\mathcal{P}^+(r, \omega)} = \frac{Z_{in}(r, s) - Z}{Z_{in}(r, s) + Z},
\] (5.44)

which follows by a rearrangement of terms in Eq. 5.36. The magnitude of the reflections depends on \( |\Gamma| \), which must be between 0 and 1. Alternatively, this equation may be obtained by solving Eq. 5.43 for \( \Gamma(r, s) \).

**Horn radiation admittance:** The horn’s acoustic input admittance \( Y_{in}(r, s) \) is defined by dividing Eq. 5.32 (p. 200) by \( \mathcal{P}^\pm \)

\[
Y_{in}^\pm(r, s) = \frac{Y(r, s)}{\mathcal{P}(r, s)} = -\frac{A(r)}{s \rho_o} \frac{d}{dr} \ln \mathcal{P}^\pm(r, s) \quad (5.46)
\]

A horn’s acoustic radiation admittance \( Y_{rad}^\pm(r, s) \) is the input admittance (Eq. 5.43) when there is no terminating load\(^{17} \)

\[
Y_{rad}^\pm(r, s) = \lim_{r \to \infty} Y_{in}^\pm(r, s).
\] (5.47)

---

\(^{16}\)It is “generalized” in the sense that it is not a Brune, rational function, impedance.

\(^{17}\)To compute the radiation impedance \( Y_{rad}^\pm \) one must know the eigenfunctions \( \mathcal{P}^\pm(r, s) \).
CHAPTER 5. STREAM 3B: VECTOR CALCULUS (10 LECTURES)

Figure 5.4: Throat acoustical resistance $r_A$ and acoustical reactance $x_A$, frequency characteristics of infinite eigenfunctions of the parabolic, conical, exponential, hyperbolic and cylindrical horns, having a throat area of 1 [cm$^2$]. Note how the "critical" frequency (defined here as the frequency where the reactive and real parts of the radiation impedance are equal) of the horn reduces dramatically with the type of horn. For the uniform horn, the reactive component is zero, so there is no cutoff frequency. For the parabolic horn (1) the cutoff is around 3 kHz. For the conical horn (2) the cutoff is at 0.6 [kHz]. For the exponential horn (3) the critical frequency is around 0.18 [kHz], which is one 16th that of the parabolic horn. For each horn the cross-sectional area is defined as 100 [cm$^2$] at a distance of 1 [m] from the throat (Olson, 1947, p. 101), (Morse, 1948, p. 283).

The input admittance becomes the radiation admittance when the horn is infinite in length, namely it is the input admittance for an eigenfunction. A table of properties is given in Table 5.2 for four different simple horns. Expressions for $Y_{rad}(x, s)$ are given in the last column of Table 5.2.

5.4.1 Complex analytic $\Gamma(s)$ and $Y_{in}(s)$

When defining the complex reflectance $\Gamma(s)$ as a function of the complex frequency $s = \sigma + j\omega$, a very important assumption has been made: even though $\Gamma(s)$ is defined by the ratio of two functions of real (radian) frequency $\omega$, like the impedance, the reflectance must be causal (postulate P1, p. 132). Namely $\Gamma(s) \leftrightarrow \gamma(t)$ is zero for $t < 0$. The same holds for the time-domain admittance and impedance $\zeta(t) \leftrightarrow Z_{in}(s) = 1/Y_{in}(s)$. That $\gamma(t)$ and $\zeta(t)$ are causal is required by the physics.

The forward and retrograde waves are functions of frequency $\omega$, as they depend on the source pressure (or velocity) and the point of horn excitation. The reflectance is a transfer function (thus the source term cancels) that depends only on the Thévenin impedance (or reflectance) looking into the system (at any position $r$).

To calculate $\Gamma(r, s)$ one must invert d’Alembert’s superposition equation (Eq. 5.40)

$$\begin{bmatrix} P^+(r, s) \\ P^-(r, s) \end{bmatrix} = \frac{1}{2Y(r)} \begin{bmatrix} Y(r) & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & Z(r) \\ 1 & -Z(r) \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}. \tag{5.48}$$

The reflectance is defined as the ratio of the two pressure eigenfunctions

$$\Gamma(r, s) \equiv \frac{P^-}{P^+} = \frac{P - ZV}{P + ZV} = \frac{Z_{in} - Z}{Z_{in} + Z} = -\frac{Y_{in} - V}{Y_{in} + V}, \tag{5.49}$$

which is related to Eq. 5.43.

Given some experience with $Y_{in}(r, s)$ and $\Gamma(r, s)$, one soon appreciates the advantage of working with the reflectance over the radiation impedance/admittance $Z_{rad}(s)$ (aka immittance). The impedance has complicated properties, all of which are difficult to verify, whereas the reflectance is easily understood (it is closer to the physics). For example, we know that for a physical passive impedance $\Re Z \geq 0$.

The corresponding property for the reflectance is $|\Gamma(\omega)| \leq 1$, with equality when the input resistance is zero.

It is important to note that because the area $A(x)$ is varying along the direction of propagation, energy is continuously being scattered back to the input, as captured by the area-dependent eigenfunctions. It is because of this scattering that the input admittance $Y_{in}(s)$ (Eq. 5.43) and the reflectance $\Gamma(r, s)$ (Eq. 5.49) depend on frequency, as explicitly shown in Fig. 5.4 (Morse, 1948, p. 283).
Exercise:

1. Show that \( \Re Y_{in}(s) \geq 0 \) if and only if \(|\Gamma| \leq 1|\). Hint: Use Eq 5.49 (or 5.43).

2. Show that the unit circle in the \( \Gamma(s) \) plane maps onto the \( \omega j \) axis in the impedance plane.

Solution: To prove this take the real part of \( Y_{in}(s) \) (Eq. 5.43) and show that it is greater than zero if \(|\Gamma(s)| \leq 1\)

\[
\frac{2}{Y'(r)} \Re Y_{in}(s) = \frac{1 - \Gamma}{1 + \Gamma} + \frac{1 - \Gamma^*}{1 + \Gamma^*} = \frac{(1 - \Gamma)(1 + \Gamma^*) + (1 + \Gamma)(1 - \Gamma^*)}{|1 + \Gamma|^2}
\]

\[
= \frac{2(1 - |\Gamma|^2)}{|1 + \Gamma|^2} \geq 0.
\]

In conclusion:

1. if \(|\Gamma| < 1\), then \( \Re Z_{in} > 0 \).

2. if \(|\Gamma| = 1\), then \( \Re Z_{in} = 0 \).
5.4.2 Exercises VC-1

**Topic of this homework:** Vector algebra and fields in \( \mathbb{R}^3 \); Gradient and scalar Laplacian operator; Definitions of Divergence and Curl; Gauss’s (divergence) & Stokes’ (Curl) Law; Schwarz inequality; Quadratic forms; System postulates

**Vector algebra in \( \mathbb{R}^3 \).**

Definitions of the vector scalar (aka dot) \( A \cdot B \), cross \( A \times B \) and triple product \( A \cdot (B \times C) \) may be found in Appendix A (p. 241), where \( A, B, C \) in \( \mathbb{R}^3 \subset \mathbb{C}^3 \). A fourth “double-cross” (\[BT\]) vector product is:

\[
A \times (B \times C) = \alpha_o B - \beta_o C.
\]

where \( \alpha_o = A \cdot C \) and \( \beta_o = A \cdot B \) (Note: \( A \times (B \times C) \neq (A \times B) \times C \)).

To Do:

1. **Scalar product** \( A \cdot B \)
   
   (a) If \( A = a_x \hat{x} + a_y \hat{y} + a_z \hat{z} \) and \( B = b_x \hat{x} + b_y \hat{y} + b_z \hat{z} \), write out the definition of \( A \cdot B \).
   
   (b) The dot product is often defined as \( ||A|| ||B|| \cos(\theta) \), where \( ||A|| = \sqrt{A \cdot A} \) and \( \theta \) is the angle between \( A, B \). If \( ||A|| = 1 \), describe how the dot product relates to the vector \( B \).

2. **Vector (cross) product** \( A \times B \)
   
   (a) If \( A = a_x \hat{x} + a_y \hat{y} + a_z \hat{z} \) and \( B = b_x \hat{x} + b_y \hat{y} + b_z \hat{z} \), write out the definition of \( A \times B \).
   
   (b) Show that the cross product is equal to the area of the parallelogram formed by \( A, B \), namely \( ||A|| ||B|| \sin(\theta) \), where \( ||A|| = \sqrt{A \cdot A} \) and \( \theta \) is the angle between \( A \) and \( B \).

3. **Triple product** \( A \cdot (B \times C) \)

   Let \( A = [a_1, a_2, a_3]^T \), \( B = [b_1, b_2, b_3]^T \), \( C = [c_1, c_2, c_3]^T \) be three vectors in \( \mathbb{R}^3 \).

---

18Greenberg p. 694, Eq. 8.
(a) Starting from the definition of the dot and cross product, explain using a diagram and/or words, how one shows that: \( \mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = \begin{vmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{vmatrix} \).

(b) Describe why \( |\mathbf{A} \cdot (\mathbf{B} \times \mathbf{C})| \) is the volume of parallelepiped generated by \( \mathbf{A}, \mathbf{B} \) and \( \mathbf{C} \).

(c) Explain why three vectors \( \mathbf{A}, \mathbf{B}, \mathbf{C} \) are in one plane if and only if the triple product \( \mathbf{A} \cdot (\mathbf{B} \times \mathbf{C}) = 0 \).

4. Given two vectors \( \mathbf{A}, \mathbf{B} \) in the \( \hat{x}, \hat{y} \) plane (see Fig. 1), with \( \mathbf{B} = \hat{y} \) (i.e., \( ||\mathbf{B}|| = 1 \)). Show that \( \mathbf{A} \) may be split into two orthogonal parts, one in the direction of \( \mathbf{B} \) and the other perpendicular (\( \perp \)) to \( \mathbf{B} \).

\[
\mathbf{A} = (\mathbf{A} \cdot \mathbf{B})\mathbf{B} + \mathbf{B} \times (\mathbf{A} \times \mathbf{B}) \\
= A_\parallel + A_\perp.
\]

**Scalar fields and the \( \nabla \) operator**

**To Do:**

1. Let \( T(x, y) = x^2 + y \) be an analytic scalar temperature field in 2 dimensions (single-valued \( \in \mathbb{R}^2 \)).

(a) Find the gradient of \( T(x) \) and make a sketch of \( T \) and the gradient.

(b) Compute \( \nabla^2 T(x) \), to determine if \( T(x) \) satisfies Laplace’s equation.

(c) Sketch the iso-temperature contours at \( T = -10, 0, 10 \) degrees.

(d) The heat flux\(^{19} \) is defined as \( \mathbf{J}(x, y) = -\kappa(x, y)\nabla T \) where \( \kappa(x, y) \) is a constant denoting thermal conductivity at the point \( (x, y) \). Assuming \( \kappa = 1 \) everywhere (the medium is homogeneous), plot the vector \( \mathbf{J}(x, y) = -\nabla T \) at \( x = 2, y = 1 \). Be clear about the origin, direction and length of your result.

(e) Find the vector \( \perp \) to \( \nabla T(x, y) \), namely tangent to the iso-temperature contours. Hint: Sketch it for one \( (x, y) \) point (e.g., \( 2,1 \)) and then generalize.

(f) The thermal resistance \( R_T \) is defined as the potential drop \( \Delta T \) over the magnitude of the heat flux \( ||\mathbf{J}|| \). At a single point the thermal resistance is

\[
R_T(x, y) = -\nabla T / ||\mathbf{J}||.
\]

How is \( R_T(x, y) \) related to the thermal conductivity \( \kappa(x, y) \)?

2. **Acoustic wave equation:** **Note: In the following problem, we will work in the frequency domain.**

The basic equations of acoustics in 1 dimension are

\[-\frac{\partial}{\partial x} \mathcal{P} = \rho_o s V \quad \text{and} \quad -\frac{\partial}{\partial x} V = \frac{s}{\eta_o P_o} \mathcal{P}.\]

Here \( \mathcal{P}(x, \omega) \) is the pressure (in the frequency domain), \( V(x, \omega) \) is the volume velocity (integral of the velocity over the wave-front having area \( A \)), \( s = \sigma + \omega \rho \), \( \rho_o = 1.2 \) is the specific density of air, \( \eta_o = 1.4 \) and \( P_o \) is the atmospheric pressure (i.e., \( 10^5 \) Pa) (see the handout Appendix F.2 for details). **Note that the pressure field \( \mathcal{P} \) is a scalar (pressure does not have direction), while the volume velocity field \( V \) is a vector (velocity has direction).**

We can generalize these equations to 3 dimensions using the \( \nabla \) operator

\[-\nabla \mathcal{P} = \rho_o s V \quad \text{and} \quad -\nabla \cdot V = \frac{s}{\eta_o P_o} \mathcal{P},\]

\(^{19}\)The heat flux is proportional to the change in temperature times the thermal conductivity \( \kappa \) of the medium https://en.wikipedia.org/wiki/Heat_equation#Derivation_in_one_dimension.
(a) Starting from these two basic equations, derive the scalar wave equation in terms of the pressure $P$,

$$\nabla^2 P = \frac{s^2}{c_0^2} P$$

where $c_0$ is a constant representing the speed of sound.

(b) What is $c_0$ in terms of $\eta_0$, $\rho_0$, and $P_0$?

(c) Rewrite the pressure wave equation in the time domain, using the time derivative property of the Laplace transform (e.g. $dx/dt \leftrightarrow sX(s)$). For your notation, define the time-domain signal using a lowercase letter, $p(x, y, z, t) \leftrightarrow P$.

Vector fields and the $\nabla$ operator

To Do:

Vector Algebra

1. Let $\mathbf{R}(x, y, z) \equiv x(t)\hat{x} + y(t)\hat{y} + z(t)\hat{z}$:

   (a) If $a, b, c$ are constants, what is $\mathbf{R}(x, y, z) \cdot \mathbf{R}(a, b, c)?$?

   (b) If $a, b, c$ are constants, what is $\frac{d}{dt}[\mathbf{R}(x, y, z) \cdot \mathbf{R}(a, b, c)]?$

2. Find the divergence and curl of the following vector fields:

   (a) $\mathbf{v} = \hat{x} + \hat{y} + 2\hat{z}$

   (b) $\mathbf{v}(x, y, z) = x\hat{x} + xy\hat{y} + z^2\hat{z}$

   (c) $\mathbf{v}(x, y, z) = x\hat{x} + xy\hat{y} + \log(z)\hat{z}$

   (d) $\mathbf{v}(x, y, z) = \nabla(1/x + 1/y + 1/z)$

Vector & scalar field identities

1. Find the divergence and curl of the following vector fields:

   (a) $\mathbf{v} = \nabla\phi$, where $\phi(x, y) = xe^y$

   (b) $\mathbf{v} = \nabla \times \mathbf{A}$, where $\mathbf{A} = x\hat{x} + y\hat{y} + z\hat{z}$

   (c) $\mathbf{v} = \nabla \times \mathbf{A}$, where $\mathbf{A} = y\hat{x} + x^2\hat{y} + z\hat{z}$

2. For any differentiable vector field $\mathbf{V}$, write down two vector-calculus identities that are equal to zero.

3. What is the most general form of a vector field may be expressed in, in terms of scalar $\Phi$ and vector $\mathbf{A}$ potentials?

4. Perform the following calculations. If you can state the answer without doing the calculation, explain why.

   (a) Let $\mathbf{v} = \sin(x)\hat{x} + y\hat{y} + z\hat{z}$. Find $\nabla \cdot (\nabla \times \mathbf{v})$ Hint: Look at Lec 41 on page 83 of the notes, Eq. 1.58, 59.

   (b) Let $\mathbf{v} = \sin(x)\hat{x} + y\hat{y} + z\hat{z}$. Find $\nabla \times (\nabla \sqrt{\mathbf{v} \cdot \mathbf{v}})$

   (c) Let $\mathbf{v}(x, y, z) = \nabla[x + y^2 + \sin(\log(z))]$. Find $\nabla \times \mathbf{v}(x, y, z)$. 
5.4. LECTURE 37: D’ALEMBERT’S SUPERPOSITION PRINCIPLE

Integral theorems

1. In a few words, identify the law, define what it means, and explain the following formula:

\[ \int_S \hat{n} \cdot \mathbf{v} \, dA = \int_V \nabla \cdot \mathbf{v} \, dV. \]

2. What is the name of this formula?

\[ \int_S (\nabla \times \mathbf{V}) \cdot d\mathbf{S} = \oint_C \mathbf{V} \cdot d\mathbf{R}. \]

Give one important application.

3. Describe a key application of the vector identity

\[ \nabla \times (\nabla \times \mathbf{V}) = \nabla (\nabla \cdot \mathbf{V}) - \nabla^2 \mathbf{V}. \]

Schwarz inequality

Below is a picture of these three vectors for an arbitrary value of \( a \) and a specific \( a = a^* \).

[Diagram showing three vectors: \( \mathbf{V} \), \( \mathbf{U} \), and \( \mathbf{E}(\alpha) \).]

1. Find the value of \( a^* \in \mathbb{R} \) such that the length (norm) of \( \mathbf{E} \) (i.e., \( ||\mathbf{E}|| \geq 0 \)) is minimum? Hint minimize

\[ ||\mathbf{E}||^2 = \mathbf{E} \cdot \mathbf{E} = (\mathbf{V} + a\mathbf{V}) \cdot (\mathbf{V} + a\mathbf{U}) \geq 0 \]

with respect to \( a \).

2. Find the formula for \( ||\mathbf{E}(a^*)||^2 \geq 0 \). Hint: Substitute \( a^* \) into Eq. 5.50, and show that this results in the Schwarz inequality

\[ |\mathbf{U} \cdot \mathbf{V}| \leq ||\mathbf{U}|| ||\mathbf{V}||. \]

3. What is the geometrical meaning of the dot product of two vectors?

4. Give the formula for the dot product between two vectors. Explain the meaning based on Fig. 5.4.2.

5. Write the formula for the “dot product” between two vectors: \( \mathbf{U} \cdot \mathbf{V} \) in \( \mathbb{R}^n \) in polar form (e.g., assume the angle between the vectors is equal to \( \theta \)).

6. How is this related to the Pythagorean theorem?

7. Starting from \( ||\mathbf{U} + \mathbf{V}|| \) derive the triangle inequality

\[ ||\mathbf{U} + \mathbf{V}|| \leq ||\mathbf{U}|| + ||\mathbf{V}||. \]

8. The triangular inequality \( ||\mathbf{U} + \mathbf{V}|| \leq ||\mathbf{U}|| + ||\mathbf{V}|| \) is true for 2 and 3 dimensions: Does it hold for 5 dimensional vectors?
Quadratic forms

A matrix that has positive eigenvalues is said to be **positive-definite**. The eigenvalues are real if the matrix is symmetric, so this is a necessary condition for the matrix to be positive-definite. This condition is related to conservation of energy since the power is the voltage times the current. Given an impedance matrix

\[ V = ZI, \]

the power \( P \) is

\[ P = I \cdot V = I \cdot ZI, \]

which must be positive definite for the system to obey conservation of energy. For the following problems, consider the \( 2 \times 2 \) matrix

\[
\begin{bmatrix}
2 & 1 \\
1 & 4
\end{bmatrix}
\]

1. Solve for the power \( P(i_1, i_2) \) by multiplying out the matrix equation below (which is in quadratic form) \( (I \equiv \begin{bmatrix} i_1 & i_2 \end{bmatrix}^T) \)

\[
P(i_1, i_2) = I^T \begin{bmatrix}
2 & 1 \\
1 & 4
\end{bmatrix} I.
\]

2. Is the impedance matrix **positive definite**? Show your work by finding the eigenvalues of the matrix \( Z \).

3. Should an impedance matrix always be positive definite? Explain.

**System Classification**

Provide a one-sentence definition of the following properties:

- L/NL : linear(L)/nonlinear(NL):
- TI/TV : time-invariant(TI)/time varying(TV):
- P/A : passive(P)/active(A):
- C/NC : causal(C)/non-causal(NC):
- Re/Clx : real(Re)/complex(Clx):

<table>
<thead>
<tr>
<th>#</th>
<th>Case</th>
<th>Definition</th>
<th>L/NL</th>
<th>TI/TV</th>
<th>P/A</th>
<th>C/NC</th>
<th>Re/Clx</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resistor</td>
<td>( v(t) = r_0 i(t) )</td>
<td>L</td>
<td>TI</td>
<td>P</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>2</td>
<td>Inductor</td>
<td>( v(t) = L \frac{di}{dt} )</td>
<td>L</td>
<td>TI</td>
<td>P</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>3</td>
<td>Switch</td>
<td>( v(t) = \begin{cases} 0 &amp; t \leq 0 \ V_0 &amp; t &gt; 0 \end{cases} )</td>
<td>L</td>
<td>TV</td>
<td>P</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>5</td>
<td>Transistor</td>
<td>( I_{out} = g_m(V_{in}) )</td>
<td>NL</td>
<td>TI</td>
<td>P</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>7</td>
<td>“Resistor”</td>
<td>( v(t) = r_0 i(t + 3) )</td>
<td>L</td>
<td>TI</td>
<td>P</td>
<td>NC</td>
<td>Re</td>
</tr>
<tr>
<td>8</td>
<td>modulator</td>
<td>( f(t) = e^{2\pi t} g(t) )</td>
<td>L</td>
<td>TV</td>
<td>P</td>
<td>C</td>
<td>Clx</td>
</tr>
</tbody>
</table>
2. Using the same classification scheme, characterize the following equations:

<table>
<thead>
<tr>
<th>#</th>
<th>Case:</th>
<th>L/NL</th>
<th>TI/TV</th>
<th>P/A</th>
<th>C/NC</th>
<th>Re/Clx</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( A(x) \frac{d^2y(t)}{dt^2} + D(t)y(x, t) = 0 )</td>
<td>L</td>
<td>TV</td>
<td>P</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>2</td>
<td>( \frac{dy(t)}{dt} + \sqrt{t} y(t) = \sin(t) )</td>
<td>L</td>
<td>TV</td>
<td>?</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>3</td>
<td>( y^2(t) + y(t) = \sin(t) )</td>
<td>NL</td>
<td>TI</td>
<td>?</td>
<td>C</td>
<td>Re</td>
</tr>
<tr>
<td>4</td>
<td>( \frac{dy(t)}{dt} + xy(t + 1) + x^2y = 0 )</td>
<td>L</td>
<td>TI</td>
<td>P</td>
<td>NC</td>
<td>Re</td>
</tr>
<tr>
<td>5</td>
<td>( \frac{dy(t)}{dt} + (t - 1) y^2(t) = ie^t )</td>
<td>NL</td>
<td>TV</td>
<td>A?</td>
<td>C</td>
<td>Clx</td>
</tr>
</tbody>
</table>
5.4.3 Finite length horns

For a horn of finite length $L$ the acoustic variables $\mathcal{P}(x,s), \mathcal{V}(x,s)$ may be expressed in terms of pressure eigenfunctions. If we define the forward wave $\mathcal{P}^{+}(x,\omega)$ as launched from $x = 0$ and the retrograde wave $\mathcal{P}^{-}(x,\omega)$ as launched from $x = L$, we may write the pressure and velocity as

$$
\begin{bmatrix}
\mathcal{P}(x) \\
\mathcal{V}(x)
\end{bmatrix} = 
\begin{bmatrix}
\mathcal{P}^{+}(x) & \mathcal{P}^{-}(x-L) \\
\mathcal{V}(x) \mathcal{P}^{+}(x) & -\mathcal{V}(x) \mathcal{P}^{-}(x-L)
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix},
$$

(5.51)

Here $\alpha(x,\omega)$ scales the forward wave and $\beta(x,\omega)$ scales the retrograde wave. Thus the reflectance $\Gamma(L,\omega) = \beta/\alpha$ is defined at the site of reflection ($x = L$). Typically the characteristic admittance $\mathcal{Y}(x) = A(x)/\rho_0 c_0$ only depends on the location $x$ but not on the Laplace frequency $s$. This formula may not be correct if the horn has losses ($\mathcal{Y} \in \mathbb{C}$), as discussed by Kirchhoff (1868); Mason (1927, 1928); Robinson (2017).

To evaluate the coefficients $\alpha(\omega)$ and $\beta(\omega)$ we must invert Eq. 5.51. The eigenfunction scale factors $\alpha, \beta$ are determined by the load admittance $\mathcal{Y}_{\text{load}}$ at the site of reflection $x = L$. If this is your first time reading this section, it may be best to skip to “Three examples of horns” and return here when you wish to read the details.

**Notation:** Adopting subscript notation: $\mathcal{P}_x^{\pm} \equiv \mathcal{P}^{\pm}(x)$, $\mathcal{P}_0^{+} \equiv \mathcal{P}^{+}(0) = 1$, $\mathcal{P}^{-}(L) \equiv \mathcal{P}^{-}_{L} = 1$, $\mathcal{V}_x^{\pm} \equiv \mathcal{V}^{\pm}(x)$. $\mathcal{Y}_x = \mathcal{Y}(x)$, and inverting Eq. 5.51 at $x = L$, gives

$$
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}_L = 
\frac{-1}{\Delta_L}
\begin{bmatrix}
-\mathcal{Y}_L \mathcal{P}_0^{1} & -\mathcal{P}_0^{1} \\
-\mathcal{Y}_L \mathcal{P}_L^{1} & \mathcal{P}_L^{1}
\end{bmatrix}
\begin{bmatrix}
\mathcal{P} \\
\mathcal{V}
\end{bmatrix}_L,
$$

(5.52)

where the determinant at $x$ is

$$
\Delta_x = -\mathcal{Y}(x) \left[ \mathcal{P}^{+}(x) \mathcal{P}^{-}(x-L) + \mathcal{P}^{+}(x) \mathcal{P}^{-}(x-L) \right]
$$

$$
= -2\mathcal{Y}(x) \mathcal{P}^{+}(x) \mathcal{P}^{-}(x-L),
$$

which at $x = L$ is

$$
\Delta_L = -2\mathcal{Y}_L \mathcal{P}_L^{+} \mathcal{P}_0^{-}.
$$

Since $\mathcal{Z}_L = 1/\mathcal{Y}_L$ and $\mathcal{P}_0^{-} = 1$,

$$
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}_L = 
\frac{1}{2 \mathcal{P}_L^{+}}
\begin{bmatrix}
\mathcal{Z}_L & \mathcal{Z}_L \\
\mathcal{P}_L^{+} & -\mathcal{Z}_L \mathcal{P}_L^{+}
\end{bmatrix}
\begin{bmatrix}
\mathcal{P} \\
-\mathcal{V}
\end{bmatrix}_L.
$$

(5.53)

The above expression quantities the general expression for the eigenfunction amplitudes $\alpha, \beta$ at the reflection site $x = L$, where the two solutions $P^{+}$ and $P^{-}$ mix for the first time. The pressure and velocity at $x = L$ form the boundary condition in terms of their ratio $Z_{\text{load}}(s)$. Note that the sign of $\mathcal{V}_L$ must be negative to satisfy the definition of every ABCD matrix (i.e., the output velocity must equal the input velocity of the next cell).

The reflectance is given by the ratio of $\beta/\alpha$ at $x = L$,

$$
\Gamma(x,s) = \frac{|\mathcal{Y}_L|}{|\mathcal{Y}_L|}_{x=L},
$$

which depends on the load impedance

$$
Z_{\text{load}}(x=L,s) = -\mathcal{P}_L/\mathcal{V}_L.
$$

Note that if the load impedance equals the local characteristic impedance $\mathcal{Z}_L, \beta = 0$. 

Substituting Eq. 5.53 back into Eq. 5.51 results in an expression for the input acoustic variables at \( x = 0 \) in terms of those at \( x = L \), with \( P_L^+ = 1 \) and \( P_L^- = 1 \):

\[
\begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_0 = \frac{1}{2P_L^+} \begin{bmatrix} 1 \\ 0 \end{bmatrix} P_0^- - \frac{1}{2P_L^-} \begin{bmatrix} 1 \\ 0 \end{bmatrix} P_0^+ - \frac{1}{2P_L^+} \begin{bmatrix} -Z_L \end{bmatrix}_L \begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_L.
\]

(5.54)

Multiplying this out gives

\[
\begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_0 = \frac{1}{2P_L^+} \begin{bmatrix} 1 + P_L^+ P_0^- \\ \gamma_0^+ (P_0^+ - P_L^+ P_0^-) \end{bmatrix} - \frac{1}{2P_L^-} \begin{bmatrix} -Z_L (1 + P_L^- P_0^-) \\ -\gamma_0^+ (P_0^- - P_L^- P_0^+) \end{bmatrix} \begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_L.
\]

(5.55)

It may be more useful to leave this expression in terms of \( \Gamma_L(s) \) than to substitute Eq. 5.52 into Eq. 5.51. This general expression will be verified below by comparing it with the uniform horn.

5.4.4 Three examples of horns

Summary of four classic horns: Figure 5.4 is taken from the classic book of Olson (1947, p. 101), showing the radiation impedance \( Z_{rad}(r, \omega) \) for five horns: 1-parabolic, 2-conical, 3-exponential, 4-hyperbolic, and 5-cylindrical. Table 5.2 (p. 203) summarizes the properties of four of these horns: (1) the uniform (cylindrical) \( A(x) = A_0 \), (2) parabolic \( A(r) = A_o r \), (3) conical (spherical) \( A(r) = A_o r^2 \) and (4) exponential \( A(r) = A_o e^{2mr} \).

1) The uniform horn

The 1D wave equation \( A(r) = A_o \)

\[
d^2 \mathcal{P} = \frac{s^2}{c_o^2} \mathcal{P}.
\]

Solution: The two eigenfunctions of this equation are the two d’Alembert waves (Eq. 4.16, p. 149)

\[
g(x, t) = \alpha(\omega) e^{\kappa x} (t - x/c) + \beta(\omega) e^{-\kappa x} (t + x/c) \leftrightarrow \alpha(\omega) e^{-\kappa(s)x} + \beta(\omega) e^{\kappa(s)(x-L)},
\]

where \( \kappa(s) = s/c_o = \omega/c \) is denoted the propagation function (aka: wave-evolution function, propagation constant, and wave number) and \( \alpha, \beta \) are defined in Eq. 5.51.

Note that for the uniform horn \( \omega/c_o = 2\pi/\lambda \). It is convenient to normalize \( P_0^+ = 1 \) and \( P_L^- = 1 \), as was done for the general case above. When the area is not constant, \( \lambda \) is a complex function of frequency, resulting in a complex input impedance (admittance), internal standing waves and wave propagation loss.

The characteristic admittance (Eq. 5.36) is independent of direction. The signs must be physically chosen, with the velocity \( \mathcal{V} \) into the port, to assure that \( \mathcal{Y} > 0 \), for both waves, where \( \mathcal{Y} \) is independent of direction and \( x \).

Applying the boundary conditions: The general solution in terms of the eigenvector matrix (Eq. 5.51), evaluated at \( x = L \), is

\[
\begin{bmatrix} \mathcal{P}(x) \\ \mathcal{V}(x) \end{bmatrix}_L = \begin{bmatrix} e^{-\kappa x} \\ \mathcal{Y} e^{-\kappa x} \end{bmatrix}_L \begin{bmatrix} \alpha \\ \beta \end{bmatrix}_L = \begin{bmatrix} e^{-\kappa L} \\ \mathcal{Y} e^{-\kappa L} \end{bmatrix}_L \begin{bmatrix} 1 \\ -\mathcal{Y} \end{bmatrix}_L \begin{bmatrix} \alpha \\ \beta \end{bmatrix}_L,
\]

(5.56)

where \( \alpha, \beta \) are the relative weights on the two unknown eigenfunctions, to be determined by the boundary conditions at \( x = 0, L \), \( \kappa = s/c \) and \( \mathcal{Y} = 1/Z = A_o/\rho_o c \).

Solving Eq. 5.56 for \( \alpha \) and \( \beta \) with determinant \( \Delta = -2\mathcal{Y} e^{-\kappa L} \),

\[
\begin{bmatrix} \alpha \\ \beta \end{bmatrix}_L = \frac{-1}{2\mathcal{Y} e^{-\kappa L}} \begin{bmatrix} -\mathcal{Y} & -1 \\ -\mathcal{Y} e^{-\kappa L} & e^{-\kappa L} \end{bmatrix} \begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_L = \frac{1}{2} \begin{bmatrix} e^{\kappa L} & -Z e^{\kappa L} \\ 1 & Z \end{bmatrix} \begin{bmatrix} \mathcal{P} \\ \mathcal{V} \end{bmatrix}_L.
\]

(5.57)
In the final step we swapped all the signs, including on $\mathcal{V}$, and moved $Z = 1/\mathcal{Y}$ inside the matrix.

We may uniquely determine these two weights given the pressure and velocity at the boundary $x = L$, which is typically determined by the load impedance ($\mathcal{P}_L/\mathcal{V}_L$).

The weights may now be substituted back into Eq. 5.56 to determine the pressure and velocity amplitudes at any point $0 \leq x \leq L$.

\[
\begin{bmatrix}
\mathcal{P}_x \\
\mathcal{V}_x
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
e^{-\kappa x} & e^{\kappa(x-L)} \\
\mathcal{V}e^{-\kappa x} & -\mathcal{V}e^{\kappa(x-L)}
\end{bmatrix} \begin{bmatrix}
1 & -Ze^{\kappa L} \\
Z & 1
\end{bmatrix} \begin{bmatrix}
\mathcal{P} \\
-\mathcal{V}
\end{bmatrix}.
\]  

(5.58)

Setting $x = 0$ and multiplying these out gives the final transmission matrix

\[
\begin{bmatrix}
\mathcal{P}_0 \\
\mathcal{V}_0
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
e^{\kappa L} + e^{-\kappa L} & Z(e^{\kappa L} - e^{-\kappa L}) \\
\mathcal{V}(e^{\kappa L} - e^{-\kappa L}) & e^{\kappa L} + e^{-\kappa L}
\end{bmatrix} \begin{bmatrix}
\mathcal{P} \\
-\mathcal{V}
\end{bmatrix}.
\]  

(5.59)

Note the diagonal terms are $\cosh \kappa L$ and off-diagonal terms are $\sinh \kappa L$.

Applying the last boundary condition, we evaluate Eq. 5.57 to obtain the ABCD matrix at the input ($x = 0$) (Pipes, 1958)

\[
\begin{bmatrix}
\mathcal{P}_0 \\
\mathcal{V}_0
\end{bmatrix} = \begin{bmatrix}
\cosh \kappa L & Z \sinh \kappa L \\
\mathcal{Y} \sinh \kappa L & \cosh \kappa L
\end{bmatrix} \begin{bmatrix}
\mathcal{P} \\
-\mathcal{V}
\end{bmatrix}.
\]  

(5.60)

Exercise: Evaluate this expression in terms of the load impedance.

Impedance matrix: Expressing Eq. 5.60 as an impedance matrix gives (algebra required)

\[
\begin{bmatrix}
\mathcal{P}_o \\
\mathcal{P}_L
\end{bmatrix} = \frac{Z}{\sinh(\kappa L)} \begin{bmatrix}
\cosh(\kappa L) & 1 \\
1 & \cosh(\kappa L)
\end{bmatrix} \begin{bmatrix}
\mathcal{V}_o \\
\mathcal{V}_L
\end{bmatrix}.
\]

Exercise: Write out the input impedance $Z_{in}(s)$ for the uniform horn.

Input admittance $Y_{in}$: Given the input admittance of the horn, it is possible to determine if it is uniform, without further analysis. Namely, if the horn is uniform and infinite in length, the input admittance at $x = 0$ is

\[
Y_{in}(x = 0, s) \equiv \frac{\mathcal{V}(0, \omega)}{\mathcal{P}(0, \omega)} = \mathcal{Y},
\]

since $\alpha = 1$ and $\beta = 0$. That is, for an infinite uniform horn, there are no reflections.

When the horn is terminated with a fixed impedance $Z_L$ at $x = L$, one may substitute pressure and velocity measurements into Eq. 5.57 to find $\alpha$ and $\beta$, and given these, one may calculate the reflectance at $x = L$ (Eq. 5.45, p. 203)

\[
\Gamma_L(s) \equiv \left. \frac{\mathcal{P}^-}{\mathcal{P}^+} \right|_{x=L} = \frac{\beta}{\alpha} = \frac{\mathcal{P}(L, \omega) - Z \mathcal{V}(L, \omega)}{\mathcal{P}(L, \omega) + Z \mathcal{V}(L, \omega)} = \frac{Z_L - Z}{Z_L + Z}
\]

given sufficiently accurate measurements of the throat pressure $\mathcal{P}(0, \omega)$, velocity $\mathcal{V}(0, \omega)$, and the characteristic impedance of the input $Z = \rho_o c/A(0)$.

2) Conical horn

For each horn we must find the natural normalization from the range variable to the normalized range variable $x$. For the conical horn the radius is proportional to the range variable $r$, thus

\[
A(r) = 4\pi \sin^2(\Theta/2) \ r^2 \ [m^2].
\]
The angle $\Theta$ is a measure of the solid (cone) angle. When $\Theta = \pi$ we have the case of the entire sphere, so the solid angle is $4\pi$ [steradian] and the area is $4\pi r^2$. The formula for the area may be simplified by defining $A_\theta \equiv 4\pi \sin^2(\Theta/2) r_o^2 [m^2]$, resulting in the more convenient relation
\[ A(r) = A_\theta (r/r_o)^2 \] [m^2].
This is a bit tricky because $A_\theta$ is not a constant since it depends on the place where the area was normalized, in this case $r_o$.

The corresponding normalized range variable $x$ goes from $x = 0$ (the throat) ($r = r_o$) to $x = 1$ at $r = L$ (the mouth) (i.e., $r(x) = r_o + (L - r_o)x$). Solving for the normalized range variable gives
\[ x = \frac{r - r_o}{L - r_o}, \]
which varies from 0 at $r = r_o$ to 1 at $r = L$. Thus
\[ A(x) = A_\theta [r_o + x(L - r_o)]^2. \]

Using the conical horn area $A(r) \propto r^2$ in Eq. 5.28, p. 199 [or Eq. 5.37 (p. 201)] results in the spherical wave equation (Section 5.1.2, p. 189)
\[ \mathcal{P}_{rr}(r, \omega) + \frac{2}{r} \mathcal{P}_r(r, \omega) = \kappa^2 \mathcal{P}(r, \omega). \quad (5.61) \]
Here $F(r) = \partial_r \ln A(r) = 2/r$, the eigenfunctions are $\delta(t \pm r/c_o)/r \leftrightarrow e^{\mp \kappa r}/r$. Using Eq. 5.37 (p. 201) and the definition of $Y_{in}(s)$ (Eq. 5.43, p. 203)
\[ Y_{in}^{\pm}(r, s) = \frac{A(r)}{sp_o} \frac{d}{dr} \ln \frac{e^{\pm \kappa r}}{r} \]
\[ = -\frac{A(r)}{sp_o} \frac{d}{dr} (\pm \kappa r - \ln r) \]
\[ = \frac{A(r)}{sp_o} \left( \mp \frac{s}{c_o} + \frac{1}{r} \right) \]
\[ = \frac{A(r)}{sp_o} \left( \mp \frac{1 + c_o/sr}{sr} \right) \]
\[ = \mathcal{Y}(r) \left[ \mp 1 + \frac{c_o}{sr} \right] \]
Thus (Table 5.2, p. 203)
\[ \frac{Y_{in}^\mp(r, s)}{\mathcal{Y}(r)} = 1 \pm \frac{c_o}{sr} \leftrightarrow \delta(t) \pm \frac{c_o}{r} u(t). \]
Note that the normalized mass is $r/c_o$.

3) Exponential horn: If we define the area as $A(r) = e^{2mr}$, the eigenfunctions of the horn are
\[ \mathcal{P}^{\pm}(r, \omega) = e^{-mr} e^{j\sqrt{\omega^2 - \omega_c^2} r/c}, \quad (5.62) \]
which may be shown by the substitution of $P_c^{\pm}(r, \omega)$ into Eq. 5.28 (p. 199), with $A(r) = e^{2mr}$. This case is of special interest because the radiation impedance is purely reactive below the horn’s cutoff frequency ($\omega < \omega_c = mc_o$), as may be seen from curves 3 and 4 of Fig. 5.4. As a result, no energy can radiate from an open horn for $\omega < \omega_c$ because
\[ \kappa(s) = -m \pm \frac{j}{c_o} \sqrt{\omega^2 - \omega_c^2} \]
is purely real (this is the case of non-propagating evanescent waves).
**Exercise:** Show that the eigenfunctions satisfy the Webster horn equation when \( A(r) = e^{2mr} \).

Using Eq. 5.46 (p. 203) the input admittance is

\[
Y_{in}(x, s) = \frac{A(x)}{s\rho_o} \left( m \pm \sqrt{m^2 + \kappa^2} \right) x.
\]

(5.63)

Kleiner (2013) gives a similar expression for \( Y_{in}(x, \omega) \) having area \( S(x) = e^{mx} \)

\[
Y_{in}(x, \omega) = \frac{S(x)}{j\omega \rho} \left[ \frac{m}{2} + j\frac{\sqrt{4\omega^2 - (mc)^2}}{2c} \right],
\]

and impedance

\[
Z_{in}(r, \omega) = \frac{\rho c}{S_T} \left[ \frac{\omega_c}{\omega} + \sqrt{1 - \left( \frac{\omega_c}{\omega} \right)^2} \right],
\]

where \( \omega_c(r) \) is the cutoff frequency.

### 5.4.5 Lec 38: Solution methods

Two distinct mathematical techniques are used to describe physical systems: partial differential equations (PDEs) and lumped parameter models (i.e., quasi-statics) (Ramo et al., 1965). We shall describe these methods for the case of the *scalar wave equation*, which describes the evolution of a scalar field, such as the average pressure or voltage, or equivalently, the flow (e.g., the volume velocity).

1. **Separable coordinate systems:** Classically PDEs are frequently solved by *separation of variables*. Morse (1948, p. 296-7) shows this method is limited to a few coordinate systems, such as rectangular, cylindrical and spherical coordinates. Even a slight deviation from separable specific coordinate systems represents a major barrier toward further analysis and understanding, blocking insight into more general cases. These special coordinate systems are special cases, having high degrees of symmetry. The wave equation is not tied to a specific coordinate system.

2. **Sturm-Liouville methods and eigenvectors:** When the coordinate system is separable the resulting PDE is always a *Sturm-Liouville equation*, an important and special class of differential equation. Sturm-Liouville equations are solved by finding their eigenfunctions, which are the basis functions for their solution. Webster horn theory (Webster, 1919; Morse, 1948; Pierce, 1981) is a generalized Sturm-Liouville equation, which adds important physics to the mathematical 19th century approach of Sturm-Liouville, in terms of the horn’s area-function. The Webster equation side-steps the seriously limiting problem of separation of variables by making it possible to use the quasi-static method rather than separation of variables, thus ignoring high-frequency higher order evanescent modes. This is essentially a 1-dimensional approximation of the wave equation. These HOMs represent admittances in parallel with the plane-wave solution (Miles, 1948).

Mathematics provides rigor, while physics provides understanding. While both are important, it is the physical applications that make a theory useful.

3. **Lumped-element method:** As previously described in Sect. 3.5 (p. 119), a system may be represented in terms of *lumped elements*, such as electrical inductors, capacitors and resistors, or their mechanical counterparts, masses, springs and dash-pots. Such systems are represented by 2x2 transmission-matrices in the \( s \) (i.e., Laplace) domain rather than by differential equations, the number of which is equal to the number of elements in the network.

When the system of lumped element *networks* contains only resistors and capacitors, or resistors and inductors, the system does not support waves, and is related to the diffusion equation in its solution. Depending on the elements in the system of equations, there can be an overlap between a diffusion process and scalar waves, represented as transmission lines, both modeled as lumped
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networks of 2x2 matrices (Eq. 3.36, p. 119) (Campbell, 1922; Brillouin, 1953; Ramo et al., 1965). Quasi-static methods provide band-limited solutions below a critical frequency \( f_c \) (where a half wavelength approaches the element spacing) for a much wider class of geometries by avoiding higher-order, high-frequency cross-modes.

When the wavelength is longer than the physical distance between the elements, the approximation is equivalent to a transmission line. As the frequency increases, and the wavelength becomes equal to \( f = f_c = c_o/2d \), the quasi-static (lumped element) model breaks down. This is under the control of the modeling process, as more elements are required to represent higher frequencies (shorter wavelengths). If the nature of the solution at high frequencies \( f > f_c \) is desired, the lumped parameter model fails and one must use the differential equation method. However, for many (perhaps most) problems, lumped elements are easy to use, and accurate. These relations are elegantly explained by Brillouin (1953); Ramo et al. (1965).

5.4.6 Eigen-solutions \( g^{\pm}(r,t) \) of the Webster horn equation

Because the wave equation (Eq. 5.25) is 2nd order in time, there are two causal independent eigen-solutions of the homogeneous (i.e., un-driven) Webster horn equation: an outbound (right-traveling) \( g^+(r,t) \) and an inbound (left-traveling) \( g^-(r,t) \) wave. The causal eigen-solutions may be Laplace transformed

\[
g^{\pm}(r,t) \leftrightarrow \mathcal{L}^{\pm}(r,s) = \int_0^\infty g^{\pm}(r,t)e^{-st}dt
\]

into the frequency-domain, also sometimes called the time-independent representation. These eigenfunctions may be normalized so that \( \mathcal{L}^{\pm}(r_o,s) = 1 \), where \( r_o \) is the source excitation reference point.

These eigenfunctions critically depend on the area function \( A(r) \) (Eq. 5.28, p. 199). Because the characteristic impedance of the wave in the horn changes with location, there must be local reflections due to these area variations. Thus there are fundamental relationships between the area change \( dA(r)/dr \), the horn’s eigenfunctions \( \mathcal{L}^{\pm}(r,s) \), eigenmodes and input impedance. \(^{20}\)

Complex vs. real frequency: We shall continue to maintain the distinction that functions of \( \omega \) are Fourier transforms and functions of Laplace frequency \( s \) correspond to Laplace transforms, which, due to Cauchy’s residue theorem (Section 4.5, p. 165), are necessarily complex analytic in \( s \) in the right half-plane (RHP) region of convergence (RoC). This distinction is critical since we typically describe impedance \( Z(s) \), and admittance \( Y(s) \), as complex analytic functions in \( s \), in terms of their poles and zeros. \(^{21}\) The eigenfunctions of Eq. 5.28 are complex analytic and thus causal.

Plane-wave eigenfunction solutions: Huygens (1690) was the first to gain insight into wave propagation, today known as “Huygens’s principle.” While his concept showed a deep insight, we now know it was seriously flawed, as it ignored the backward traveling wave (Miller, 1991). In 1747 d’Alembert published the first correct solution for the plane-wave scalar wave equation

\[
g(x,t) = f(t-x/c_o) + g(t+x/c_o), \tag{5.64}
\]

where \( f(\cdot) \) and \( g(\cdot) \) are general functions of their argument. Why this is the solution may be easily shown by use of the chain rule, by taking partials with respect to \( x \) and \( t \). Surprisingly, this solution is valid even when the functions are not differentiable. For example, \( u(t \mp x/c_o) \) and \( \delta(t \mp x/c_o) \) are valid solutions.

\(^{20}\)These relationships will be explored in Section ??, p. ??.

\(^{21}\)When an analytic function of complex variable \( s \) includes the pole it is called a Laurent series in \( s \). For example, the impedance of a capacitor \( C \) is \( Z_C(s) = 1/sC \), which is analytic in \( s \) everywhere other than \( s = 0 \). The capacitor has a voltage time response given by the integral of the current, i.e., \( v(t) = \frac{1}{C} \int_0^t i(t)dt = \frac{1}{C} u(t) \star i(t) \), where \( u(t) \) is the Heaviside step function and \( \star \) represents convolution.
In terms of the physics, d’Alembert’s general solution describes two arbitrary wave-forms \( f(\cdot), g(\cdot) \) traveling at a speed \( c_o \), one forward and one reversed. Thus his solution is quite easily visualized. As previously discussed, Newton (1687) was the first to calculate the speed of sound \( c_o \), albeit with an error of \( \sqrt{1.4} \). This error was not corrected for over 200 years, following the creation of thermodynamics and the concept of an adiabatic process.

**Exercise:** By the use of the chain rule, prove that d’Alembert’s formula satisfies the 1D wave equation.

**Example:** Assuming \( f(\cdot), g(\cdot) \) are \( \delta(\cdot) \), find the Laplace transform of the solution.

**3D d’Alembert spherical eigenfunctions:** The d’Alembert solution generalizes to spherical waves by changing the area function of Eq. 5.28 to \( A(r) = A_o r^2 \) (Table 5.2, p. 203). The wave equation then becomes

\[
\nabla^2 \rho(r, t) = \frac{1}{r} \frac{\partial^2}{\partial r^2} r \rho(r, t) = \frac{1}{c_o^2} \frac{\partial^2}{\partial t^2} \rho(r, t).
\]

Multiplying by \( r \) results in the general spherical (3D) d’Alembert wave equation solution

\[
\rho(r, t) = f\left(t - \frac{r}{c_o}\right) + \frac{g\left(t + \frac{r}{c_o}\right)}{r}
\]

for arbitrary wave-forms \( f(\cdot) \) and \( g(\cdot) \). These are the eigenfunctions for the spherical scalar wave equation.

### 5.5 Lec 39: Integral forms of \( \nabla() \), \( \nabla \cdot () \) and \( \nabla \times () \)

The vector wave equation describes the evolution of a vector field, such as Maxwell’s electric field vector \( E(x, t) \). When these fields are restricted to a one-dimensional domain they are known as guided waves constrained by wave guides.

These equations use three differential vector operators, the gradient, divergence and the curl. There are two forms of definitions for each of these three operators: differential and integral. The integral form provides a more intuitive view of the operator which in the limit converges to the differential form. Following a discussion of the gradient, divergence and curl operators, these two forms are discussed.

In addition there are two fundamental vector theorems: Gauss’s law (divergence theorem) and Stokes’s law (curl theorem). Without the use of these very fundamental vector calculus theorems, Maxwell’s equations cannot be understood.

#### 5.5.1 Gradient: \( E = -\nabla \phi(x, y, z) \)

As shown in Fig. 5.1 (p. 184) the gradient maps \( \mathbb{R}^1 \rightarrow \mathbb{R}^3 \). The gradient may alternatively be defined in terms of the integral

\[
\nabla \phi(x, y, z) \equiv \lim_{S, V \rightarrow 0} \left\{ \frac{\int_S \phi(x, y, z) \hat{\mathbf{n}} \, dS}{V} \right\} \quad [V/m]
\]

over a closed surface \( S \), having area \( \mathcal{A} \) and volume \( \mathcal{V} \), centered at \( (x, y, z) \) (Greenberg, 1988, p. 773).

Here \( \hat{\mathbf{n}} \) is a dimensionless unit vector perpendicular to the surface \( S \):

\[
\hat{\mathbf{n}} = \frac{\nabla \phi}{\|\nabla \phi\|}.
\]

---

22This form of the spherical Laplacian is discussed in Section 5.1.2, Eq. 5.11, p. 189.

The dimensions of Eq. 5.65 are in the units of the potential times the area, divided by the volume, as needed for a gradient (e.g., [V/m]). The units are potential-dependent. If \( \phi \) were temperature, the units would be [deg/m].

**Exercise:** Justify the units of Eq. 5.65.

The natural way to define the surface and volume is to place the surface on the iso-potential surfaces, forming either a cube or pill-box shaped volume. As the volume \( |S| \) goes to zero, so must the area \( |S| \).

One must avoid irregular volumes where the area is finite as the volume goes to zero (Greenberg, 1988, footnote p. 762).

A well-known example is the potential \( \phi(x, y, z) = \frac{Q}{\epsilon_o \sqrt{x^2 + y^2 + z^2}} \) around a point charge \( Q \) [SI Units of Coulombs]. The constant \( \epsilon_o \) is the permittivity [farad/m].

A second well-known example is the acoustic pressure potential around an oscillating sphere, which has the same form (Table 5.2, p. 203).

**How does this work?** To better understand what Eq. 5.65 means, consider a three-dimensional Taylor series expansion of the potential in \( x \) about the limit point \( x_o \)

\[
\phi(x) \approx \phi(x_o) + \nabla \phi(x) \cdot (x - x_o) + \text{HOT}.
\]

We could define the gradient using this relationship as

\[
\nabla \phi(x_o) = \lim_{x \to x_o} \frac{\phi(x) - \phi(x_o)}{x - x_o}.
\]

For this definition to apply, \( x \) must approach \( x_o \) along \( \hat{n} \). To compute the higher order terms (HOT) one needs the Hessian matrix.\(^{24}\)

The natural way to define a surface \( |S| \) is to take find the iso-potential contours. The gradient is in the direction of maximum change in the potential, thus perpendicular to the iso-potential contours. The secret to the integral definition is in taking the limit. As the volume \( |S| \) shrinks to zero, the HOT terms are small, and the integral reduces to the first-order term in the Taylor expansion since the constant term integrates to zero. Such a construction was used in the proof of the Webster horn equation (5.3.1, p. 199; Fig. 5.3, p. 200).

### 5.5.2 Divergence: \( \nabla \cdot D = \rho \) [Col/m\(^3\)]

As briefly summarized by Eq. 5.5 on p. 186, the definition of the divergence at \( x = [x, y, z]^T \) is

\[
\nabla \cdot D(x, t) \equiv [\partial_x, \partial_y, \partial_z] \cdot D(x, t) = \left[ \frac{\partial D_x}{\partial x} + \frac{\partial D_y}{\partial y} + \frac{\partial D_z}{\partial z} \right](x, t) = \rho(x, t),
\]

which maps \( \mathbb{R}^3 \to \mathbb{R}^1 \).

### 5.5.3 Divergence and Gauss’s law

Like the gradient, the divergence of a vector field may be defined as the surface integral of a compressible vector field, as a limit as the volume, enclosed by the surface, goes to zero. As for the case of the gradient, for this definition to make sense, the surface \( \hat{S} \) must be closed, defining volume \( \mathcal{V} \). The difference is

\(^{24}H_{i,j} = \partial^2 \phi / \partial x_i \partial x_j \), which will exist if the potential is analytic in \( x \) at \( x_o \).
The first equation is the integral definition of the divergence of \( \mathbf{D} \) as an integral over the closed surface \( S \) of the normal component of \( \mathbf{D} \), in the limit as the surface and volume shrink to 0. The second equation states the enclosed charge \( Q_{\text{enc}} \) in terms of the surface integral of the normal component of \( \mathbf{D} \). The third equation gives the charge enclosed in terms of a volume integral over the enclosed charge density \( \rho_{\text{enc}} \).

\[
\nabla \cdot \mathbf{D} \equiv \lim_{V,S \to 0} \left\{ \frac{\int_S \mathbf{n} \cdot \mathbf{D} \, dS}{V} \right\} \quad \text{[Col/m}^3]\n
Q_{\text{enc}} = \int_S \mathbf{n} \cdot \mathbf{D} \, dS \n
= \iiint_V \rho_{\text{enc}} \, dV \quad \text{[Col]}
\]

Figure 5.6: The first equation is the integral definition of the divergence of \( \mathbf{D} \) as an integral over the closed surface \( S \) of the normal component of \( \mathbf{D} \), in the limit as the surface and volume shrink to 0. The second equation states the enclosed charge \( Q_{\text{enc}} \) in terms of the surface integral of the normal component of \( \mathbf{D} \). The third equation gives the charge enclosed in terms of a volume integral over the enclosed charge density \( \rho_{\text{enc}} \).

As with the case of the gradient we have defined the surface as \( S \), its area as \( S \) and the volume within as \( V \). It is a necessary condition that as the area \( S \) goes to zero, so does the volume \( V \).

As before, \( \mathbf{n} \) is a unit vector normal to the surface \( S \). The limit, as the volume and surface simultaneously go to zero, defines the total flux across the surface. Thus the surface integral is a measure of the total flux \( \perp \) to the surface. It is helpful to compare this formula with that for the gradient Eq. 5.65.

**Gauss’s law:** The above definitions resulted in a major breakthrough in vector calculus, the fundamental theorem of vector calculus (aka, Gauss’s law):

The surface integral over the normal component of the flux (i.e., the total flux) is equal to the volume integral over the divergence of the flux.

For the electrical case this is equivalent to the observation that the total flux across the surface is equal to the net charge enclosed by the surface. Since the volume integral over charge density \( \rho(x, y, z) \) is total charge enclosed \( Q_{\text{enc}} \),

\[
Q_{\text{enc}} = \iiint_V \nabla \cdot \mathbf{D} \, dV = \iiint_S \mathbf{D} \cdot \mathbf{n} \, dS. \quad \text{[Col]} \quad (5.67)
\]

When the surface integral over the normal component of \( \mathbf{D}(x) \) is zero, the total charge is zero. If there is only positive (or negative) charge inside the surface, \( \nabla \cdot \mathbf{D} = \rho(x) = 0 \) charge density must also be zero.

Taking the derivative with respect to time gives the total current, normal to the surface:

\[
I_{\text{enc}} = \iint_S \mathbf{D} \cdot \mathbf{n} \, dS = \dot{Q}_{\text{enc}} = \iiint_V \dot{\rho}_{\text{enc}} \, dV. \quad \text{[A]} \quad (5.68)
\]

As summarized by Feynman (1970c, p. 13-2):

The current leaving the closed surface \( S \) equals the rate of the charge leaving that volume \( V \), defined by that surface.

Of course to define a volume, the surface must be closed, a necessary condition for Gauss’s law. This reduces to a common-sense summary that can be grasped intuitively.
5.5. LECTURE 39: (WEEK 14) INTEGRAL DEFINITIONS OF $\nabla()$, $\nabla \cdot ()$ AND $\nabla \times ()$

5.5.4 Integral definition of the curl: $\nabla \times H = C$

As briefly summarized on page 187, the differential definition of the curl maps $\mathbb{R}^3 \mapsto \mathbb{R}^3$. The curl of the magnetic field strength $H(x)$ is the current density $C = \sigma E + \dot{D}$

$$\nabla \times H \equiv \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial_x & \partial_y & \partial_z \\ H_x & H_y & H_z \end{vmatrix} = C \quad \text{[A/m}^2].$$

Curl and Stokes’s law: As in the cases of the gradient and divergence, the curl also may be written in integral form, allowing for the physical interpretation of its meaning:

The surface integral definition of $\nabla \times H = C$ [A/m$^2$], where the current density $C$ is $\perp$ to the rotation plane of $H$.

Stokes’s law states that the open surface integral over the normal component of the curl of the magnetic field strength ($\hat{n} \cdot \nabla \times H$ [A/m$^2$]) is equal to the line integral $\int_{\mathcal{B}} H \cdot dl$ along the boundary $\mathcal{B}$. As summarized in Fig. 5.7, Stokes’s law is

$$I_{enc} = \iint_S (\nabla \times H) \cdot \hat{n} \, dS \quad \text{[A]}$$

$$= \iint_S C \cdot \hat{n} \, dS \quad \text{(5.69)}$$

namely

The line integral of $H$ along the open surface’s boundary $\mathcal{B}$ is equal to the total current enclosed $I_{enc}$.

In many texts the normalization (denominator under the integral) is a volume $V$ (e.g., Greenberg (1988, p. 778,823-4)). However because the surface is open, this volume does not exist (when defining a volume the a surface must be closed). The definition must hold even in the limit when the curved surface $S$ degenerates to a plane, with the boundary $\mathcal{B}$ enclosing $S$. In this limit there clearly is no volume.

To resolve this dilemma, we have taken the normalization to be the surface $S$. Note that in the limit $S \rightarrow 0$, the limiting definition is independent of any curvature, since the integral is over the normal component of $H$ (i.e., $\hat{n} \perp H(x,t)$). The net flux is independent of the curvature of $S$ as $S \rightarrow 0$.

Finally, when one normalizes by a volume, the area units fail to cancel.

Figure 5.7: The integral definition of the curl is related to that of the divergence (Eq. 5.66) as an integration over the tangent to the surface, except: (1) the curl is defined as the cross product $\hat{n} \times H$ [A/m$^2$], of $\hat{n}$ with the current density $H$, and (2) the surface is open, leaving a boundary $\mathcal{B}$ along the open edge. As with the divergence, which leads to Gauss’s law, this definition leads to a second fundamental theorem of vector calculus: Stokes’s law (aka the curl theorem).
Summing it up: Since integration is a linear process (sums of smaller elements), one may tile, or tessellate, the surface, breaking it up into smaller surfaces and their boundaries, the sum of which is equal to the integral over the original boundary. This is an important concept, which leads to the proof of Stokes’s law.

Table 4.1 provides a description of the basic integration theorems, along with their mapping domains. The integral formulations of Gauss’s and Stokes’s laws use $\hat{n} \cdot D$ and $H \times \hat{n}$ in the integrands. The key distinction between the two laws naturally follows from the properties of the scalar ($A \cdot B$) and vector ($A \times B$) products, as discussed in Sect. 3.4, p. 110, and detailed in Fig. 3.3, p. 112. To fully appreciate the differences between Gauss’s and Stokes’s laws, these two types of vector products must be mastered.

Paraphrasing Feynman (1970c, 3-12),

1. $V_2 = V_1 + \int_{I_1} \nabla \Phi \cdot dS$
2. $\oint D \cdot \hat{n} \, dS = \oint \nabla \cdot D \, dV$
3. $\oint B \cdot d\ell = \oint_S (\nabla \times E) \cdot \hat{n} \, dS$

5.5.5 Lec 40: Second-order operators: Terminology

Besides the above first-order vector derivatives, second-order combinations exist, the most important being the scalar Laplacian $\nabla \cdot \nabla () = \nabla^2 ()$ (Table 5.1, p. 186; Appendix 5.1.2, p. 189).

There are other important second-order combinations of $\nabla$, enough that we need a memory aid to remember all of them. We define six mnemonics:

1. DoG: Divergence of the gradient (i.e., Laplacian) $\nabla \cdot \nabla = \nabla^2$
2. GoD: the vector Laplacian $\nabla^2$
3. gOd: Gradient of the Divergence (little-god) $\nabla^2$
4. DoC: Divergence of the curl ($\nabla \cdot \nabla \times = 0$)
5. CoG: Curl of the gradient ($\nabla \times \nabla = 0$)
6. CoC: Curl of the curl ($\nabla \times \nabla \times$)

DoC(·) and CoG(·) are special because they are always zero:

$\nabla \times \nabla \phi = 0; \quad \nabla \cdot \nabla \times A = 0,$

making them useful in proving the fundamental theorem of vector calculus, such as Helmholtz’ decomposition (Eq. 5.77, p. 229).

A third special vector identity CoC is

$$\nabla \times \nabla \times A = \nabla (\nabla \cdot A) - \nabla^2 A,$$

(5.70)

which operates on vector fields and is useful for defining the important vector Laplacian GoD

$$\nabla^2 () = \nabla \nabla (\cdot) - \nabla \times \nabla \times (\cdot),$$

as the difference between little-god (gOd) and CoC (i.e., CoC = gOd - GoD). The role of little-god is commonly ignored because it is zero for the magnetic wave equation, due to there being no magnetic charge ($\nabla \cdot B(x,t) = 0$). However for the electric vector wave equation it becomes

$$\nabla \nabla \cdot \phi(x,t) = -\nabla E(x,t) = -\frac{1}{\varepsilon_0} \nabla \nabla \cdot D(x,t) = -\frac{1}{\varepsilon_0} \nabla \rho(x,t).$$

When the charge density is inhomogeneous (as in the case of a plasma such as the sun), this term will play an important role as a source term to the electric wave equation. This case needs to be further explored via realistic examples.
5.5. LECTURE 39: (WEEK 14) INTEGRAL DEFINITIONS OF $\nabla()$, $\nabla\cdot()$ AND $\nabla\times()$

**Exercise:** Show that GoD and gOd differ.

**Discussion:** It is helpful to split these six identities into two groups: the utility operators DoG, gOd, GoD, and the identity operators CoC (Eq. 5.70), DoC=0 and CoG=0. It is logically helpful to view these two groups as having different roles.

When using second-order differential operators one must be careful with the order of operations, which can be subtle in a few cases. Most of this is common sense. For example, don’t operate on a scalar field with $\nabla\times$, and don’t operate on a vector field with $\nabla$. The vector Laplacian GoD must not be confused with little-god $\nabla(\nabla\cdot A)$ (i.e., gOd), rather it acts as the Laplacian on each vector component $\nabla^2 A = \nabla^2 A_x\hat{x} + \nabla^2 A_y\hat{y} + \nabla^2 A_z\hat{z}$.

---

Figure 5.8: Left: von Helmholtz portrait taken from Helmholtz (1978). Right: Gustav Kirchhoff. Together they were the first to account for viscous (Helmholtz, 1858, 1978, 1863b) and thermal (Kirchhoff, 1868, 1974) losses in the acoustic propagation of airborne sound, as first experimentally verified by Mason (1928) (Lec. 5.7, p. 230).

5.5.6 Helmholtz’s decomposition

We may now restate everything defined above in terms of the two types of vector fields that decompose every analytic vector field. The irrotational field is defined as one that is “curl free.” An incompressible field is one that is “divergence free.” According to Helmholtz’s decomposition, every analytic vector field may be decomposed into independent rotational and compressible components. Another name for Helmholtz decomposition is the fundamental theorem of vector calculus (FTVC); Gauss’s and Stokes’s theorems, along with Helmholtz’s decomposition form the three key fundamental theorems of vector calculus. Portraits of Helmholtz and Kirchhoff are provided in Fig. 5.8.

A magnetic solenoidal field is one that is generated by a solenoidal coil, and is an excellent approximation, uniform inside the coil. As a result, the divergence of a solenoidal field is, to a good approximation, zero, making it incompressible ($\nabla\cdot = 0$) and rotational ($\nabla\times \neq 0$). Since it is widely used, I recommend you know this term, but suggest the preferred terms incompressible and rotational. Strictly speaking, the term “solenoidal field” only applies to a magnetic field produced by a solenoid, thus the term is specific to that case.

**The decomposition of differentiable vector fields:** This theorem is easily stated (and proved), but less easily appreciated (Heras, 2016). A physical description facilitates: Every vector field may be split

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25This operation defines a dyadic tensor https://en.wikipedia.org/wiki/Dyadics, a useful generalization of a vector.

26The theorems are integral relations. The laws physical relationships which follow from the theorems.
into two independent parts: dilation and rotation. We have seen this same idea appear in vector algebra, where the scalar and cross products of two vectors are perpendicular (Fig. 3.3, p. 112). Also think of linear and angular momentum, which are independent in that they represent different ways of absorbing and delivering kinetic energy, leading to independent degrees of freedom. Thus the idea of the linear and rotational parts being independent is a common theme, rooted in geometry. In the same sense, a vector field may be split into dilation and rotational parts, which are independent (but can interact under certain conditions). An object with mass can be moving along a path, and independently be rotating. The two modes of motion define different types of kinetic energy: translational (compressional) and rotational. In some real sense, Helmholtz decomposition quantifies these degrees of freedom: one DoF for translation and three DoFs for rotation. Each eigenmode of vibration can be viewed as a DoF. The role of the FTVC is especially powerful when applied to Maxwell’s Eqs.

Table 5.3: The four possible classifications of scalar and vector potential fields: rotational/irrotational and compressible/incompressible. Rotational fields are generated by the vector potential (e.g., \( A(x, t) \)), while compressible fields are generated by the scalar potentials (e.g., voltage \( \phi(x, t) \), velocity \( \psi \), pressure \( \rho(x, t) \) or temperature \( T(x, t) \)).

<table>
<thead>
<tr>
<th>Field: ( v(x, t) )</th>
<th>Compressible</th>
<th>Incompressible</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nabla \cdot v \neq 0 )</td>
<td>( v = \nabla \phi + \nabla \times \omega )</td>
<td>( v = \nabla \times w )</td>
</tr>
<tr>
<td>Rotational ( \nabla \times v \neq 0 )</td>
<td>Vector wave Eq. (EM)</td>
<td>Lubrication theory</td>
</tr>
<tr>
<td>( \nabla^2 v = \frac{1}{c^2} \ddot{v} )</td>
<td>Boundary layers</td>
<td></td>
</tr>
<tr>
<td>Irrotational Conservative</td>
<td>Acoustics</td>
<td>Statics</td>
</tr>
<tr>
<td>( \nabla \times v = 0 )</td>
<td>( \nabla \phi = \frac{1}{c^2} \ddot{\phi} (x, t) )</td>
<td>Laplace’s Eq. ((c \rightarrow \infty))</td>
</tr>
</tbody>
</table>

The four categories of linear fluid flow: The following is a summary of the four cases for fluid flow, as summarized in Fig. 5.3:

1.1 Compressible and rotational fluid (general case): \( \nabla \phi \neq 0, \nabla \times w \neq 0 \). This is the case of wave propagation in a medium where viscosity cannot be ignored, as in the case of acoustics close to the boundaries, where viscosity contributes to losses (Batchelor, 1967).

1.2 Incompressible, rotational fluid (Lubrication theory): \( v = \nabla \times w \neq 0, \nabla \cdot v = 0, \nabla^2 \phi = 0 \). In this case the flow is dominated by the walls, while the viscosity and heat transfer introduce shear. This is typical of lubrication theory and solenoidal fields.

2.1 Fluid compressible irrotational flow (acoustics): \( v = \nabla \phi, \nabla \times w = 0 \). Here losses (viscosity and thermal diffusion) are small (assumed to be zero). One may define a velocity potential \( \psi \), the gradient of which gives the air particle velocity, thus \( v = -\nabla \phi \). Thus for an irrotational fluid \( \nabla \times v = 0 \) (Greenberg, 1988, p. 826). This is the case of the conservative field, where \( \int v \cdot \hat{n} dR \) only depends on the end points, and \( \oint v \cdot \hat{n} dl R = 0 \). When a fluid may be treated as having no viscosity, it is typically assumed to be irrotational, since it is the viscosity that introduces the shear (Greenberg, 1988, p. 814). A fluid’s angular velocity is \( \Omega = \frac{1}{2} \nabla \times v = 0 \), thus irrotational fluids have zero angular velocity \( \Omega = 0 \).

2.2 Incompressible and irrotational fluid (statics): \( \nabla \cdot v = 0 \) and \( \nabla \times v = 0 \) thus \( v = \nabla \phi \) and \( \nabla^2 \phi = 0 \). An example of such a case is water in a small space at low frequencies, where the wavelength is long compared to the size of the container; the fluid may be treated as incompressible. When \( \nabla \times v = 0 \), the effects of viscosity may be ignored, as it is the viscosity that creates the shear leading to rotation. This is the case of modeling the cochlea, where losses are ignored and the quasi-static limit is justified.
In summary, each of the cases is some sort of approximation that best applies in the low frequency limit. This is why it is called quasi-static, meaning low, but not zero frequency, where the wavelength is large compared with the dimensions (e.g., diameter).

Table 5.4: The variables of Maxwell’s equations have names (e.g., EF, MI) and units (in square brackets [SI Units]). The units are required to gain a full understanding of each of the four variable and their corresponding equation. For example, Eq. EF has units [V/m]. When you integrate $E$ from $x = a, b$, you obtain the voltage difference between those two points. The speed of light in-vacuo is $c = 3 \times 10^8 = 1/\sqrt{\mu_0 \varepsilon_0}$ [m/s], and the characteristic resistance of light $r_o = 377 = \sqrt{\mu_0 / \varepsilon_0}$ [Ω] (i.e., ohms). The dot over a vector is shorthand for the partial with respect to time (i.e., $\dot{B} = \partial B/\partial t$).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Units</th>
<th>Maxwell’s Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>EF: Electric Field strength</td>
<td>[V/m]</td>
<td>$\nabla \times E = -\partial_t B$</td>
</tr>
<tr>
<td>$D = \varepsilon_o E$</td>
<td>ED: Electric Displacement (flux density)</td>
<td>[Col/m$^2$]</td>
<td>$\nabla \cdot D = \rho$</td>
</tr>
<tr>
<td>$H$</td>
<td>MF: Magnetic Field strength</td>
<td>[A/m]</td>
<td>$\nabla \times H = J + \partial_t D$</td>
</tr>
<tr>
<td>$B = \mu_o H$</td>
<td>MI: Magnetic Induction (flux density)</td>
<td>[Wb/m$^2$]</td>
<td>$\nabla \cdot B = 0$</td>
</tr>
</tbody>
</table>

5.6 Lec 41: The unification of electricity and magnetism

Once you have mastered the three basic vector operations – the gradient, divergence and curl – you are ready to appreciate Maxwell’s equations. Like the vector operations, these equations may be written in integral or differential form. An important difference is that with Maxwell’s equations, we are dealing with well defined physical quantities. The scalar and vector fields take on meaning, and units. Thus to understand these important equations, one must master the names of the four fields $E, H, B, D$ as described in Table 5.4.

Field strengths $E, H$: As summarized by Eqs. 5.71 there are two field strengths, the electric $E$ with units of [V/m] and the magnetic $H$ having units of [A/m]. The ratio $|E|/|H| = \sqrt{\mu_0 / \varepsilon_0} = 377$ [ohms] for in-vacuo plane-waves ($\mu_o, \varepsilon_o$).

To understand the meaning of $E$, if two conducting plates are placed 1 [m] apart, with 1 [V] across them, the electric field is $E = 1$ [V/m]. If a charge (i.e., an electron) is placed in an electric field, it feels a force $f = qE$, where $q$ is the magnitude of the charge [Col].

To understand the meaning of $H$, consider the solenoid made of wire, as shown in Fig. 5.9, which carries a current of 1 [A]. The magnetic field $H$ inside such a solenoid is uniform and is pointed along the long axis, with a direction that depends on the polarity of the applied voltage (i.e., direction of the current in the wire).

Flux: Flux is a flow, such as the mass flux of water flowing in a pipe [kg/s], driven by a force (pressure drop) across the ends of the pipe, or the heat flux in a thermal conductor, having a temperature drop across it (i.e., a window or a wall). The flux is the same as the flow, be it current, mass or heat. In Maxwell’s equations there are also two fluxes: the electric flux $D$, and the magnetic flux $B$. The flux density units for $D$ are [A/m$^2$] (flux in [A]) and the magnetic flux $B$ is measured in webers [Wb] [A/m$^2$]) or [tesla] (henry-amps/area) [H-A/m$^2$].
Maxwell’s equations

Maxwell’s equations in matrix format are
\[
\nabla \times \begin{bmatrix} E(x, t) \\ H(x, t) \end{bmatrix} = \partial_t \begin{bmatrix} -B(x, t) \\ D(x, t) \end{bmatrix} = \begin{bmatrix} 0 & -\mu_0 \\ \epsilon_0 & 0 \end{bmatrix} \partial_t \begin{bmatrix} E(x, t) \\ H(x, t) \end{bmatrix} \leftrightarrow \begin{bmatrix} 0 & -s\mu_0 \\ se_0 & 0 \end{bmatrix} \begin{bmatrix} E(x, \omega) \\ H(x, \omega) \end{bmatrix}.
\]

When the medium is conducting, \( \partial_t D \) must be replaced by \( C = \sigma E + \partial_t D \rightarrow (\sigma + se)D(x, \omega). \)

As described by Eqs. 5.71, Maxwell’s equations consist of two curl equations, operating on the field strengths \( E \) and \( H \), and two divergence equations, operating of the field fluxes \( D \) and \( B \). Stokes’s law follows from the curl equations and Gauss’s law from the divergence equations. This should be logically obvious.

**Example:** When a static current is flowing in a wire in the \( \hat{z} \) direction, the magnetic flux is determined by Stokes’s theorem (Fig. 5.7). Thus, just outside of the wire we have
\[
\mathcal{I}_{\text{enc}} = \oint_S (\nabla \times H) \cdot \hat{n} d|S| = \oint_B H \cdot dl. \quad [A]
\]
For this simple geometry, the current in a wire is related to \( H(x, t) \) by
\[
\mathcal{I}_{\text{enc}} = \oint_B H \cdot dl = H_\phi 2\pi r.
\]
Here \( H_\phi \) is perpendicular to both the radius \( r \) and the direction of the current \( \hat{z} \). Thus
\[
H_\phi = \frac{\mathcal{I}_{\text{enc}}}{2\pi r},
\]
and we see that \( H \), and thus \( B = \mu_0 H \), drop off as the reciprocal of the radius \( r \).

**Exercise:** Explain how Stokes’s theorem may be applied to \( \nabla \times E = -\dot{B} \), and explain what it means. Hint: This is the identical argument given above for the current in a wire, but for the electric case.

If we apply Gauss’s theorem to the divergence equations, we find the total flux crossing the closed surface.

**Exercise:** Apply Gauss’s theorem to equation ED and explain what it means in physical terms.

**Summary:** Maxwell’s four equations relate the field strengths to the flux densities. There are two types of variables: field strengths \( (E, H) \) and flux densities \( (D, B) \). There are two classes: electric \( (E, D) \) and magnetic \( H, B \). One might naturally view this as a 2x2 matrix, with rows being electric and magnetic strengths, and columns being electric and magnetic and flux densities, defining a total of four variables:

<table>
<thead>
<tr>
<th>Strength</th>
<th>Flux density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric</td>
<td>( E ) [V/m]</td>
</tr>
<tr>
<td>Magnetic</td>
<td>( H ) [A/m]</td>
</tr>
</tbody>
</table>

Applying Stokes’s “curl” theorem to the forces induces a Thévenin voltage (emf) or Norton current source. Applying Gauss’ “divergence” theorem to the flows gives the total charge enclosed. The magnetic charge is zero \( (\nabla \cdot B = 0) \) because magnetic mono-poles do not exist. However, magnetic dipoles do exist, as in the example of the electron which contains a magnetic dipole.
5.6.2 Derivation of the vector wave equation

Next we provide the derivation of the vector wave equation starting from Maxwell’s equations (Eq. 5.71), similar to the derivation of the Webster horn equation. Working in the frequency domain, and taking the curl of both sides, gives

\[
\nabla \times \nabla \times \begin{bmatrix} E \\ H \end{bmatrix} = \begin{bmatrix} 0 & -s\mu_0 \\ s\varepsilon_0 & 0 \end{bmatrix} \nabla \times \begin{bmatrix} E \\ H \end{bmatrix} = \begin{bmatrix} 0 & -s\mu_0 \\ s\varepsilon_0 & 0 \end{bmatrix} \begin{bmatrix} E \\ H \end{bmatrix} = -\frac{s^2}{c_0^2} \begin{bmatrix} E \\ H \end{bmatrix}
\]

Using the CoC identity \(\nabla \times \nabla \times () = \nabla \nabla \cdot () - \nabla^2 ()\) (Eq. 5.70, p. 222) gives

\[
\nabla^2 \begin{bmatrix} E \\ H \end{bmatrix} - \nabla \nabla \cdot \begin{bmatrix} E \\ H \end{bmatrix} = \frac{s^2}{c_0^2} \begin{bmatrix} E \\ H \end{bmatrix}.
\]

or finally Maxwell’s vector wave equation

\[
\nabla^2 \begin{bmatrix} E \\ H \end{bmatrix} - \frac{s^2}{c_0^2} \begin{bmatrix} E \\ H \end{bmatrix} = \nabla \left[ \frac{1}{\varepsilon_0} \nabla \cdot \mathbf{D} \right] - \frac{1}{\mu_0} \nabla \cdot \mathbf{B} \right] \begin{bmatrix} 0 \\ 0 \end{bmatrix},
\]

with the electric excitation term \(\nabla \rho(x, s)\). Note that if \(\mu\) and \(\varepsilon\) depended on space, the turns on the right would not be zero. In deep outer space with black holes and plasmas everywhere (e.g., inside the sun) this seems possible, even likely.

Recall the d’Alembert solutions of the scalar wave equation (Eq. 4.16, p. 149)

\[
E(x, t) = f(x - ct) + g(x + ct),
\]

where \(f, g\) are arbitrary vector fields. This result applies to the vector case since it represents three identical, yet independent, scalar wave equations, in the three dimensions.

**Poynting’s vector:** The energy flux density \(\mathcal{P}\) [W/m²] is perpendicular to \(E\) and \(B\), denoted as

\[
\mathcal{P} = \frac{1}{\mu_0} E \times B.
\]

**Electrical impedance seen by an electron:** Up to now we have only considered the Brune impedance which is a special case with no branch points or branch cuts. We can define impedance for the case of diffusion, as in the case of the diffusion of heat. There is also the diffusion of electrical and magnetic fields at the surface of a conductor, where the resistance of the conductor dominates the dielectric properties, which is called the electrical skin effect, where the conduction currents are dominated by the conductivity of the metal rather than the displacement currents. In such cases the impedance is proportional to \(\sqrt{s}\), implying that it has a branch cut. Still in this case the real part of the impedance must be positive in the right \(s\) half-plane, the required condition of all impedances, such that postulate P3 (p. 132) is satisfied.
**Example:** When we deal with Maxwell’s equations the force is defined by the *Lorentz force*
\[
f = qE + qv \times B = qE + C \times B,\]
which is the force on a charge (e.g., electron) due to the electric \(E\) and magnetic \(B\) fields. The magnetic field plays a role when the charge has a velocity \(v\). When a charge is moving with velocity \(v\), it may be viewed as a current \(C = qv\).

The complex impedance density is
\[
Z(s) = \sigma + se_o \quad [\Omega/m^2],
\]
which when integrated over an area is the impedance in ohms (Feynman, 1970c, p. 13-1). Here \(\sigma\) is the electrical conductivity and \(e_o\) is the electrical permittivity. Since \(\omega e_o \ll \sigma\) this reduces to the resistance of the wire, per unit length.??

### 5.6.3 General solutions to Maxwell’s equations

By the use of potentials and Helmholtz’s theorem (FTVC) we may rewrite Maxwell’s equation in a more general form, viewed as the *generalized solution*, in terms of the potentials
\[
E(x, t) = -\nabla \phi(x, t) - \frac{\partial A(x, t)}{\partial t}, \quad [\text{V/m}]
\]
\[
B(x, t) = \nabla \times A(x, t) \quad [\text{Wb/m}^2].
\]
These are the “solutions” to Maxwell’s equations expressed in terms of the potentials \(\phi(x, s)\) and \(A(x, s)\), as determined at the boundaries (Sommerfeld, 1952, p. 146). As shown below, these relations are invariant to certain functions added to each potential, as shown below. They are equivalent to Maxwell’s equations following the application of DoC and CoG.

**Exercise:** Explain why \(\phi(x, t)\) does not appear in Eq. 5.73.

### Helmholtz theorem and the potential representation of Maxwell’s equations:

Next we wish to show that the potential equations are consistent with Maxwell’s equations.

Taking the curl of Eq. 5.3, and using CoG=0
\[
\nabla \times E = -\nabla \times \nabla \phi + \nabla \times \frac{\partial A}{\partial t} = -\frac{\partial B}{\partial t}
\]
recovers Maxwell’s electric equation (Eq. 5.71, p. 226).

If we follow this with the divergence, and use DoC=0
\[
\nabla \cdot \nabla \times E = -\frac{\partial \nabla \cdot B(x, t)}{\partial t} = 0,
\]
we see that \(\nabla \cdot B\) is independent of time, and therefore that
\[
\nabla \cdot B(x) = 0.
\]
Thus we see that the potential representations are equivalent to Maxwell’s equations.

---

??For copper \(\omega \ll \omega_c = \sigma/e_o \approx 6 \times 10^7/9 \times 10^{-12} \approx 6.66 \times 10^{18} \text{[rad/s]}, or } f_c = 10^{18} \text{[Hz]. This corresponds to a wavelength of } \lambda_o \approx c_o/f_c = 0.30 \text{[nm]. For comparison, the Bohr radius (hydrogen) is } \approx 0.053 \text{[nm] (5.66 times smaller) and the Lorentz radius (of the electron) is estimated to be } 2.8 \times 10^{-13} \text{[m] (2.8 \text{[femto meters]}.}
Implications of potential representation: Next we would like to show how to recover Maxwell’s magnetic equation $\nabla \times H = C$ from the potential solution. Taking the curl of Eq. 5.4 gives

$$\frac{1}{\mu_0} \nabla \times B = \nabla \times H = C = \nabla \times \nabla \times A = \nabla \nabla \cdot A - \nabla^2 A.$$  

It directly follows from Eq. 5.4 that the current $C$ only depends on $A$.

Since $A$ must satisfy the wave equation,

$$\nabla^2 A = \frac{s^2}{c_0^2} A - C,$$

which requires that

$$\nabla \nabla \cdot A = \frac{s^2}{c_0^2} A.$$

Taking the divergence of Eq. 5.3 gives an expression for $\nabla \cdot A$:

$$\frac{1}{\epsilon_0} \nabla \cdot D = \rho/\epsilon_0 = -\nabla^2 \phi - \partial_t \nabla \cdot A.$$

In conclusion, Eq. 5.3, along with DoC=0 and CoG=0, gives Maxwell’s Eq. 5.74 and Eq. 5.76 result. It would appear that Eq. 5.3 is the key. This equation defines the magnetic component of the field, expressed in terms of its vector potential, in the same way as Eq. 5.1 describes $E(x, t)$ in terms of the scalar potential (voltage). Does the same argument apply for Eq. 5.4?

Exercise: Starting from the values of the speed of light $c_0 = 3 \times 10^8$ [m/s] and the characteristic resistance of light waves $r_0 = 377$ [ohms], use the formula for $c_0 = 1/\sqrt{\mu_0 \epsilon_0}$ and $r_0 = \sqrt{\epsilon_0/\mu_0}$ to find values for $\epsilon_0$ and $\mu_0$.

Exercise: Take the divergence of Maxwell’s equation for the magnetic intensity

$$\nabla \times H(x, t) = J(x, t) + \frac{\partial}{\partial t} D(x, t)$$

and explain what results ($J = \sigma E$). which is conservation of charge (i.e., Gauss’s theorem).

Helmholtz’s decomposition is expressed as the linear sum of a scalar potential $\phi(x, y, z)$ (think voltage) and a vector potential (think magnetic vector potential). Specifically

$$E(x, s) = -\nabla \phi(x, s) + \nabla \times A(x, s),$$

(5.77)

where $\phi$ is the scalar and $A$ is the vector potential, as a function of the Laplace frequency $s$. Of course this decomposition is general (not limited to the electro-magnetic case). It applies to linear fluid vector fields, which include most liquids and air. When the rotational and dilation become coupled, this relation must break down.

To show how this relationship splits the vector fields $E$ into its two parts, we need DoC and CoG, the two key vector identities that are always zero for analytic fields: the curl of the gradient (CoG)

$$\nabla \times \nabla \phi(x) = 0,$$

(5.78)

and the divergence of the curl (DoC)

$$\nabla \cdot (\nabla \times A) = 0.$$

(5.79)

---

28The nonlinear Navier–Stokes equations may be an example.

29Helmholtz was the first person to apply mathematics in modeling the eye and the ear (Helmholtz, 1863a).
The above identities are easily verified by working out a few specific examples, based on the definitions of the three operators, gradient, divergence and curl, or in terms of the operator’s integral definitions, defined in Sect. 5.5, p. 218. The identities have a physical meaning, as stated above: every vector field may be split into its translational and rotational parts. If \( E \) is the electric field [V/m], \( \phi \) is the voltage and \( A \) is the induced rotational part, induced by a current. We shall explore this in our discussion of Maxwell’s equations in Sections 5.6 and ??.

By applying these two identities to Helmholtz’s decomposition, we can better appreciate the theorem’s significance. It is a form of proof actually, once you have satisfied yourself that the vector identities are true. In fact one can work backward using a physical argument, that rotational momentum (rotational energy) is independent of the translational momentum. Once these forces are made clear, the vector operations all take on a very well defined meaning, and the mathematical constructions, centered around Helmholtz’s theorem, begin to provide some common-sense meaning. One could conclude that the physics is simply related to the geometry via the scalar and vector product.

Specifically, if we take the divergence of Eq. 5.77, and use the DoG, then
\[
\nabla \cdot E = \nabla \cdot \{-\nabla \phi + \nabla \times A\}^0 = -\nabla \cdot \nabla \phi = -\nabla^2 \phi,
\]
since the DoG zeros the vector potential \( A(x, y, z) \). If instead we use the CoG, then
\[
\nabla \times E = \nabla \times \{-\nabla \phi + \nabla \times A\} = \nabla \times \nabla \times A = \nabla (\nabla \cdot A) - \nabla^2 A,
\]
since the CoG zeros the scalar field \( \phi(x, y, z) \). The last expression requires GoD.

### 5.7 Lec 42: The Quasi-static approximation

There are a number of assumptions and approximations that result in special cases, many of which are classic. These manipulations are typically done at the differential equation level, by making assumptions that change the basic equations that are to be solved. These approximations are distinct from assumptions made while solving a specific problem.\(^{30}\)

A few important examples include

1. **In-vacuo waves** (free-space scalar wave equation)
2. Expressing the vector wave equation in terms of scalar and vector potentials
3. **Quasi-statics**
   a. scalar wave equation
   b. Kirchhoff’s low-frequency lumped approximation (LRC networks)
   c. Transmission line equations (telephone and telegraph equations)

One of the very first insights into wave propagation was due to Huygens (c1640) (Fig. 4.1, p. 144).

**Quasi-statics and its implications:** Quasi-statics (Postulate P10, p. 133) is an approximation used to reduce a partial differential equation to a scalar (one-dimensional) equation (Sommerfeld, 1952); that is, Quasi-statics is a way of reducing a three-dimensional problem to a one-dimensional problem. So that it is not miss-applied, it is important to understand the nature of this approximation, which goes to the heart of transmission line theory. The quasi-static approximation states that the wavelength \( \lambda \) is greater than the dimensions of the object \( \Delta \) (e.g., \( \lambda \gg \Delta \)). The best known examples, Kirchhoff’s current and voltage laws, KCL and KVL, almost follow from Maxwell’s equations given the quasi-static

\[^{30}\text{You simply must watch this magical video by Carl Sagan about Einstein’s views on the speed of light. } \text{https://www.youtube.com/watch?v=_pEiA0-r5A8} \]
approximation (Ramo et al., 1965). These laws, based on Ohm’s law, state that the sum of the currents at a node must be zero (KCL) and the sum of the voltages around a loop must be zero (KCL).

These well-known laws are the analog of Newton’s laws of mechanics. The sum of the forces at a point is the analog of the sum of the loop voltages. Voltage \( \phi \) is the force potential, since the electric field \( E = -\nabla \phi \). The sum of the currents is the analog of the vector sum of velocities (mass) at a point, which is zero.

The acoustic wave equation describes how the scalar field pressure \( p(x, t) \) and the vector force density potential \( f(x, t) = -\nabla p(x, t) \) [N/m\(^2\)] propagate in three dimensions. The net force is the integral of the pressure gradient over an area. If the wave propagation is restricted to a pipe (e.g., organ pipe), or to a string (e.g., an guitar or lute), the transverse directions may be ignored, due to the quasi-static approximation. What needs to be modeled by the equations is the wave propagation along the pipe (string). Thus we may approximate the restricted three-dimensional wave by a one-dimensional wave.

However, if we wish to be more precise about this reduction in geometry \( (\mathbb{R}^2 \to \mathbb{R}) \), we need to consider the quasi-static approximation, as it makes assumptions about what is happening in the other directions, and quantifies the effect \( (\lambda \gg \Delta) \). Taking the case of wave propagation in a tube, say the ear canal, there is the main wave direction, down the tube. But there is also wave propagation in the transverse direction, perpendicular to the direction of propagation. As shown in Table J.1 (p. 286), the key statement of the quasi-static approximation is that the wavelength in the transverse direction is much larger that the radius of the pipe. This is equivalent to saying that the radial wave reaches the walls and is reflected back, in a time that is small compared to the distance propagated down the pipe. Clearly the speed of sound down the pipe and in the transverse direction is the same if the medium is homogeneous (i.e., air or water). Thus the sound reaches the walls and is returned (reflected) to the center line in a time that the axial wave traveled about 1 diameter along the pipe. So if the distance traveled is several diameters, the radial parts of the wave have time to come to equilibrium. So the question one must ask is: What are the properties of this equilibrium? The most satisfying answer is provided by looking at the internal forces on the air, due to the gradients in the pressure.

The pressure \( p(x, t) \) is a potential, thus its gradient is a force density \( f(x, t) = -\nabla p(x, t) \). This equation tells us how the pressure wave evolves as it propagates down the horn. Any curvature in the pressure wave-front induces stresses, which lead to changes (strains) in the local wave velocity, in the directions of the force density. The main force is driving the wave-front forward (down the horn), but there are radial (transverse) forces as well, which tend to rapidly go to zero.

For example, if the tube has a change in area (or curvature), the local forces will create radial flow, which is immediately reflected by the walls, due to the small distance to the walls, causing the forces to average out. After traveling a few diameters, these forces will come to equilibrium and the wave will trend towards a plane wave (or satisfy Laplace’s equation if the distortions of the tube are sever). The internal stress caused by this change in area will quickly equilibrate.

There is a very important caveat, however: only at low frequencies, such that \( ka < 1 \), can the plane wave mode dominate. At higher frequencies \( (ka \geq 1) \) where the wavelength is small compared to the diameter, the distance traveled between reflections is much greater than a few diameters. Fortunately the frequencies where this happens are so high that they play no role in frequencies that we care about in the ear canal. This effect results from cross-modes, which are radial and angular standing waves.

Of course such modes exist in the ear canal above 20 [kHz]. However, they are much more obvious on the eardrum where the sound wave speed is much slower than that in air (Parent and Allen, 2010; Allen, 2014). Because of the slower speed, the ear drum has low-frequency cross-modes, and these may be seen in the ear canal pressure, and are easily observable in ear canal impedance measurements. Yet they seem to have a negligible effect on our ability to hear sound with high fidelity. The point here is that the cross modes are present, but we call upon the quasi-static approximation as a justification for ignoring them, to get closer to the first-order physics.
5.7.1 Quasi-statics and Quantum Mechanics

It is important to understand the meaning of Planck’s constant $h$, which appears in the relations of both photons (light “particles”) and electrons (mass particles). If we could obtain a handle on what exactly Planck’s constant means, we might have a better understanding of quantum mechanics, and physics in general. By cataloging the dispersion relations (the relation between the wavelength $\lambda(\nu)$ and the frequency $\nu$) between electrons and photons, this may be attainable.

Basic relations from quantum mechanics for photons and electrons include:

1. Photons (mass=0, velocity = $c$)
   
   (a) $c = \lambda \nu$: The speed of light $c$ is the product of its wavelengths $\lambda$ times its frequency $\nu$. This relationship is only for mono-chromatic (single frequency) light.
   
   (b) The speed of light is
   $$c_0 = \frac{1}{\sqrt{\mu_o/\epsilon_o}} = 3 \times 10^8 \text{ [m/s]}.$$
   
   (c) The characteristic resistance of light
   $$r_o = \sqrt{\mu_o/\epsilon_o} = \frac{|E|}{|H|} = 377 \text{ [ohms]}$$
   is defined as the magnitude of the ratio of the electric $E$ and magnetic $H$ field, of a plane wave in-vacuo.
   
   (d) $E = h\nu$: the photon energy is given by Planck’s constant
   $$h \approx 6.623 \times 10^{-34} \text{ [joule \cdot s]}$$
   times the frequency (i.e., bandwidth) of the photon.

2. Electrons (mass = $m_e$, velocity $V = 0$):
   
   (a) $E_e = m_e c^2 \approx 0.91 \cdot 10^{-30} \cdot 0.3^2 \cdot 10^{12} = 8.14 \times 10^{-20}$ [J] is the electron rest energy (velocity $V = 0$) of every electron, of mass $m_e = 9.1 \times 10^{-31}$ [kgm], where $c_o$ is the speed of light.
   
   (b) $p = h/\lambda$: The momentum $p$ of an electron is given by Planck’s constant $h$ divided by the wavelength of an electron $\lambda$. It follows that the bandwidth of the photon is given by
   $$\nu_e = \frac{E_e}{h},$$
   
   and the wavelength of an electron is
   $$\lambda_e = \frac{h}{p_e}.$$
Models of the electron: It is helpful to consider the physics of the electron, a negatively charged particle that is frequently treated as a single point in space. If the size were truly zero, there could be no magnetic moment (spin). The accepted size of the electron is known as the Lorentz radius, \( R = 2.8 \times 10^{-15} \) [m]. One could summarize the Lorentz radius as follows: Here lie many unsolved problems in physics. More specifically, at dimensions of the Lorentz radius, what exactly is the structure of the electron?

Ignoring these difficulties, if one integrates the charge density of the electron over the Lorentz radius and places the total charge at a single point, then one may make a grossly oversimplified model of the electron. For example, the electric displacement \( (D = \varepsilon_o E) \) (flux density) around a point charge is

\[
D = -\varepsilon_o \nabla \phi(R) = -Q \nabla \left\{ \frac{1}{R} \right\} = -Q \delta(R). \quad [\text{Col/m}^2]
\]

This is a formula taught in many classic texts, but one should remember how crude a model of an electron it is. But it does describe the electric flux in an easily remembered form. However, computationally, it is less nice, due to the delta function. The main limitation of this model is that the electron has a magnetic dipole moment (aka, spin), which a simple point charge model does not capture. When placed in a magnetic field, due to the magnetic dipole, the electron will align itself with the field.

One may apply a similar analysis to the gravitational potential. At the surface of the earth we are so far from the center of the earth that the potential appears to be linear, because the height is a tiny fraction of the radius of the earth.

5.7.2 Conjecture on photon energy:

Photons are seen as quantized because they are commonly generated by atoms, which freely radiate photons (light-particles) having the difference in two energy (quantum, or eigen-states) levels. The relation \( E = h\nu \) does not inherently depend on \( \nu \) being a fixed frequency. Planck’s constant \( h \) is the EM energy density over frequency, and \( E(\nu_o) \) is the integral over frequency

\[
E(\nu_o) = h \int_{-\nu_o}^{\nu_o} d\nu = 2h \nu_o.
\]

When the photon is generated by an atom, \( \nu_o \) is quantized by the energy level difference that corresponds to the frequency (energy level difference) of the photon jump.31

Summary: Mathematics began as a simple way of keeping track of how many things there were. But eventually physics and mathematics cleverly and mysteriously evolved, to become tools to help us navigate our environment, both locally and globally, to: (1) solve daily problems such as food, water and waste management, (2) understand the solar system and the stars, (3) defend ourselves using tools of war, such as the hydrogen bomb. All powerful ideas have both bright and dark sides.

Based on the historical record of the abacus, one can infer that people precisely understood the concepts of counting, addition, subtraction, multiplication (recursive addition) and division (recursive subtraction with a fractional remainder). There is evidence that the abacus, a simple counting tool formalizing the addition of very large numbers, was introduced by the Romans to the Chinese, who used it for trade.

However, this working knowledge of arithmetic did not show up in written number systems. The Roman numerals were not useful for doing calculations done on the abacus. Only the final answer could be expressed in terms of the Roman number system.

According to the known written record, the number zero had no written symbol until the time of Brahmagupta (628 CE). One should not assume the concept of zero was not understood simply because there was no symbol for it in the Roman numeral system. Negative numbers and zero would have

31There is no better example of this than the properties of very large Rydberg atoms, as beautifully articulated by MIT professor of physics Daniel Kleppner https://www.youtube.com/watch?v=e0IWPehmMho.
been obvious when using the abacus. Numbers between the integers would naturally be represented as fractional numbers ($\mathbb{F}$), since any irrational number ($\mathbb{Q}$) may be approximated with arbitrary accuracy using fractional ($\mathbb{F}$) numbers.

Mathematics is the science of formalizing a repetitive method into a set of rules (an algorithm), and then generalizing it as much as possible. Generalizing the multiplication and division algorithms to different types of numbers becomes increasingly more interesting as we move from integers to rational numbers, irrational numbers, real and complex numbers and, ultimately, vectors and matrices. How do you multiply two vectors, or multiply and divide one matrix by another? Is it subtraction as in the case of two numbers? Multiplying and dividing polynomials (by long division) generalizes these operations even further. Linear algebra is a further important generalization, fallout from the fundamental theorem of algebra, and essential for solving the generalizations of the number systems.

Many of the concepts about numbers naturally evolved from music, where the length of a string (along with its tension) determined the pitch (Stillwell, 2010, pp. 11, 16, 153, 261). Cutting the string’s length by half increased the frequency by a factor of 2. One fourth of the length increases the frequency by a factor of 4. One octave is a factor of 2 and two octaves a factor of 4 while a half octave is $\sqrt{2}$. The musical scale was soon factored into rational parts. This scale almost worked, but did not generalize (sometimes known as the Pythagorean comma\footnote{https://en.wikipedia.org/wiki/Pythagorean_comma}), resulting in today’s well tempered scale, which is based on 12 equal geometric steps along one octave, or 1/12 octave ($\frac{12}{\sqrt{2}} \approx 1.05946 \approx \frac{18}{17} = 1 + \frac{1}{17}$).

But the concept of a factor was clear. Every number may be written as either a sum or a product (i.e., a repetitive sum). This led the early mathematicians to the concept of a prime number, which is based on a unique factoring of every integer. At this same time (c5000 BCE), the solution of a second-degree polynomial was understood, which led to a generalization of factoring, since the polynomial, a sum of terms, may be written in factored form. If you think about this a bit, it is an amazing idea that needed to be discovered. This concept led to an important string of theorems on factoring polynomials, and how to numerically describe physical quantities. Newton was one of the first to master these tools with his proof that the orbits of the planets are ellipses, not circles. This led him to expanding functions in terms of their derivatives and power series. Could these sums be factored? The solution to this problem led to calculus.

So mathematics, a product of the human mind, is a highly successful attempt to explain the physical world. All aspects of our lives were, and are impacted by these tools. Mathematical knowledge is power. It allows one to think about complex problems in increasingly sophisticated ways. Does mathematics have a dark side? Perhaps no more than language itself. An equation is a mathematical sentence, expressing deep knowledge. Witness $E = mc^2$ and $\nabla^2 \psi = \ddot{\psi}$. 

\begin{footnotesize}
\end{footnotesize}
5.7.3 Exercises VC-2

**Topic of this homework:** Maxwell’s equations (ME) and variables (E, D; B, H); Compressible and rotational properties of vector fields; fundamental theorem of vector calculus (Helmholtz’ Theorem); Riemann zeta function; Wave equation.

**Notation:** The following notation is used in this assignment:

1. \( s = \sigma + j\omega \) is the *Laplace frequency*, as used in the Laplace transform.

2. A Laplace transform pair are indicated by the symbol \( \leftrightarrow \): e.g., \( f(t) \leftrightarrow F(s) \).

3. \( \pi_k \) is the \( k^{th} \) prime (i.e., \( \pi_k \in \mathbb{P} \), e.g., \( \pi_k = [2, 3, 5, 7, 11, 13 \cdots] \) for \( k = 1 \ldots 6 \)).

**Partial differential equations (PDEs): Wave equation**

1. Show that d’Alembert’s solution, \( \rho(x,t) = f(t-x/c) + g(t+x/c) \), is a solution to the acoustic pressure wave equation, in 1-dimension:

   \[
   \frac{\partial^2 \rho(x,t)}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 \rho(x,t)}{\partial t^2},
   \]

   where \( f(\xi) \) and \( g(\xi) \) are arbitrary functions.

2. Solution to the wave equation in spherical coordinates (i.e., 3-dimensions):

   (a) Write out the wave equation in spherical coordinates \( \rho(r,\theta,\phi,t) \). Only consider the radial term \( r \) (i.e., dependence on angles \( \theta, \phi \) is assumed to be zero). *Hint: The form of the Laplacian as a function of the number of dimensions is given in the last appendix on Transmission lines and Acoustic Horns. Alternatively, look it up on the internet or in a calculus book.*

   (b) Show that the following is true:

   \[
   \nabla_r^2 \rho(r) \equiv \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial}{\partial r} \rho(r) \right) = \frac{1}{r} \frac{\partial^2}{\partial r^2} r \rho(r). \tag{5.80}
   \]

   *Hint: Expand both sides of the equation.*

   (c) Use the results from Eq. 5.80 to show that the solution to the spherical wave equation is

   \[
   \nabla_r^2 \rho(r,t) = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \rho(r,t) \tag{5.81}
   \]

   \[
   \rho(r,t) = \frac{f(t-r/c)}{r} + \frac{g(t+r/c)}{r}. \tag{5.82}
   \]

   (d) With \( f(\xi) = \sin(\xi) \) and \( g(\xi) = e^{\xi} u(\xi) \) [\( u(\xi) \) is the step function] (Eq. 5.82) write down the solutions to the spherical wave equation.

   (e) Sketch this last case for several times (e.g., 0, 1 2 seconds), and describe the behavior of the pressure \( \rho(r,t) \) as a function of time \( t \) and radius \( r \).

   (f) What happens when the inbound wave reaches the center at \( r = 0 \)?
CHAPTER 5. STREAM 3B: VECTOR CALCULUS (10 LECTURES)

Helmholtz formula

Every differentiable vector field may be written as the sum of a scalar potential \( \phi \) and vector potential \( \mathbf{w} \). This relationship is best known as The Fundamental theorem of vector calculus (Helmholtz’ formula).

\[ \mathbf{v} = -\nabla \phi + \nabla \times \mathbf{w}, \quad (5.83) \]

where \( \phi \) is the scalar potential and \( \mathbf{w} \) is the vector potential. This formula seems a natural extension of the algebraic \( \mathbf{A} \cdot \mathbf{B} \perp \mathbf{A} \times \mathbf{B} \), since \( \mathbf{A} \cdot \mathbf{B} \propto ||\mathbf{A}|| ||\mathbf{B}|| \cos(\theta) \) and \( \mathbf{A} \times \mathbf{B} \propto ||\mathbf{A}|| ||\mathbf{B}|| \sin(\theta) \) as developed in the notes (Fig. A.1). Thus these orthogonal components have magnitude 1 when we take the norm, due to Euler’s identity \( \cos^2(\theta) + \sin^2(\theta) = 1 \).

As described in Table 5.1 (p. 186), Helmholtz’ formula separates a vector field (i.e., \( \mathbf{v}(x) \)) into compressible and rotational parts:

1. The rotational (e.g. angular) part is defined by the vector potential \( \mathbf{w} \), requiring \( \nabla \times \nabla \times \mathbf{w} \neq 0 \). A field is irrotational (conservative) when \( \nabla \times \mathbf{v} = 0 \), meaning that the field \( \mathbf{v} \) can be generated using only a scalar potential, \( \mathbf{v} = \nabla \phi \) (note this is how a conservative field is usually defined, by saying there exists some \( \phi \) such that \( \mathbf{v} = \nabla \phi \)).

2. The compressible (e.g. radial) part of a field is defined by the scalar potential \( \phi \), requiring \( \nabla \cdot \nabla \phi \neq 0 \). A field is incompressible (solenoidal) when \( \nabla \cdot \mathbf{v} = 0 \), meaning that the field \( \mathbf{v} \) can be generated using only a vector potential, \( \mathbf{v} = \nabla \times \mathbf{w} \).

The definitions and generating potential functions of irrotational (conservative) and incompressible (solenoidal) fields naturally follow from two key vector identities:

1. \( \nabla \cdot (\nabla \times \mathbf{w}) = 0 \)
2. \( \nabla \times (\nabla \phi) = 0 \)

Exercises:

1. Define the following:
   - A conservative vector field
   - A irrotational vector field
   - An incompressible vector field
   - A solenoidal vector field

2. When is a conservative field irrotational?

3. When is a incompressible field irrotational?

4. For each of the following, (i) compute \( \nabla \cdot \mathbf{v} \), (ii) compute \( \nabla \times \mathbf{v} \), (iii) classify the vector field (e.g., conservative, irrotational, incompressible, etc.):
   
   \[
   \begin{align*}
   (a) \quad & \mathbf{v}(x, y, z) = -\nabla [3yx^3 + y \log(xy)] \\
   (b) \quad & \mathbf{v}(x, y, z) = xy\hat{x} - z\hat{y} + f(z)\hat{z} \\
   (c) \quad & \mathbf{v}(x, y, z) = \nabla \times [x\hat{x} - z\hat{y}] \\
   \end{align*}
   \]

33A note about the relationship between the generating function and the test: You might imagine special cases where \( \nabla \times \mathbf{w} \neq 0 \) but \( \nabla \times \nabla \times \mathbf{w} = 0 \) (or \( \nabla \phi \neq 0 \) but \( \nabla^2 \phi = 0 \)). In these cases, the vector (or scalar) potential can be recast as a scalar (or vector) potential.

Example: Consider a field \( \mathbf{v} = \nabla \phi_0 + \mathbf{b} \) where \( \mathbf{b} = x\hat{x} + y\hat{y} + z\hat{z} \). Note that \( \mathbf{b} \) can actually be generated by either a scalar potential \( \phi_1 = \frac{1}{2} [x^2 + y^2 + z^2] \), such that \( \nabla \phi_1 = \mathbf{b} \) or a vector potential \( \mathbf{w}_0 = \frac{1}{2} [x^2\hat{x} + x^2\hat{y} + y^2\hat{z}] \), such that \( \nabla \times \mathbf{w}_0 = \mathbf{b} \). We find that \( \nabla \times \mathbf{v} = 0 \), therefore \( \mathbf{v} \) must be irrotational. Therefore, we say this irrotational field is generated by \( \nabla \phi = \nabla (\phi_0 + \phi_1) \).
Maxwell’s Equations

The variables have the following names and defining equations:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Equation</th>
<th>Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>( \nabla \times E = -\dot{B} )</td>
<td>Electric Field strength</td>
<td>[Volts/m]</td>
</tr>
<tr>
<td>D</td>
<td>( \nabla \cdot D = \rho )</td>
<td>Electric Displacement (flux density)</td>
<td>[Col/m²]</td>
</tr>
<tr>
<td>H</td>
<td>( \nabla \times H = J + \dot{D} )</td>
<td>Magnetic Field strength</td>
<td>[Amps/m]</td>
</tr>
<tr>
<td>B</td>
<td>( \mu_0 H )</td>
<td>Magnetic Induction (flux density)</td>
<td>[Webers/m²]</td>
</tr>
</tbody>
</table>

Note that \( J = \sigma E \) is the current density (which has units of [Amps/m²]). Furthermore the speed of light in vacuo is \( c_0 = 3 \times 10^8 \) [m/s], and the characteristic resistance of light \( r_0 = \frac{\sqrt{\mu_0/\epsilon_0}}{1} \) [Ω (i.e., ohms)].

Speed of light

The speed of light in vacuo is \( c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \approx 3 \times 10^8 \) [m/s]. The characteristic resistance in in-vacuo is \( r_o = \sqrt{\mu_0/\epsilon_0} \approx 377 \) [Ω]. Find a formula for the in-vacuo permittivity \( \epsilon_o \) and permeability in terms of \( c_0 \) and \( r_0 \). Based on your formula, what are the numeric values values of \( \epsilon_o \) and \( \mu_o \)?

Application of ME

\( E \) is the electric field strength and \( \dot{B} \) is the time rate of change of the magnetic induction field, or simply the magnetic flux density. Consider this equation integrated over a two-dimensional surface \( S \), where \( \hat{n} \) is a unit vector normal to the surface (you may also find it useful to define the closed path \( C \) around the surface):

\[
\iint_S \left( \nabla \times E \right) \cdot \hat{n} dS = -\frac{\partial}{\partial t} \iint_S B \cdot \hat{n} dS
\]

1. Apply Stokes’ theorem to the left-hand side of the equation.
2. Consider the right-hand side of the equation. How is it related to the magnetic flux \( \Psi \) through the surface \( S \)?
3. Assume the right-hand side of the equation is zero. Can you relate your answer to part (a) to one of Kirchhoff’s laws?

The magnetic Maxwell equation is \( \nabla \times H = C \equiv J + \dot{D} \), where \( H \) is the magnetic field strength, \( J = \sigma E \) is the conductive (resistive) current density and the displacement current \( \dot{D} \) is the time rate of change of the electric flux density \( D \). Here we defined a new variable \( C \) as the total current density.

1. First consider the equation over a two dimensional surface \( S \),

\[
\iint_S \left( \nabla \times H \right) \cdot \hat{n} dS = \iint_S \left( J + \dot{D} \right) \cdot \hat{n} dS = \iint_S C \cdot \hat{n} dS
\]

Apply Stokes’ theorem to the left-hand side of this equation. In a sentence or two, explain the meaning of the resulting equation. \textit{Hint: What is the right-hand side of the equation?}

2. Now consider this equation in three dimensions. Take the divergence of both sides, and integrate over a volume \( V \) (closed surface \( S \)).

\[
\iiint_V \nabla \cdot \left( \nabla \times H \right) dV = \iiint_V \nabla \cdot C dV
\]

(a) What happens to the left-hand side of this equation? \textit{Hint: Can you apply a vector identity?}
(b) Apply the divergence theorem (sometimes known as Gauss’s theorem) to the right-hand side of the equation, and interpret your result. \textit{Hint: Can you relate your result to one of Kirchhoff’s laws?}
Second-order differentials

1. If \( \mathbf{v}(x, y, z) = \nabla \phi(x, y, z) \), then what is \( \nabla \cdot \mathbf{v}(x, y, z) \)?

2. Evaluate \( \nabla^2 \phi \) and \( \nabla \times \nabla \phi \) for \( \phi(x, y) = xe^y \).

3. Evaluate \( \nabla \cdot (\nabla \times \mathbf{v}) \) and \( \nabla \times (\nabla \times \mathbf{v}) \) for \( \mathbf{v} = x\mathbf{\hat{x}} + y\mathbf{\hat{y}} + z\mathbf{\hat{z}} \).

4. When \( \mathbf{V}(x, y, z) = \nabla (1/x + 1/y + 1/z) \) what is \( \nabla \times \mathbf{V}(x, y, z) \)?

5. When was Maxwell born (and die)? How long did he live (within ±10 years)?

Capacitor analysis

1. Find the solution to the Laplace equation between two infinite parallel plates, separated by a distance of \( d \). Assume that the left plate, at \( x = 0 \), is at a voltage of \( V(0) = 0 \), and the right plate, at \( x = d \), is at a voltage of \( V_d \equiv V(d) \).

2. Write down Laplace’s equation in one dimension for \( V(x) \).

3. Write down the general solution to your differential equation for \( V(x) \).

4. Apply the boundary conditions \( V(0) = 0 \) and \( V(d) = V_d \) to solve for the constants in your equation from the previous part.

5. Find the charge density per unit area (\( \sigma = Q/A \), where \( Q \) is charge and \( A \) is area) on the surface of each plate. \( \text{Hint: } \mathbf{E} = -\nabla V, \text{ and Gauss’s Law states that } \iint_S \mathbf{D} \cdot \mathbf{n} \, dS = Q_{\text{enclosed}}. \)

6. Determine the per-unit-area capacitance \( C \) of the system.

Webster Horn Equation

Horns provide an important generalization of the solution of the 1D wave equation, in regions where the properties (i.e., area of the tube) vary along the axis of wave propagation. Classic applications of horns are vocal tract acoustics, loudspeaker design, cochlear mechanics, any case having wave propagation.

To do: Write out the formula for the Webster horn equation, and explain the variables.

---

34We study plates that are infinite because this means the electric field lines will be perpendicular to the plates, running directly from one plate to the other. However, we will solve for per-unit-area characteristics of the capacitor.
5.8 Reading List

The above concepts come straight from mathematical physics, as developed in the 17th–19th centuries. Much of this was first developed in acoustics by Helmholtz, Stokes and Rayleigh, following in Green’s footsteps, as described by Lord Rayleigh (1896). When it comes to fully appreciating Green’s theorem and reciprocity, I have found Rayleigh (1896) to be a key reference. If you wish to repeat my reading experience, start with Brillouin (1953, 1960), followed by Sommerfeld (1952) and Pipes (1958).

Second-tier reading contains many items: Morse (1948); Sommerfeld (1949); Morse and Feshbach (1953); Ramo et al. (1965); Feynman (1970a); Boas (1987). A third tier might include Helmholtz (1863a); Fry (1928); Lamb (1932); Bode (1945); Montgomery et al. (1948); Beranek (1954); Fagen (1975); Lighthill (1978); Hunt (1952); Olson (1947). It would be a mistake to ignore other important physics writings by stalwart authors, J.C. Slater35 and Landau and Lifshitz,36 and their impressive series of mathematical physics books.

You must enter at a level that allows you to understand. Successful reading of these books critically depends on what you already know, after rudimentary (high school) level math has been mastered. Read in the order that helps you best understand the material.

36https://www.amazon.com/Mechanics-Third-Course-Theoretical-Physics/dp/0750628960
Appendix A

Notation

A.1 Number systems

The notation used in this book is defined in this appendix so that it may be quickly accessed.\(^1\) Where the definition is sketchy, page numbers are provided where these concepts are fully explained, along with many other important and useful definitions. For example a discussion of \(\mathbb{N}\) may be found on page 34. Math symbols such as \(\mathbb{N}\) may be found at the top of the index, since they are difficult to alphabetize.

A.1.1 Units

Strangely, or not, classical mathematics, as taught today in schools, does not seem to acknowledge the concept of physical units. Units seem to have been abstracted away. This makes mathematics distinct from physics, where almost everything has units. Presumably this makes mathematics more general (i.e., abstract). But for the engineering mind, this is not ideal, or worse, as it necessarily means that important physical meaning, by design, has been surgically removed. We shall use SI units whenever possible, which means this book is not a typical book on mathematics. Spatial coordinates are quoted in meters \([m]\), and time in seconds \([s]\). Angles in degrees have no units, whereas radians have units of inverse-seconds \([s^{-1}]\). For a complete list of SI units, refer to https://physics.nist.gov/cuu/pdf/sp811.pdf.

A.1.2 Symbols and functions

For more on basic math notation, see to Graham et al. (1994).

We use \(\ln\) as the log function base \(e\), \(\log\) as base 2, and \(\pi k\) to indicate the \(k\)th prime (e.g., \(\pi_1 = 2, \pi_2 = 3\)).

When working with Fourier \(\mathcal{F} T\) and Laplace \(\mathcal{L} T\) transforms, lower case symbols are in the time domain while upper case indicates the frequency domain, as \(f(t) \leftrightarrow F(\omega)\). An important exception is Maxwell’s equations because they are so widely used as upper-case bold letters (e.g., \(E(x, \omega)\)). It seems logical to change this to conform to lower case, with \(e(x, t) \leftrightarrow E(x, \omega)\) as the preferred notation.

A.1.3 Common mathematical symbols:

There are many pre-defined symbols in mathematics, too many to summarize here. We shall only use a small subset, defined here.

- A set is a collection of objects that have a common property. A set is defined using braces. For example, if set \(P = \{a, b, c\}\) such that \(a^2 + b^2 = c^2\), then members of \(P\) obey the Pythagorean theorem. Thus we could say that \(\{1, 1, \sqrt{2}\} \in P\).

\(^1\)https://en.wikipedia.org/wiki/List_of_mathematical_symbols_by_subject#Definition_symbols
• Number sets: \( \mathbb{N}, \mathbb{P}, \mathbb{Z}, \mathbb{Q}, \mathbb{F}, \mathbb{I}, \mathbb{R}, \mathbb{C} \) are briefly discussed below, and in greater detail in Section 2.1 (pp. 34–35).

• One can define sets of sets and subsets of sets, and this is prone (in my experience) to error. For example, what is the difference between the number 0 and the null set \( \emptyset = \{ \} \)? Is \( 0 \in \emptyset \)? Ask a mathematician. This seems a lackluster construction in the world of engineering.

• Define a vector as an n-tuple.

• The symbol \( \perp \) is used in many different ways to indicate two things are perpendicular, orthogonal, or in disjoint sets. In set theory \( A \perp B \) is equivalent to \( A \cap B = \emptyset \). If two vectors \( \mathbf{E}, \mathbf{H} \) are perpendicular \( \mathbf{E} \perp \mathbf{H} \), then their inner product \( \mathbf{E} \cdot \mathbf{H} = 0 \) is zero. One must infer the meaning of \( \perp \) from its context.

| Table A.1: List of all upper and lower case Greek letters used in the text. |
|---|---|---|---|---|---|
| A | A | \( \alpha \) | \( \alpha \) | alpha | N | N | \( \nu \) | \( \nu \) | nu |
| B | B | \( \beta \) | \( \beta \) | beta | \( \Xi \) | \( \Xi \) | \( \xi \) | \( \xi \) | xi |
| \( \Gamma \) | \( \Gamma \) | \( \gamma \) | \( \gamma \) | gamma | O | O | \( \omicron \) | \( \omicron \) | omicron |
| \( \Delta \) | \( \Delta \) | \( \delta \) | \( \delta \) | delta | \( \Pi \) | \( \Pi \) | \( \pi \) | \( \pi \) | pi |
| E | E | \( \epsilon \) | \( \epsilon \) | epsilon | \( \varphi \) | \( \varphi \) | \( \rho \) | \( \rho \) | rho |
| Z | Z | \( \zeta \) | \( \zeta \) | zeta | \( \Sigma \) | \( \Sigma \) | \( \sigma \) | \( \sigma \) | sigma |
| H | H | \( \eta \) | \( \eta \) | eta | \( \Theta \) | \( \Theta \) | \( \upsilon \) | \( \upsilon \) | upsilon |
| \( \Theta \) | \( \Theta \) | \( \theta \) | \( \theta \) | theta | \( \Phi \) | \( \Phi \) | \( \phi \) | \( \phi \) | phi |
| K | K | \( \kappa \) | \( \kappa \) | kappa | X | X | \( \chi \) | \( \chi \) | chi |
| \( \Lambda \) | \( \Lambda \) | \( \lambda \) | \( \lambda \) | lambda | \( \Psi \) | \( \Psi \) | \( \psi \) | \( \psi \) | psi |
| M | M | \( \mu \) | \( \mu \) | mu | \( \Omega \) | \( \Omega \) | \( \omega \) | \( \omega \) | omega |

A.1.4 Greek letters

Frequently Greek letters, as provided in Fig. A.1, are associated in engineering and physics with a specific physical meaning. For example, \( \omega \) [rad] is the radian frequency \( 2\pi f \), \( \rho \) [kgm/m\(^3\)] is commonly the density. \( \phi, \psi \) are commonly used to indicate angles of a triangle, and \( \zeta(s) \) is the Riemann zeta function. Many of these are so well established it makes no sense to define new terms, so we will adopt these common terms (and define them).

Likely you do not know all of these Greek letters, commonly used in mathematics. Some of them are pronounced in strange ways. The symbol \( \xi \) is pronounced “see,” \( \zeta \) is “zeta,” \( \beta \) is “beta,” and \( \chi \) is “kie” (rhymes with pie and sky). I will assume you know how to pronounce the others, which are more phonetic in English. One advantage of learning \LaTeX{} is that all of these math symbols are built in, and thus more easily learned, once you have adopted this powerful open-source math-oriented word-processing system (e.g., used to write this book).

A.1.5 Double-Bold notation

Table A.2 indicates the symbol followed by a page number indication where it is discussed, and the Genus (class) of the number type. For example, \( \mathbb{N} > 0 \) indicates the infinite set of counting numbers \( \{1, 2, 3, \cdots \} \), not including zero. Starting from any counting number, you get the next one by adding 1. Counting numbers are also known as the cardinal numbers.

We say that a number is in the set with the notation \( 3 \in \mathbb{N} \subset \mathbb{R} \), which is read as “3 is in the set of counting numbers, which in turn is in the set of real numbers,” or in vernacular language “3 is a real counting number.”
A.2. ROUNDING SCHEMES

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Table A.2: Double-bold notation for the types of numbers. (#) is a page number. Symbol with an exponent denote the dimensionality. Thus \( \mathbb{R}^2 \) represents the real plane. An exponent of 0 denotes point, e.g., \( j \in \mathbb{C}^0 \).

<table>
<thead>
<tr>
<th>Symbol (p, #)</th>
<th>Genus</th>
<th>Examples</th>
<th>Counter Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbb{N} ) (34)</td>
<td>Counting</td>
<td>1,2,17,3, ( 10^{20} )</td>
<td>-5, 0, ( \pi ), -10, 5j</td>
</tr>
<tr>
<td>( \mathbb{P} ) (34)</td>
<td>Prime</td>
<td>2,17,3, ( 10^{20} )</td>
<td>0, 1, 4, ( 3^2 ), 12, ( -5 )</td>
</tr>
<tr>
<td>( \mathbb{Z} ) (34)</td>
<td>Integer</td>
<td>-1, 0, 17, 5j, ( -10^{20} )</td>
<td>( 1/2, \pi, \sqrt{2} )</td>
</tr>
<tr>
<td>( \mathbb{Q} ) (35)</td>
<td>Rational</td>
<td>2/1, 3/2, 1.5, 1.14</td>
<td>( \sqrt{2}, 3^{-1/3}, \pi )</td>
</tr>
<tr>
<td>( \mathbb{F} ) (35)</td>
<td>Fractional</td>
<td>1/2, 7/22</td>
<td>( 1/\sqrt{2} )</td>
</tr>
<tr>
<td>( \mathbb{I} ) (35)</td>
<td>Irrational</td>
<td>( \sqrt{2}, 3^{-1/3}, \pi, e )</td>
<td>Vectors</td>
</tr>
<tr>
<td>( \mathbb{R} ) (35)</td>
<td>Reals</td>
<td>( \sqrt{2}, 3^{-1/3}, \pi )</td>
<td>2( \pi j )</td>
</tr>
<tr>
<td>( \mathbb{C} ) (35)</td>
<td>Complex</td>
<td>1, ( \sqrt{2} j ), ( 3^{-j/3} ), ( \pi j )</td>
<td>Vectors</td>
</tr>
<tr>
<td>( \mathbb{G} )</td>
<td>Gaussian integers</td>
<td>( 3 - 2j \in \mathbb{Z} \cup \mathbb{C} )</td>
<td>complex integers</td>
</tr>
</tbody>
</table>

Prime numbers (\( \mathbb{P} \subset \mathbb{N} \)) are taken from the counting numbers, but do not include 1.

The signed integers \( \mathbb{Z} \) include 0 and negative integers. Rational numbers \( \mathbb{Q} \) are historically defined to include \( \mathbb{Z} \), a somewhat inconvenient definition, since the more interesting class are the fractionals \( \mathbb{F} \), a subset of rationals \( \mathbb{F} \subset \mathbb{Q} \) that exclude the integers (i.e., \( \mathbb{F} \perp \mathbb{Z} \)). This is a useful definition because the rationals \( \mathbb{Q} = \mathbb{Z} \cup \mathbb{F} \) are formed from the union of integers and fractionals.

The rationals may be defined, using set notation (a very sloppy notation with an incomprehensible syntax), as

\[
\mathbb{Q} = \{ p/q : q \neq 0 \& p, q \in \mathbb{Z} \},
\]

which may be read as ‘the set ‘{···}’ of all \( p/q \) such that ‘:’ \( q \neq 0 \), ‘and’ \( p, q \subset \mathbb{Z} \).’ The translation of the symbols is in single (‘···’) quotes.

Irrational numbers \( \mathbb{I} \) are very special: They are formed by taking a limit of fractionals, as the numerator and denominator \( \to \infty \), and approach a limit point. It follows that irrational numbers must be approximated by fractionals.

The reals (\( \mathbb{R} \)) include complex numbers (\( \mathbb{C} \)) having a zero imaginary part (i.e., \( \mathbb{R} \subset \mathbb{C} \)).

The size of a set is denoted by taking the absolute value (e.g., \( |\mathbb{N}| \)). Normally in mathematics this symbol indicates the cardinality, so we are defining it differently from the standard notation.

Classification of numbers: From the above definitions there exists a natural hierarchical structure of numbers:

\[
\mathbb{P} \subset \mathbb{N}, \quad \mathbb{Z} : \{ \mathbb{N}, 0, -\mathbb{N} \}, \quad \mathbb{F} \perp \mathbb{Z}, \quad \mathbb{Q} : \mathbb{Z} \cup \mathbb{F}, \quad \mathbb{R} : \mathbb{Q} \cup \mathbb{I} \subset \mathbb{C}
\]

1. The primes are a subset of the counting numbers: \( \mathbb{P} \subset \mathbb{N} \).
2. The signed integers \( \mathbb{Z} \) are composed of \( \pm \mathbb{N} \) and 0, thus \( \mathbb{N} \subset \mathbb{Z} \).
3. The fractionals \( \mathbb{F} \) do not include of the signed integers \( \mathbb{Z} \).
4. The rationals \( \mathbb{Q} = \mathbb{Z} \cup \mathbb{F} \) are the union of the signed integers and fractionals.
5. Irrational numbers \( \mathbb{I} \) have the special properties \( \mathbb{I} \perp \mathbb{Q} \).
6. The reals \( \mathbb{R} : \mathbb{Q}, \mathbb{I} \) are the union of rationals and irrational \( \mathbb{I} \).
7. Reals \( \mathbb{R} \) may be defined as a subset of those complex numbers \( \mathbb{C} \) having zero imaginary part.
A.2 Rounding schemes

In Matlab/Octave there are five different rounding schemes (i.e., mappings): \texttt{round(x)}, \texttt{fix(x)}, \texttt{floor(x)}, \texttt{ceil(x)}, \texttt{roundb(x)}, with \( x \in \mathbb{R} \). Function \( \texttt{round(\pi)} = 3 \) (e.g., \( 3 = \lfloor \pi \rfloor \)) rounds to the nearest integer, whereas \( \texttt{floor(\pi)} \) (i.e., \( 3 = \lfloor \pi \rfloor \)) rounds down and \( \texttt{ceil(\pi)} \) rounds up (i.e., \( 4 = \lceil \pi \rceil \)).

Note \( \texttt{round()} \equiv \lfloor \pi \rfloor \) introduces negative remainders, when ever a number rounds up. The expressions in brackets is the notation for the continued fraction expansion (p. 55).

A.3 Periodic functions

Fourier series tells us that periodic functions are discrete in frequency, with frequencies given by \( nT_x \), where \( T_x \) is the sample period (\( T_x = 1/2F_{max} \) and \( F_{min} = F_{max}/NFT \)).

This concept is captured by the Fourier series, which is a frequency expansion of a periodic function. This concept is quite general. Periodic in frequency implies discrete in time. Periodic and discrete in time requires periodic and discrete in frequency (the case of the DFT). The modulo function \( mmodn \) is periodic with period \( n \).

A periodic function may be conveniently indicated using double-parentheses notation. This is sometimes known as modular arithmetic. For example,

\[
 f((t))_T = f(t) = f(t \pm kT)
\]

is periodic on \( t, T \in \mathbb{R} \) with a period of \( T \) and \( k \in \mathbb{Z} \). This notation is useful when dealing with Fourier series of periodic functions.

When a discrete valued (e.g., time \( t \in \mathbb{N} \) sequence is periodic with period \( N \in \mathbb{Z} \), we use square brackets

\[
 f[[n]]_N = f[n] = f[n \pm kN],
\]

with \( k \in \mathbb{Z} \). This notation will be used with discrete-time signals that are periodic, such as the case of the DFT.

A.4 Differential equations vs. polynomials

A polynomial has degree \( N \) defined by the largest power. A quadratic equation is degree 2, and a cubic has degree 3. We shall indicate a polynomial by the notation

\[
 P_N(z) = z^N + a_{N-1}z^{N-1} \cdots a_0.
\]

It is a good practice to normalize the polynomial so that \( a_N = 1 \). This will not change the roots, defined by Eq. 3.7 (p. 74). The coefficient on \( z^{N-1} \) is always the sum of the roots \( z_n (a_{N-1} = \sum_{n}^{N} z_n) \), and \( a_0 \) is always their product \( (a_0 = \prod_{n}^{N} z_n) \).

Differential equations have order (polynomials have degree). If a second-order differential equation is Laplace transformed (Lec. 3.7, p. 130), one is left with a degree 2 polynomial.

Example:

\[
 \frac{d^2}{dt^2}y(t) + b \frac{d}{dt}y(t) + cy(t) = \alpha \left( \frac{d}{dt}x(t) + \beta x(t) \right) \leftrightarrow \quad (A.1)
\]

\[
 (s^2 + bs + c)Y(s) = \alpha(s + \beta)X(s). \quad (A.2)
\]

\[
 \frac{Y(s)}{X(s)} = \alpha \frac{s + \beta}{s^2 + bs + c} \equiv H(s) \leftrightarrow h(t). \quad (A.3)
\]
Using the same argument as for polynomials, the lead coefficient must always be 1. The coefficient $\alpha \in \mathbb{R}$ is called the gain. The complex variable $s$ is the Laplace frequency.

The ratio of the output $Y(s)$ over the input $X(s)$ is called the system transfer function $H(s)$. When $H(s)$ is the ratio of two polynomials in $s$, the transfer function is said to be bilinear, since it is linear in both the input and output. The roots of the numerator are called the zeros and those of the denominator, the poles. The inverse Laplace transform of the transfer function is called the system impulse response, which describes the system’s output signal $y(t)$ for any given input signal $x(t)$, via convolution (i.e., $y(t) = h(t) \ast x(t)$).
Appendix B

Tables of Laplace Transforms

Properties of the Laplace Transform

1. Time \( t \in \mathbb{R} \) [s] and Laplace frequency [rad] are defined as \( s = \sigma + \omega j \in \mathbb{C} \).

2. Given a Laplace transform (LT) pair \( f(t) \leftrightarrow F(s) \), in the engineering literature, the time domain is always lower case \([f(t)]\) and causal (i.e., \( f(t < 0) = 0 \)) and the frequency domain is upper-case [e.g. \( F(s) \)]. Maxwell’s venerable equations are the unfortunate exception to this otherwise universal rule.

3. The target time function \( f(t < 0) = 0 \) (i.e., it must be causal). The time limits are \( 0^{-} < t < \infty \). Thus the integral must start from slightly below \( t = 0 \) to integrate over a delta function at \( t = 0 \). For example if \( f(t) = \delta(t) \), the integral must include both sides of the impulse. If you wish to include non-causal functions such as \( \delta(t + 1) \), it is necessary to extend the lower time limit. In such cases simply set the lower limit of the integral to \( -\infty \), and let the integrand \( (f(t)) \) determine the limits.

4. When taking the forward transform \( (t \rightarrow s) \), the sign of the exponential is negative. This is necessary to assure that the integral converges when the integrand \( f(t) \rightarrow \infty \) as \( t \rightarrow \infty \). For example, if \( f(t) = e^{\sigma t}u(t) \) (i.e., without the negative \( \sigma \) exponent), the integral does not converge.

5. The limits on the integrals of the forward transform are \( t : (0^{-}, \infty) \in \mathbb{R} \), and the reverse LTs are \([\sigma_o - \infty j, \sigma_o + \infty j] \in \mathbb{C} \). These limits will be further discussed in Section 4.5.3 (p. 176).

6. When taking the inverse Laplace transform, the normalization factor of \( 1/2\pi j \) is required to cancel the \( 2\pi j \) in the differential \( ds \) of the integral.

7. The frequency for the LT must be complex, and in general \( F(s) \) is complex analytic for \( \sigma > \sigma_o \). It follows that the real and imaginary parts of \( F(s) \) are related. Given \( \Re\{F(s)\} \) it is possible to find \( \Im\{F(s)\} \) (Boas, 1987). More on this in Section 3.7 (p. 130).

8. To take the inverse Laplace transform, we must learn how to integrate in the complex \( s \) plane. This will be explained in Sections 4.4-4.5.3 (p. 163-176).

9. The Laplace step function is defined as

\[
\begin{align*}
u(t) &= \int_{-\infty}^{t} \delta(t)dt = \begin{cases} 1 & \text{if } t > 0 \\ \text{NaN} & t = 0 \\ 0 & \text{if } t < 0 \end{cases}.
\end{align*}
\]

Alternatively one could define \( \delta(t) = du(t)/dt \).
10. It is easily shown that $u(t) \leftrightarrow 1/s$ by direct integration

$$F(s) = \int_{0}^{\infty} u(t) e^{-st} dt = -\left. \frac{e^{-st}}{s} \right|_{0}^{\infty} = \frac{1}{s}.$$  

With the LT step ($u(t)$) there is no Gibbs ringing effect.

11. In many physical applications, the Laplace transform takes the form of a ratio of two polynomials. In such case the roots of the numerator polynomial are called the *zeros* while the roots of the denominator polynomial are called the *poles*. For example the LT of $u(t) \leftrightarrow 1/s$ has a pole at $s = 0$, which represents integration, since

$$u(t) * f(t) = \int_{-\infty}^{\infty} f(\tau) d\tau \leftrightarrow \frac{F(s)}{s}.$$  

12. The LT is quite different from the FT in terms of its analytic properties. For example, the step function $u(t) \leftrightarrow 1/s$ is complex analytic everywhere, except at $s = 0$. The FT of $1 \leftrightarrow 2\pi \delta(\omega)$ is not analytic anywhere.

13. Dilated step function ($a \in \mathbb{R}$)

$$u(at) \leftrightarrow \int_{-\infty}^{\infty} u(at) e^{-st} dt = \frac{1}{a} \int_{-\infty}^{\infty} u(\tau) e^{-s(\tau/a)} d\tau = \frac{1}{|a|} \frac{1}{s} = \pm \frac{1}{s},$$

where we have made the change of variables $\tau = at$. The only effect that $a$ has on $u(at)$ is the sign of $t$, since $u(t) = u(2t)$. However $u(-t) \neq u(t)$, since $u(t) \cdot u(-t) = 0$, and $u(t) + u(-t) = 1$, except at $t = 0$, where it is not defined.

Once complex integration in the complex plane has been defined (Section 4.2.2, p. 147), we can justify the definition of the inverse LT (Eq. 3.48).\(^1\)

\(^1\)https://en.wikipedia.org/wiki/Laplace_transform#Table_of_selected_Laplace_transforms
Table B.1: Functional relationships between Laplace transforms.

<table>
<thead>
<tr>
<th>Functional properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f(t) \ast g(t) = \int_{t=0}^{t} f(t-\tau)g(\tau)d\tau \leftrightarrow F(s)G(s)$</td>
</tr>
<tr>
<td>convolution</td>
</tr>
<tr>
<td>$u(t) \ast f(t) = \int_{0}^{t} f(t)dt \leftrightarrow \frac{F(s)}{s}$</td>
</tr>
<tr>
<td>convolution</td>
</tr>
<tr>
<td>$f(at)u(at) \leftrightarrow \frac{1}{a}F\left(\frac{s}{a}\right)$ $a \in \mathbb{R} \neq 0$</td>
</tr>
<tr>
<td>scaling</td>
</tr>
<tr>
<td>$f(t)e^{-at}u(t) \leftrightarrow F(s+a)$</td>
</tr>
<tr>
<td>damped</td>
</tr>
<tr>
<td>$f(t-T)e^{-a(t-T)}u(t-T) \leftrightarrow e^{-sT}F(s+a)$</td>
</tr>
<tr>
<td>damped and delayed</td>
</tr>
<tr>
<td>$f(-t)u(-t) \leftrightarrow F(-s)$</td>
</tr>
<tr>
<td>reverse time</td>
</tr>
<tr>
<td>$f(-t)e^{-at}u(-t) \leftrightarrow F(a-s)$</td>
</tr>
<tr>
<td>time-reversed &amp; damped</td>
</tr>
<tr>
<td>$\frac{d}{dt}f(t) = \delta'(t) \ast f(t) \leftrightarrow sF(s)$</td>
</tr>
<tr>
<td>deriv</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Additional transforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sin(t)u(t)}{t} \leftrightarrow \tan^{-1}(1/s)$</td>
</tr>
<tr>
<td>half-sync</td>
</tr>
</tbody>
</table>
### Table B.2: Laplace transforms of $f(t)$, $\delta(t)$, $u(t)$, $\text{rect}(t), T_0, p, e, \in \mathbb{R}$ and $F(s), G(s), s, a \in \mathbb{C}$. Given a Laplace transform ($\mathcal{L}T$) pair $f(t) \leftrightarrow F(s)$, the frequency domain will always be upper-case [e.g. $F(s)$] and the time domain lower case [$f(t)$] and causal (i.e., $f(t < 0) = 0$). An extended table of transforms is given in Table B.1 on page 249.

<table>
<thead>
<tr>
<th>$f(t)$ ↔ $F(s)$</th>
<th>$t \in \mathbb{R}$; $s, F(s) \in \mathbb{C}$</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta(t)$ ↔ 1</td>
<td>$t \in \mathbb{R}$</td>
<td>Dirac</td>
</tr>
<tr>
<td>$\delta(</td>
<td>t</td>
<td>) \leftrightarrow \frac{1}{</td>
</tr>
<tr>
<td>$\delta(t - T_0) \leftrightarrow e^{-sT_0}$</td>
<td></td>
<td>delayed Dirac</td>
</tr>
<tr>
<td>$\delta(t - T_0) * f(t) \leftrightarrow F(s)e^{-sT_0}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sum_{n=0}^{\infty} \delta(t - nT_0) = \frac{1}{1 - \delta(t - T_0)} \leftrightarrow \frac{1}{1 - e^{-sT_0}} = \sum_{n=0}^{\infty} e^{-snT_0}$</td>
<td></td>
<td>one-sided impulse train</td>
</tr>
<tr>
<td>$u(t) \leftrightarrow \frac{1}{s}$</td>
<td></td>
<td>step</td>
</tr>
<tr>
<td>$u(-t) \leftrightarrow -\frac{1}{s}$</td>
<td></td>
<td>anti-causal step</td>
</tr>
<tr>
<td>$u(at) \leftrightarrow \frac{a}{s}$</td>
<td>$a \neq 0 \in \mathbb{R}$</td>
<td>dilated or reversed step</td>
</tr>
<tr>
<td>$e^{-at}u(t) \leftrightarrow \frac{1}{s + a}$</td>
<td>$a &gt; 0 \in \mathbb{R}$</td>
<td>damped step</td>
</tr>
<tr>
<td>$\cos(at)u(t) \leftrightarrow \frac{1}{2} \left( \frac{1}{s - a} + \frac{1}{s + a} \right)$</td>
<td>$a \in \mathbb{R}$</td>
<td>cos</td>
</tr>
<tr>
<td>$\sin(at)u(t) \leftrightarrow \frac{1}{2j} \left( \frac{1}{s - a} - \frac{1}{s + a} \right)$</td>
<td>$a \in \mathbb{C}$</td>
<td>“damped” sin</td>
</tr>
<tr>
<td>$u(t - T_0) \leftrightarrow \frac{1}{s} e^{-sT_0}$</td>
<td>$T_0 &gt; 0 \in \mathbb{R}$</td>
<td>time delay</td>
</tr>
<tr>
<td>$\text{rect}(t) = \frac{1}{T_0} [u(t) - u(t - T_0)] \leftrightarrow \frac{1}{T_0} \left( 1 - e^{-sT_0} \right)$</td>
<td></td>
<td>rect-pulse</td>
</tr>
<tr>
<td>$u(t) * u(t) = tu(t) \leftrightarrow 1/s^2$</td>
<td></td>
<td>ramp</td>
</tr>
<tr>
<td>$u(t) * u(t) = tu(t) \leftrightarrow 1/s^3$</td>
<td></td>
<td>double ramp</td>
</tr>
<tr>
<td>$\frac{1}{\sqrt{t}}u(t) \leftrightarrow \sqrt{\frac{\pi}{s}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t^p u(t) \leftrightarrow \frac{\Gamma(p+1)}{s^{p+1}}$</td>
<td>$\Re p &gt; -1, q \in \mathbb{C}$</td>
<td></td>
</tr>
<tr>
<td>$J_n(\omega_0 t) u(t) \leftrightarrow \frac{\left( \sqrt{s^2 + \omega_0^2} - s \right)^n}{\omega_0^n \sqrt{s^2 + \omega_0^2}}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Table B.3: The following table provides an extended table of Laplace Transforms. $J_0, K_1$ are Bessel functions of the first and second kind.

<table>
<thead>
<tr>
<th>$f(t)$ ↔ $F(s)$</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta(at)$ ↔ $1/a$</td>
<td>$a \neq 0$; Time-scaled Dirac</td>
</tr>
<tr>
<td>$\delta(t + T_0)$ ↔ $e^{sT_0}$</td>
<td>negative delay</td>
</tr>
<tr>
<td>$u(at)$ ↔ $a/s$</td>
<td>$a \neq 0$; dilate</td>
</tr>
<tr>
<td>$u(-t)$ ↔ $-1/s$</td>
<td>anti-causal step</td>
</tr>
<tr>
<td>$e^{at}u(-t)$ ↔ $1/(-s + a)$</td>
<td>anticausal damped step</td>
</tr>
</tbody>
</table>

\[
\frac{d^{1/2}}{dt^{1/2}} f(t)u(t) \leftrightarrow \sqrt{s} F(s)
\]

\[
\frac{d^{1/2}}{dt^{1/2}} u(t) \leftrightarrow \sqrt{s}
\]

\[
\frac{1}{\sqrt{\pi t}} u(t) \leftrightarrow \sqrt{s}
\]

\[
\text{erfc}(\alpha \sqrt{t}) \leftrightarrow \frac{1}{s} e^{-2\alpha\sqrt{s}} \quad \text{(Morse-Feshbach-II, p. 1582)} \quad \alpha > 0; \text{ erfc}
\]

<table>
<thead>
<tr>
<th>$f(t)$ ↔ $F(s)$</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_0(at)u(t)$ ↔ $1/(s^2 + a^2)$</td>
<td>Bessel</td>
</tr>
<tr>
<td>$J_1(t)u(t)/t \leftrightarrow \sqrt{s^2 + 1} - s$</td>
<td></td>
</tr>
<tr>
<td>$J_1(t)u(t)/t + 2u(t) \leftrightarrow \sqrt{s^2 + 1} + s = e^{\sinh^{-1}(s)}$</td>
<td></td>
</tr>
<tr>
<td>$\delta(t) + J_1(t)u(t)/t \leftrightarrow \sqrt{s^2 + 1}$</td>
<td></td>
</tr>
<tr>
<td>$I_0(t)u(t) \leftrightarrow 1/\sqrt{s^2 - 1}$</td>
<td></td>
</tr>
<tr>
<td>$u(t)/\sqrt{t + 1} \leftrightarrow e^{s} \frac{\pi}{s} \text{erfc}(\sqrt{s})$</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{t}u(t) * \sqrt{1 + tu(t)} \leftrightarrow e^{s/2} K_1(s/2)/2s$</td>
<td></td>
</tr>
</tbody>
</table>
Methods for automating the calculation of residues

In this appendix we shall set up the general problem of finding $K_k$ given Eq. 3.12 (Gustavsen and Semlyen, 1999).

$$Z(s) = \frac{N(s)}{D(s)} = \frac{sL_o + R_o + \sum_{k=0}^{K} K_k}{s - s_k},$$

(B.1)
given the roots $s_k$ of polynomial $D(s) = \prod_{k=1}^{K}(s - s_k) = 0$.

1. First discuss the general properties of $Z(s) = K_{-1}s + K_0 + \sum_{k=1}^{K} K_k s - s_k$.

Exercise: The impedance may be written as

$$Z(s) = \frac{N(s)}{D(s)} = \sum_{m} m s^m \sum_{k} d_k s^k.$$

Thus the companion matrix for the numerator polynomial $N(s)$ is

$$Z_N = \begin{bmatrix} -d_{N-1} & d_{N-2} & \cdots & \cdots & -d_0 \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix},$$

(B.2)

thus numerator polynomial of $Z(s)$ is $N(s) = |Z_N - sI_N|$.

The companion matrix for the denominator polynomial $D(s)$ is

$$Y_N = \begin{bmatrix} -n_{N-1} & n_{N-2} & \cdots & \cdots & -n_0 \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix},$$

(B.3)

while the denominator polynomial of $Z(s)$ is $D(s) = |Y_N - sI_N|$.

2. Note that these equations need to include the determination of unknowns $L_o$ and $R_o$, which in some cases will be zero.

3. Next transform the residue expansion into its companion matrix (Sect. 3.1.3, Eq. 3.17 p. 81). By definition, the eigenvalues of the companion matrix are the same as the roots of the impedance matrix.

4. Matlab/Octave provides a general method to find the residue expansions of an impedance based on the method of Gustavsen and Semlyen (1999).

5. This method has close ties to the classic CFA, where it has been called the Cauer decomposition, named after its inventor Wilhelm Cauer (Cauer and Mathis, 1995; Cauer et al., 2000; Cauer, 1958; Cauer et al., 1958), who acted as the primary thesis advisor for Brune (Brune, 1931b; Van Valkenburg, 1964b).
Appendix C

Matrix algebra: Systems

C.1 Vectors

Vectors as columns of ordered sets of scalars \( \in \mathbb{C} \). When we write them out in text, we typically use row notation, with the transpose symbol:

\[
[a, b, c]^T = \begin{bmatrix} a \\ b \\ c \end{bmatrix}.
\]

This is strictly to save space on the page. The notation for conjugate transpose is \( \dagger \), for example

\[
\begin{bmatrix} a \\ b \\ c \end{bmatrix}^\dagger = \begin{bmatrix} a^* \\ b^* \\ c^* \end{bmatrix}.
\]

The above example is said to be a 3-dimensional vector because it has three components.

**Row vs. column vectors:** With rare exceptions, vectors are columns, denoted *column-major*.\(^1\) To avoid confusion, it is a good rule to make your mental default column-major, in keeping with most signal processing (vectorized) software.\(^2\) Column vectors are the unstated default of Matlab/Octave, only revealed when matrix operations are performed. The need for the column (or row) major is revealed as a consequence of efficiency when accessing long sequences of numbers from computer memory. For example, when forming the sum of many numbers using the Matlab/Octave command \( \text{sum}(A) \), where \( A \) is a matrix, by default Matlab/Octave operates on the columns, returning a row vector of column sums. Specifically,

\[
\text{sum}\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} = [4, 6].
\]

If the data were stored in “row-major” order, the answer would have been the column vector \( \begin{bmatrix} 3 \\ 7 \end{bmatrix} \).

**Scalar products:** A vector *dot product* is defined to weight vector elements before summing them, resulting in a scalar. The transpose of a vector (a *row-vector*) is typically used as a *scale factor* (i.e., weights) on the elements of a vector. Scalar products (aka dot products) play an important role in vector algebra and calculus. For example,

\[
\begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix}^T = \begin{bmatrix} 1 & 2 & -1 \\ 2 \\ 3 \end{bmatrix} = 1 + 2 \cdot 2 - 3 = 2.
\]

\(^1\)https://en.wikipedia.org/wiki/Row-_and_column-major_order

\(^2\)In contrast, reading words in English is ‘row-major.’
A more interesting example is
\[
\begin{bmatrix}
1 \\
2 \\
4 \\
\end{bmatrix} 
\cdot 
\begin{bmatrix}
1 \\
s \\
s^2 \\
\end{bmatrix} = 
\begin{bmatrix}
1 \\
2 \\
4 \\
\end{bmatrix}^T 
\begin{bmatrix}
1 \\
1 \\
s \\
\end{bmatrix} = 
\begin{bmatrix}
1 \\
2 \\
4 \\
\end{bmatrix} 
\begin{bmatrix}
1 \\
s \\
s^2 \\
\end{bmatrix} = 1 + 2s + 4s^2.
\]

**Scalar product:** The scalar product in polar coordinates is
\[
B \cdot C = \|B\| \|C\| \cos(\theta),
\]
where \(\cos(\theta)\) is called the direction cosine between \(B\) and \(C\).

**Norm of a vector:** The norm of a vector is the dot product of it with itself
\[
\|A\| = \sqrt{A \cdot A} \geq 0,
\]
forming the Euclidean length of the vector.

**Euclidean distance between two points in \(\mathbb{R}^3\):** The dot product of the difference between two vectors
\[
(A - B) \cdot (A - B)
\]
is the Euclidean distance between the points they define
\[
\|A - B\| = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2}.
\]

**Triangle inequality**
\[
\|A + B\| = \sqrt{(a_1 + b_1)^2 + (a_2 + b_2)^2 + (a_3 + b_3)^2} \leq \|A\| + \|B\|.
\]

**Vector product:** The vector product (aka cross product) \(A \times B = \|A\| \|B\| \sin(\theta)\) is defined between the two vectors \(A\) and \(B\). In Cartesian coordinates
\[
A \times B = \det
\begin{vmatrix}
\hat{x} & \hat{y} & \hat{z} \\
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_3
\end{vmatrix}.
\]

**The triple product:** This is defined between three vectors as
\[
A \cdot (B \times C) = \det
\begin{vmatrix}
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_3 \\
c_1 & c_2 & c_3
\end{vmatrix},
\]
also defined in Fig. ???. This may be indicated without the use of parentheses, since there can be no other meaningful interpretation. However for rigor, parentheses should be used. The triple product is the volume of the parallelepiped (3D-crystal shape) outlined by the three vectors, shown in Fig. ??, p. 206.

**Dialects of vector notation:** Physical fields are, by definition, functions of space \(x\) [m], and in the most general case, time \(t\) [s]. When Laplace transformed, the fields become functions of space and complex frequency (e.g., \(E(x, t) \leftrightarrow E(x, s)\)). As before, there are several equivalent vector notations.

For example, \(E(x, t) = \begin{bmatrix} E_x, & E_y, & E_z \end{bmatrix}^T = E_x(x, t)\hat{x} + E_y(x, t)\hat{y} + E_z(x, t)\hat{z}\) is “in-line,” to save space. The same equation may written in “displayed” notation as:
\[
E(x, t) = \begin{bmatrix}
E_x(x, t) \\
E_y(x, t) \\
E_z(x, t)
\end{bmatrix} = \begin{bmatrix}
E_x \\
E_y \\
E_z
\end{bmatrix}(x, t) = \begin{bmatrix} E_x, & E_y, & E_z \end{bmatrix}^T = E_x\hat{x} + E_y\hat{y} + E_z\hat{z}.
\]

Note the three notations for vectors, bold font, element-wise columns, element-wise transposed rows and dyadic format. These are all shorthand notations for expressing the vector. Such usage is similar to a dialect in a language.
Complex elements: When the elements are complex (∈ ℂ), the transpose is defined as the complex conjugate of the elements. In such complex cases the transpose conjugate may be denoted with a † rather than T

\[
\begin{bmatrix}
-2j \\
3j \\
1
\end{bmatrix}^\dagger = \begin{bmatrix}
2j \\
-3j \\
1
\end{bmatrix} ∈ ℂ.
\]

For this case when the elements are complex, the dot product is a real number

\[
\mathbf{a} \cdot \mathbf{b} = a^\dagger \mathbf{b} = \begin{bmatrix}
a_1^* & a_2^* & a_3^*
\end{bmatrix}
\begin{bmatrix}
b_1 \\
b_2 \\
b_3
\end{bmatrix} = a_1^*b_1 + a_2^*b_2 + a_3^*b_3 ∈ ℜ.
\]

Norm of a vector: The dot product of a vector with itself is called the norm of \( \mathbf{a} \)

\[
||\mathbf{a}|| = \sqrt{\mathbf{a}^\dagger \mathbf{a}} ≥ 0.
\]

which is always non-negative.

Such a construction is useful when \( \mathbf{a} \) and \( \mathbf{b} \) are related by an impedance matrix

\[
\mathbf{V}(s) = \mathbf{Z}(s)\mathbf{I}(s)
\]

and we wish to compute the power. For example, the impedance of a mass is \( m \mathbf{s} \) and a capacitor is \( 1/\mathbf{s}C \). When given a system of equations (a mechanical or electrical circuit) one may define an impedance matrix.

Complex power: In this special case, the complex power \( \mathcal{P}(s) ∈ ℜ(s) \) is defined, in the complex frequency domain (s), as

\[
\mathcal{P}(s) = \mathbf{I}^\dagger(s)\mathbf{V}(s) = \mathbf{I}^\dagger(s)\mathbf{Z}(s)\mathbf{I}(s) ↔ p(t) \quad [W].
\]

The real part of the complex power must be positive. The imaginary part corresponds to available stored energy.

The case of three-dimensions is special, allowing definitions that are not easily defined in more than three dimensions. A vector in \( \mathbb{R}^3 \) labels the point having the coordinates of that vector.

C.2 Matrices

When working with matrices, the role of the weights and vectors can change, depending on the context. A useful way to view a matrix is as a set of column vectors, weighted by the elements of the column-vector of weights multiplied from the right. For example

\[
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1M} \\
a_{21} & a_{22} & a_{23} & \cdots & a_{2M} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{N1} & a_{N2} & a_{N3} & \cdots & a_{NM}
\end{bmatrix}
\begin{bmatrix}
w_1 \\
w_2 \\
\vdots \\
w_M
\end{bmatrix} = \begin{bmatrix}
a_{11} & a_{12} & a_{13} & \cdots & a_{1M} \\
a_{21} & a_{22} & a_{23} & \cdots & a_{2M} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
a_{N1} & a_{N2} & a_{N3} & \cdots & a_{NM}
\end{bmatrix}
\begin{bmatrix}
w_1 \\
w_2 \\
\vdots \\
w_M
\end{bmatrix} = w_1 \begin{bmatrix}
a_{11} \\
a_{21} \\
\vdots \\
a_{N1}
\end{bmatrix} + w_2 \begin{bmatrix}
a_{12} \\
a_{22} \\
\vdots \\
a_{N2}
\end{bmatrix} + \cdots + w_M \begin{bmatrix}
a_{1M} \\
a_{2M} \\
\vdots \\
a_{NM}
\end{bmatrix},
\]

where the weights are \( [w_1, w_2, \ldots, w_M]^T \). Alternatively, the matrix is a set of row vectors of weights, each of which is applied to the column vector on the right \( ([w_1, w_2, \cdots, W_M]^T) \).

The determinant of a matrix is denoted either as det \( \mathbf{A} \) or simply \( |\mathbf{A}| \) (as in the absolute value). The inverse of a square matrix is \( \mathbf{A}^{-1} \) or inv \( \mathbf{A} \). If \( |\mathbf{A}| = 0 \), the inverse does not exist. \( \mathbf{A} \mathbf{A}^{-1} = \mathbf{A}^{-1} \mathbf{A} \).
Matlab/Octave’s notional convention for a row-vector is \([a, b, c]\) and a column-vector is \([a; b; c]\). A prime on a vector takes the complex conjugate transpose. To suppress the conjugation, place a period before the prime. The : argument converts the array into a column vector, without conjugation. A tacit prime on a vector takes the complex conjugate transpose. To suppress the conjugation, place a period before the prime. Matlab defines the notation \(1:4\) as the “row-vector” [1, 2, 3, 4], which is unfortunate as it leads users to assume that the default vector is a row. This can lead to serious confusion later, as Matlab’s default vector is a column. I have not found the above convention explicitly stated, and it took me years to figure this out for myself.

When writing a complex number we shall adopt the notation \(1 + 0i\). In matrix notation, this is typically represented as a single row \([1, 0]\). Ex: \(\sin(\pi) = e^{i\pi/2}\).

### C.2.1 2x2 matrices

**Definitions:**

1. **Scalar:** A number, e.g. \(\{a, b, c, \alpha, \beta, \cdots\} \in \{\mathbb{Z}, \mathbb{Q}, \mathbb{I}, \mathbb{R}, \mathbb{C}\}\)

2. **Vector:** A quantity having direction as well as magnitude, often denoted by a bold-face letter with an arrow, \(\mathbf{x}\). In matrix notation, this is typically represented as a single row \([x_1, x_2, x_3, \ldots]\) or single column \([x_1, x_2, x_3, \ldots]^T\) (where \(T\) indicates the transpose). In this class we will typically use column vectors. The vector may also be written out using unit vector notation to indicate direction. For example: \(x_{3 \times 1} = x_1 \hat{x} + x_2 \hat{y} + x_3 \hat{z} = [x_1, x_2, x_3]^T\), where \(\hat{x}, \hat{y}, \hat{z}\) are unit vectors in the \(x, y, z\) Cartesian directions (here the vector’s subscript \(3 \times 1\) indicates its dimensions). The type of notation used may depend on the engineering problem you are solving.

3. **Matrix:** \(A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1M} \\ a_{21} & a_{22} & \cdots & a_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NM} \end{bmatrix}_{N \times M}\) can be a non-square matrix if the number of elements in each of the vectors (\(N\)) is not equal to the number of vectors (\(M\)). When \(M = N\), the matrix is square. It may be inverted if its determinant \(|A| = \prod \lambda_k \neq 0\) (where \(\lambda_k\) are the eigenvalues).

We shall only work with \(2 \times 2\) and \(3 \times 3\) square matrices throughout this course.

4. **Linear system of equations:** \(Ax = b\) where \(x\) and \(b\) are vectors and matrix \(A\) is a square.

(a) **Inverse:** The solution of this system of equations may be found by finding the inverse \(x = A^{-1}b\).

(b) **Equivalence:** If two systems of equations \(A_0x = b_0\) and \(A_1x = b_1\) have the same solution (i.e., \(x = A_0^{-1}b_0 = A_1^{-1}b_1\)), they are said to be equivalent.

(c) **Augmented matrix:** The first type of augmented matrix is defined by combining the matrix with the right-hand side. For example, given the linear system of equations of the form \(Ax = y\)

\[
\begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix},
\]

the augmented matrix is

\[
[A|y] = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}.
\]

A second type of augmented matrix may be used for finding the inverse of a matrix (rather than solving a specific instance of linear equations \(Ax = b\)). In this case the augmented matrix is

\[
[A|I] = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.
\]
Performing Gaussian elimination on this matrix, until the left side becomes the identity matrix, yields \( A^{-1} \). This is because multiplying both sides by \( A^{-1} \) gives \( A^{-1}A|A^{-1}I = I|A^{-1} \).

5. **Permutation matrix** \( (P) \): A matrix that is equivalent to the identity matrix, but with scrambled rows (or columns). Such a matrix has the properties \( \det(P) = \pm 1 \) and \( P^2 = I \). For the 2x2 case, there is only one permutation matrix:

\[
P = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad P^2 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.
\]

A permutation matrix \( P \) swaps rows or columns of the matrix it operates on. For example, in the 2x2 case, pre-multiplication swaps the rows

\[
PA = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} a & b \\ \alpha & \beta \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ a & b \end{bmatrix},
\]

whereas post-multiplication swaps the columns

\[
AP = \begin{bmatrix} a & b \\ \alpha & \beta \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} b & a \\ \beta & \alpha \end{bmatrix}.
\]

For the 3x3 case there are \( 3 \cdot 2 = 6 \) such matrices, including the original 3x3 identity matrix (swap a row with the other 2, then swap the remaining two rows).

6. **Gaussian elimination (GE) operations** \( G_k \): There are three types of elementary row operations, which may be performed without fundamentally altering a system of equations (e.g. the resulting system of equations is equivalent). These operations are (1) swap rows (e.g. using a permutation matrix), (2) scale rows, or (3) perform addition/subtraction of two scaled rows. All such operations can be performed using matrices.

For lack of a better term, we’ll describe these as ‘Gaussian elimination’ or ‘GE’ matrices.³ We will categorize any matrix that performs only elementary row operations (but any number of them) as a ‘GE’ matrix. Therefore, a cascade of GE matrices is also a GE matrix.

Consider the GE matrix

\[
G = \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}.
\]

(a) This pre-multiplication scales and subtracts row (1) from (2) and returns it to row (2).

\[
GA = \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} a & b \\ \alpha & \beta \end{bmatrix} = \begin{bmatrix} a & b \\ a - \alpha & b - \beta \end{bmatrix}.
\]

The shorthand for this Gaussian elimination operation is \( (1) \leftarrow (1) \) and \( (2) \leftarrow (1) - (2) \).

(b) Post-multiplication adds and scales columns.

\[
AG = \begin{bmatrix} a & b \\ \alpha & \beta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix} = \begin{bmatrix} a - b & b \\ \alpha - \beta & \beta \end{bmatrix}.
\]

Here the second column is subtracted from the first, and placed in the first. The second column is untouched. **This operation is not a Gaussian elimination.** Therefore, to put

³The term ‘elementary matrix’ may also be used to refer to a matrix that performs an elementary row operation. Typically, each elementary matrix differs from the identity matrix by one single row operation. A cascade of elementary matrices could be used to perform Gaussian elimination.
Gaussian elimination operations in matrix form, we form a cascade of **pre-multiply** matrices.

Here \( \det(G) = 1 \), \( G^2 = I \), which won’t always be true if we scale by a number greater than 1. For instance, if \( G = \begin{bmatrix} 1 & 0 \\ m & 1 \end{bmatrix} \) (scale and add), then we have \( \det(G) = 1 \), \( G^m = \begin{bmatrix} 1 \\ n \cdot m & 1 \end{bmatrix} \).

**Exercise:** Find the solution to the following 3x3 matrix equation \( Ax = b \) by Gaussian elimination. Show your intermediate steps. You can check your work at each step using Matlab.

\[
\begin{bmatrix}
1 & 1 & -1 \\
3 & 1 & 1 \\
1 & -1 & 4 \\
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
\end{bmatrix}
= 
\begin{bmatrix}
1 \\
9 \\
8 \\
\end{bmatrix}
\]

1. Show (i.e., verify) that the first GE matrix \( G_1 \), which zeros out all entries in the first column, is given by

\[
G_1 = \begin{bmatrix} 1 & 0 & 0 \\ -3 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}.
\]

Identify the elementary row operations that this matrix performs. **Solution:** Operate with GE matrix on \( A \)

\[
G_1[A|b] = \begin{bmatrix} 1 & 0 & 0 \\ -3 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & 1 \\ 1 & -1 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 9 \\ 8 \end{bmatrix} = \begin{bmatrix} 1 & 1 & -1 & 1 \\ 0 & -2 & 4 & 6 \\ 0 & -2 & 5 & 7 \end{bmatrix}.
\]

The second row of \( G_1 \) scales the first row by -3 and adds it to the second row

\( (2) \leftarrow -3(1) + (2) \).

The third row of \( G_1 \) scales the first row by -1 and adds it to the third row \( (3) \leftarrow -(1) + (3) \).

2. Find a second GE matrix, \( G_2 \), to put \( G_1A \) in upper triangular form. Identify the elementary row operations that this matrix performs. **Solution:**

\[
G_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix},
\]

or \( (2) \leftarrow -(2) + (3) \). Thus we have

\[
G_2G_1[A|b] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ -3 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 & -1 \\ 1 & 1 & 1 \\ 1 & -1 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 9 \\ 8 \end{bmatrix} = \begin{bmatrix} 1 & 1 & -1 & 1 \\ 0 & -2 & 4 & 6 \\ 0 & 0 & 1 & 1 \end{bmatrix}.
\]

3. Find a third GE matrix, \( G_3 \), which scales each row so that its leading term is 1. Identify the elementary row operations that this matrix performs. **Solution:**

\[
G_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/2 & 0 \\ 0 & 0 & 1 \end{bmatrix},
\]
which scales the second row by -1/2. Thus we have

\[
G_3G_2G_1[A|b] = \begin{bmatrix}
1 & 0 & 0 \\
0 & -1/2 & 0 \\
0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & -1 \\
0 & -2 & 4 \\
0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & -1 \\
0 & 1 & -2 \\
0 & 0 & 1 \\
\end{bmatrix}.
\]

4. Finally, find the last GE matrix, \( G_4 \), that subtracts a scaled version of row 3 from row 2, and scaled versions of rows 2 and 3 from row 1, such that you are left with the identity matrix \( G_4G_3G_2G_1A = I \). **Solution:**

\[
G_4 = \begin{bmatrix}
1 & -1 & -1 \\
0 & 1 & 2 \\
0 & 0 & 1 \\
\end{bmatrix}.
\]

Thus we have

\[
G_4G_3G_2G_1[A|b] = \begin{bmatrix}
1 & -1 & -1 \\
0 & 1 & 2 \\
0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
1 & 1 & -1 \\
0 & 1 & -2 \\
0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 3 \\
0 & 1 & -1 \\
0 & 0 & 1 \\
\end{bmatrix}.
\]

5. Solve for \([x_1, x_2, x_3]^T\) using the augmented matrix format \( G_4G_3G_2G_1[A|b] \) (where \([A|b]\) is the augmented matrix). Note that if you’ve performed the preceding steps correctly, \( x = G_4G_3G_2G_1b \).

**Solution:** From the preceding problems, we see that \([x_1, x_2, x_3]^T = [3, -1, 1]^T\).

---

**Inverse of the 2x2 matrix**

We shall now apply Gaussian elimination to find the solution \([x_1, x_2]\) for the 2x2 matrix equation \( Ax = y \) (Eq. 3.28, left). We assume to know \([a, b, c, d]\) and \([y_1, y_2]\). We wish to show that the intersection (solution) is given by the equation on the right.

Here we wish to prove that the left equation (i) has an inverse given by the right equation (ii):

\[
\begin{align*}
\begin{bmatrix}
a & b \\
c & d \\
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} &=
\begin{bmatrix}
y_1 \\
y_2 \\
\end{bmatrix} \quad \text{(i)}; \\
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} &=
\frac{1}{\Delta}
\begin{bmatrix}
d & -b \\
-c & a \\
\end{bmatrix}
\begin{bmatrix}
y_1 \\
y_2 \\
\end{bmatrix} \quad \text{(ii)}.
\end{align*}
\]

**How to take inverse:**

1) **Swap the diagonal, 2) change the signs of the off-diagonal, and 3) divide by \( \Delta \).**

**Derivation of the inverse of a 2x2 matrix**

1. Step 1: To derive (ii) starting from (i), normalize the first column to 1.

\[
\begin{bmatrix}
1 & \frac{b}{a} \\
1 & \frac{c}{a} \\
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{a} & 0 \\
\frac{1}{a} & \frac{1}{c} \\
\end{bmatrix}
\begin{bmatrix}
y_1 \\
y_2 \\
\end{bmatrix}.
\]

2. Step 2: Subtract row (1) from row (2): (2) \( \leftarrow (2)-(1) \)

\[
\begin{bmatrix}
1 & \frac{b}{a} - \frac{b}{a} \\
0 & \frac{c}{a} - \frac{c}{a} \\
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{a} & 0 \\
\frac{1}{c} & \frac{1}{c} \\
\end{bmatrix}
\begin{bmatrix}
y_1 \\
y_2 \\
\end{bmatrix}.
\]

3. Step 3: Multiply row (2) by \( ca \) and express result in terms of the determinate \( \Delta = ad - bc \).

\[
\begin{bmatrix}
1 & \frac{b}{a} \\
0 & \Delta \\
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{a} & 0 \\
\frac{1}{c} & \frac{1}{c} \\
\end{bmatrix}
\begin{bmatrix}
y_1 \\
y_2 \\
\end{bmatrix}.
\]
4. Step 4: Solve row (2) for $x_2$: $x_2 = -\frac{c}{\Delta}y_1 + \frac{a}{\Delta}y_2$.

5. Step 5: Solve row (1) for $x_1$:

$$x_1 = \frac{1}{a}y_1 - \frac{b}{a}x_2 = \left[\frac{1}{a} + \frac{b}{a\Delta}\right]y_1 - \frac{b}{a\Delta}y_2.$$ 

Rewriting in matrix format, in terms of $\Delta = ad - bc$, gives:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{a} + \frac{bc}{a\Delta} & -\frac{b}{a\Delta} \\ -\frac{c}{a\Delta} & \frac{b}{a\Delta} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} \Delta + bc & -b \\ -c & a \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix},$$

since $d = (\Delta + bc)/a$.

**Summary:** This is a lot of messy algebra, so this is why it is essential you memorize the final result: 1) Swap diagonal, 2) change off-diagonal signs, 3) normalize by $\Delta$. 
Appendix D

Eigenanalysis

Eigenanalysis is critical in engineering applications. It is useful in solving differential and difference equations, data-science applications, numerical approximation and computing, and linear algebra applications. Typically one must take a course in linear algebra to become knowledgeable in the inner workings of this method. In this appendix we provide sufficient basics to allow one to understand the fundamental, as needed in the text.

D.1 Calculating the eigenvalue matrix ($\Lambda$):

Given $2 \times 2$ matrix $A$, the related matrix eigen-equation is

$$AE = E\Lambda.$$  \hspace{1cm} (D.1)

Pre-multiplying by $E^{-1}$ diagonalizes $A$, resulting in the eigenvalue matrix

$$\Lambda = E^{-1}AE \hspace{1cm} (D.2)$$

$$= \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}. \hspace{1cm} (D.3)$$

Post-multiplying by $E^{-1}$ recovers $A$

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = E\Lambda E^{-1}. \hspace{1cm} (D.4)$$

Matrix product formula:

This last relation is the entire point of the eigenvector analysis, since it shows that any power of $A$ may be computed from powers of the eigenvalues. Specifically,

$$A^n = E\Lambda^n E^{-1}. \hspace{1cm} (D.5)$$

For example, $A^2 = AA = E\Lambda (E^{-1}E) \Lambda E^{-1} = E\Lambda^2E^{-1}$.

Equations D.1, D.3 and D.4 are the key to eigenvector analysis, and you need to memorize them. You will use them repeatedly throughout this course, and possibly for a long time after it is over.

Showing that $A - \lambda_{\pm}I_2$ is singular:

If we restrict Eq. D.1 to a single eigenvector (one of $e_{\pm}$), along with the corresponding eigenvalue $\lambda_{\pm}$, we obtain a matrix equations

$$Ae_{\pm} = e_{\pm}\lambda_{\pm} = \lambda_{\pm}e_{\pm}.$$
APPENDIX D. EIGENANALYSIS

Note the swap in the order of $E_\pm$ and $\lambda_\pm$. Since $\lambda_\pm$ is a scalar, this is legal (and critically important), since this allows us to factor out $e_\pm$

$$ (A - \lambda_\pm I_2)e_\pm = 0. \quad (D.6) $$

The matrix $A - \lambda_\pm I_2$ must be singular because when it operates on $e_\pm$, having nonzero norm, it must be zero.

It follows that its determinant (i.e., $|(A - \lambda_\pm I_2)| = 0$) must be zero. This equation uniquely determines the eigenvalues $\lambda_\pm$.

D.2 Calculating the eigenvalues $\lambda_\pm$:

The eigenvalues $\lambda_\pm$ of $A$ may be determined from $|(A - \lambda_\pm I_2)| = 0$. As an example we let $A$ be Pell’s equation (Eq. 2.13, p. 61). In this case the eigenvalues may be found from

$$ \begin{vmatrix} 1 - \lambda_\pm & N \\ 1 & 1 - \lambda_\pm \end{vmatrix} = (1 - \lambda_\pm)^2 - N^2 = 0. $$

For our case of $N = 2$, $\lambda_\pm = (1 \pm \sqrt{2})$.\(^1\)

D.3 Calculating the eigenvectors $e_\pm$:

Once the eigenvalues have been determined, they are substituted into Eq. D.6, which determines the eigenvectors $E = [e_+, e_-]$, by solving

$$ (A - \lambda_\pm) e_\pm = \begin{bmatrix} 1 - \lambda_\pm & 2 \\ 1 & 1 - \lambda_\pm \end{bmatrix} e_\pm = 0, \quad (D.7) $$

where $1 - \lambda_\pm = 1 - (1 \pm \sqrt{2}) = \mp \sqrt{2}$.

Recall that Eq. D.6 is singular because we are using an eigenvalue, and each eigenvector is pointing in a unique direction (this is why it is singular). You might expect that this equation has no solution. In some sense you would be correct. When we solve for $e_\pm$, the two equations defined by Eq. D.6 are co-linear (the two equations describe parallel lines). This follows from the fact that there is only one eigenvector for each eigenvalue.

Expecting trouble, yet proceeding to solve for $e_+ = [e_1^+, e_2^+]^T$,

$$ \begin{bmatrix} -\sqrt{2} & 2 \\ 1 & -\sqrt{2} \end{bmatrix} \begin{bmatrix} e_1^+ \\ e_2^+ \end{bmatrix} = 0. $$

This gives two identical equations $-\sqrt{2}e_1^+ + 2e_2^+ = 0$ and $e_1^+ - \sqrt{2}e_2^+ = 0$. This is the price of an over-specified equation (the singular matrix is degenerate). The most we can determine is $e_+ = c [-\sqrt{2}, 1]^T$, where $c$ is a constant. We can determine eigenvector direction, but not its magnitude.

Following exactly the same procedure for $\lambda_-$, the equation for $e_-$ is

$$ \begin{bmatrix} \sqrt{2} & 2 \\ 1 & \sqrt{2} \end{bmatrix} \begin{bmatrix} e_1^- \\ e_2^- \end{bmatrix} = 0. $$

In this case the relation becomes $e_1^- + \sqrt{2}e_2^- = 0$, thus $E_- = c [\sqrt{2}, 1]^T$ where $c$ is a constant.

\(^1\)It is a convention to order the eigenvalues from largest to smallest.
D.3.1 Normalization of the eigenvectors:
The constant $c$ may be determined by normalizing the eigenvectors to have unit length. Since we cannot determine the length, we set it to 1. In some sense the degeneracy is resolved by this normalization. Thus $c = 1/\sqrt{3}$, since
\[
(\pm \sqrt{2})^2 + 1^2 = 3 = 1/c^2.
\]

D.4 Summary:
Thus far we have shown
\[
E = [e_+, e_-] = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\sqrt{2} \\ 1 & 1 \end{bmatrix}
\]
and
\[
\Lambda = \begin{bmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{bmatrix} = \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix}.
\]

Exercise: Verify that $\Lambda = E^{-1}AE$. Solution: To find the inverse of $E$, 1) swap the diagonal values, 2) change the sign of the off diagonals, and 3) divide by the determinant $\Delta = 2\sqrt{2}/\sqrt{3}$ (see Appendix C).
\[
E^{-1} = \frac{\sqrt{3}}{2\sqrt{2}} \begin{bmatrix} 1 & \sqrt{2} \\ -1 & \sqrt{2} \end{bmatrix} = \begin{bmatrix} 0.6124 & 0.866 \\ -0.6124 & 0.866 \end{bmatrix}.
\]

By definition for any matrix $E^{-1}E = EE^{-1} = I_2$. Taking the product gives
\[
E^{-1}E = \frac{\sqrt{3}}{2\sqrt{2}} \begin{bmatrix} 1 & \sqrt{2} \\ -1 & \sqrt{2} \end{bmatrix} \cdot \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\sqrt{2} \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I_2.
\]

We wish to show that $\Lambda = E^{-1}AE$
\[
\begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \cdot \frac{\sqrt{3}}{2\sqrt{2}} \begin{bmatrix} 1 & \sqrt{2} \\ -1 & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \cdot \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\sqrt{2} \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & \sqrt{2} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & \sqrt{2} \\ -\sqrt{2} & 1 \end{bmatrix},
\]
which is best verified with Matlab.

Exercise: Verify that $A = E\Lambda E^{-1}$. Solution: We wish to show that
\[
\begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\sqrt{2} \\ 1 & 1 \end{bmatrix} \cdot \left[ \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \cdot \frac{\sqrt{3}}{2\sqrt{2}} \begin{bmatrix} 1 & \sqrt{2} \\ -1 & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \cdot \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\sqrt{2} \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & \sqrt{2} \\ -\sqrt{2} & 1 \end{bmatrix} \right],
\]
All the above equations have been verified with Octave.

Eigenmatrix diagonalization is helpful in generating solutions for finding the solutions of Pell’s and Fibonacci’s equations using transmission matrices.

Example: If the matrix corresponds to the delay on a transmission line, the eigenvalues are delays
\[
\begin{bmatrix} V^+ \\ V^- \end{bmatrix}_n = e^{-st_o} \begin{bmatrix} 1 & 0 \\ 0 & e^{st_o} \end{bmatrix} \begin{bmatrix} V^+ \\ V^- \end{bmatrix}_{n+1}.
\]

(D.8)
In the time domain the forward traveling wave $v_{n+1}^+(t - (n + 1)T_o) = v_n^+(t - nT_o)$ is delayed by $T_o$. Two applications of the matrix delays the signal by $2T_o$. 

Eigenmatrix diagonalization is helpful in generating solutions for finding the solutions of Pell’s and Fibonacci’s equations using transmission matrices.
Appendix E

Symbolic analysis of $TE = E \Lambda$

E.1 General case

Here we assume

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

with $\Delta_T = 1$.

The eigenvectors $e_{\pm}$ of $T$ are

$$e_{\pm} = \left( \frac{1}{2} \left[ (A - D) \mp \sqrt{(A - D)^2 + 4BC} \right] \right)$$

and eigenvalues are

$$\lambda_{\pm} = \frac{1}{2} \left( (A + D) - \sqrt{(A + D)^2 - 4AD} \right).$$

E.1.1 Case of the Transmission matrix:

For the case of the ABCD matrix the eigenvalues depend on reciprocity, since $\Delta_T = 1$ if $T(s)$ is reciprocal, and $\Delta_T = -1$ if it is anti-reciprocal. Thus it is helpful to display the eigenfunctions and values in terms of $\Delta_T$ so this distinction is explicit.

The term under the radical (i.e., the discriminant) may be rewritten in terms of the determinant of $T$ (i.e., $\Delta_T = AD - BC$), since

$$(A - D)^2 - (A + D)^2 = -4AD.$$ 

The for the ABCD matrix the expression under the radical becomes

$$(A - D)^2 + 4BC = A^2 + D^2 - 4AD + 4BC = A^2 + D^2 - 4\Delta_T.$$ 

Rewriting the eigenvectors and eigenvalues in terms of $\Delta_T$ we find

$$e_{\pm} = \left( \frac{1}{2\Delta_T} \left[ (A - D) \mp \sqrt{(A + D)^2 - 4\Delta_T} \right] \right)$$

and eigenvalues are

$$\lambda_{\pm} = \frac{1}{2} \left( (A + D) - \sqrt{(A + D)^2 - 4\Delta_T} \right).$$
For the reversible transmission matrix:

When \( A = D \) the transmission matrix is said to be reversible, thus

\[
\lambda_{\pm} = \left[ \begin{array}{c} A - \sqrt{BC} \\ A + \sqrt{BC} \end{array} \right].
\]

(E.5)

**Example:** An application of the above results may be found in the Train problem (p. 179).

### E.2 Special cases having symmetry

Each 2x2 matrix has four entries, each of which can be complex. This leads to 4x2=8 possible special symmetries (an eight-fold way), discussed next, in quasi-order of their importance. Each symmetry is related to properties of \( T \). For example if \( T = T^\dagger \), the matrix is said to have Hermitian symmetry. When \( T = T^T \) the matrix is symmetric, and when \( T = -T^T \) is said to be skew-symmetric. Each of these eight-fold symmetries corresponds to some sort of physical constraint, as discussed below.

#### E.2.1 Reversible systems

When the values of \( T \) on its diagonal are equal (\( A = D \)), the matrix is called reversible, and the eigenvectors and eigenvalues greatly simplify to

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = \begin{bmatrix}
-\sqrt{\frac{B}{C}} \\
\frac{1}{C}
\end{bmatrix}, \quad \Lambda = \begin{bmatrix}
A - \sqrt{BC} & 0 \\
0 & A + \sqrt{BC}
\end{bmatrix}.
\]

(E.6)

**Reversibility** (P7) is a common symmetry. Its utility is in describing transmission lines as discussed in Sections 3.5 (p. 119), ?? and 4.5.5 (pp ??.-178).

#### E.2.2 Reciprocal systems

When the matrix is symmetric (\( B = C \)), the corresponding system is said to be reciprocal. Most physical systems are reciprocal. The determinant of the transmission matrix of a reciprocal network \( \Delta_T = AD - BC = 1 \). For example, electrical networks composed of inductors, capacitors and resistors are always reciprocal. It follows that the complex impedance matrix is symmetric (Van Valkenburg, 1964a).

Magnetic systems such as dynamic loudspeakers are anti-reciprocal, and correspondingly \( \Delta_T = -1 \). The impedance matrix of a loudspeaker is skew symmetric (Kim and Allen, 2013). All impedance matrices are either symmetric or anti-symmetric, depending on whether they are reciprocal (LRC networks) or anti-reciprocal (magnetic networks). These systems have complex eigenvalues with negative real parts, corresponding to lossy systems. In some sense, all of this follows from conservation of energy, but the precise general case is waiting for enlightenment. The impedance matrix is never Hermitian. It is easily proved that Hermitian matrices have real eigenvalues, which correspond to lossless networks. Any physical system of equations that has any type of loss cannot be Hermitian.

In summary, given a reciprocal system, the \( T \) matrix has \( \Delta_T = 1 \), and the corresponding impedance matrix is symmetric (*not* Hermitian).

### E.3 Impedance matrix

As previously discussed in Section 3.5 (p. 119), the \( T \) matrix corresponding to an impedance matrix is

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = \begin{bmatrix}
Z(s) \\
1
\end{bmatrix} \begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} = \begin{bmatrix}
1 & \Delta_T \\
\frac{1}{C} & D
\end{bmatrix} \begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}.
\]
Reciprocal systems have skew-symmetric impedance matrices, namely \( z_{12} = -z_{21} \). When the system is both reversible \( A = D \) and reciprocal, the impedance matrix simplifies to

\[
Z(s) = \frac{1}{C} \begin{bmatrix} A & 1 \\ 1 & A \end{bmatrix}.
\]

For such systems there are only two degrees of freedom, \( A \) and \( C \). As discussed previously in Sect. 3.5 (p. 119), each of these has a physical meaning: \( 1/A \) is the Thévenin source voltage given a voltage drive and \( B/C \) is the Thévenin impedance.

### E.3.1 Transmission matrices and symmetry

The transmission matrix fully characterizes a two-port network (Sect. 3.5, p. 119).

### E.3.2 Hermitian symmetry

When a system is Hermitian its matrix is conjugate symmetric

\[
Z(s) = Z^\dagger(s),
\]

a stronger condition than reciprocal, but not the symmetric symmetry of a Brune impedance matrix. Impedance is not Hermitian unless the diagonal elements are real, but it does have symmetric symmetry.

In the case of a Hermitian matrix, the eigenvalues are always real. To show this start from the definition of an impedance eigen-equation (\( V \) is a vector of voltages, \( I \) a current vector and \( Z \) an impedance matrix)

\[
V = ZI = IA,
\]

where \( Z, I, V, A \in \mathbb{C}, A = A^\dagger \) is a square conjugate-symmetric matrix, and \( I, V \) are vectors of the size of \( Z \). Here \( Z^\dagger \) is the complex transpose (see Appendix A, p. 255). The power \( P \) is the real part of the voltage times the current

\[
2P = V^\dagger I + VI^\dagger = (ZI)^\dagger I + ZII^\dagger = I^\dagger Z^\dagger I + ZII^\dagger.
\]

Subtracting the two equations gives . . . .

### E.3.3 Double roots

For the 2x2 case of double roots the matrix has Jordan form

\[
T = \begin{bmatrix} \lambda & 1 \\ 0 & \lambda \end{bmatrix}.
\]

Then

\[
T^n = \begin{bmatrix} \lambda^n & n\lambda^{n-1} \\ 0 & \lambda^n \end{bmatrix}.
\]

This generalizes to \( n \times n \) matrices having arbitrary combinations of degeneracies (multiple roots), as in symmetric (square) drums, for example . . . .

### Octave vs. Matlab seeming conflict

Using Octave (version 4.2.2, June 21, 2018):

\[
e_{1,1} = \frac{-b}{\frac{a}{2} - \frac{d}{2} + \frac{1}{2} \sqrt{a^2 - 2ad + 4bc + d^2}} = \frac{-2b}{(a-d) + \sqrt{(a-d)^2 + 4bc}}.
\]
This looks very different from the Matlab output (above).

Here is what I get with the same command, from Matlab (June 21, 2018):

$$e_{1,1} = \frac{a + d}{2} - \frac{\sqrt{a^2 - 2ad + d^2 + 4bc}}{2} = \frac{1}{2c} \left[ (a - d) - \sqrt{(a - d)^2 + 4bc} \right].$$

Here we derive the eigenmatrix $E$, and eigenvalue matrix $\Lambda$ given a 2x2 transmission matrix

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix},$$

such that $TE = EA$, using symbolic algebra methods, given by the Matlab/Octave’s script

```matlab
syms A B C D T E L %Use symbolic Matlab/Octave
T = [A B; C D] %Given matrix T
[E,L] = eig(T) %Find eigenvector matrix E and eigenvalue matrix L
```

These results have been numerically verified to be the same using CkEig.m. Conclusions from the numerical experiment with $(A = [1, 2; 3, 5])$ are:

1. The Octave and Matlab symbolic formulas give the same numeric results for eigenmatrix and eigenvalues.
2. The symbolic and numeric results correctly diagonalize the matrix, that is $\Gamma = E^{-1}AE$.
3. The numeric equations are normalized to 1: $\text{norm}(e_\pm) = 1$.
4. The symbolic Eigenvectors are not normalized to 1, rather $E(2,:) = 1$.
5. When the numeric result is normalized by the lower element (making it 1) all results agree.
Appendix F

Analysis of Pell equation (N=2, 3, M)

Section ?? (p. ??) showed that the solution \([x_n, y_n]^T\) to Pell’s equation, for \(N = 2\), is given by powers of Eq. 2.12. To find an explicit formula for \([x_n, y_n]^T\), one must compute powers of

\[
A = 1_j \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}.
\]  

We wish to find the solution to Pell’s equation (Eq. 2.12), based on the recursive solution, Eq. 2.13 (p. 61). Thus we need powers of \(A\), that is \(A^n\), which gives a closed form expression for \([x_n, y_n]^T\). By the diagonalization of \(A\), its powers are simply the powers of its eigenvalues. This diagonalization is called an eigenvalue analysis, a very general method rooted in linear algebra. This type of analysis allows us to find the solution to most of the linear the equations we encounter.

From Matlab/Octave with \(N = 2\) the eigenvalues of Eq. F.1 are \(
\lambda \pm \approx [2.4142, -0.4142] \) (i.e., \(\lambda \pm = 1_j(1 \pm \sqrt{2})\)). The final solution to Eq. F.1 is given in Eq. ?? (p. ??). The solution for \(N = 3\) is provided in Appendix F.1.1 (p. 270).

Once the matrix has been diagonalized, one may compute powers of that matrix as powers of the eigenvalues. This results in the general solution given by

\[
\begin{bmatrix} x_n \\ y_n \end{bmatrix} = 1_j^n A^n \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 1_j^n E \Lambda^n E^{-1} \begin{bmatrix} 1 \\ 0 \end{bmatrix}.
\]

The eigenvalue matrix \(D\) is diagonal with the eigenvalues sorted, largest first. The Matlab/Octave command \([E, D]=eig(A)\) is helpful to find \(D\) and \(E\) given any \(A\). As we saw above,

\[
\Lambda = 1_j \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \approx \begin{bmatrix} 2.4142 & 0 \\ 0 & -0.4142 \end{bmatrix}.
\]

F.1 Pell equation eigenvalue-eigenvector analysis

Here we show how to compute the eigenvalues and eigenvectors for the 2x2 Pell matrix for \(N = 2\)

\[
A = \begin{bmatrix} 1 & 2 \\ 1 & 1 \end{bmatrix}.
\]

The Matlab/Octave command \([E, D]=eig(A)\) returns the eigenvector matrix \(E\)

\[
E = [e_+, e_-] = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} \\ 1 \end{bmatrix} - \frac{\sqrt{2}}{1} = \begin{bmatrix} 0.8165 & -0.8165 \\ 0.5774 & 0.5774 \end{bmatrix}
\]

and the eigenvalue matrix \(\Lambda\) (Matlab/Octave’s \(D\))

\[
\Lambda \equiv \begin{bmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{bmatrix} = \begin{bmatrix} 1 + \sqrt{2} & 0 \\ 0 & 1 - \sqrt{2} \end{bmatrix} \approx \begin{bmatrix} 2.4142 & 0 \\ 0 & -0.4142 \end{bmatrix}.
\]
The factor $\sqrt{3}$ on $E$ normalizes each eigenvector to 1 (i.e., Matlab/Octave’s command `norm([\sqrt{2}, 1])` gives $\sqrt{3}$).

In the following discussion we show how to determine $E$ and $D$ (i.e., $\Lambda$), given $A$.

Table F.1: Summary of the solution of Pell’s equation due to the Pythagoreans using matrix recursion, for the case of $N=3$. The integer solutions are shown on the right. Note that $x_n/y_n \to \sqrt{3}$, in agreement with the Euclidean algorithm. The Matlab/Octave program for generating this data is `PellSol3.m`. It seems likely that the powers of $\beta_0$ could be absorbed in the starting solution, and then be removed from the recursion.

### Pell’s Equation for $N = 3$

**Case of $N = 3$ & $[x_0, y_0]^T = [1, 0]^T$, $\beta_0 = j/\sqrt{2}$**

Note: $x_n^2 - 3y_n^2 = 1$, $x_n/y_n \to \sqrt{3}$

\[
\begin{align*}
[x_1] &= \beta_0 \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} = \beta_0 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (\beta_0)^2 - 3\beta_0^2 = 1 \\
[y_1] &= 1 \\
[x_2] &= \beta_0^2 \begin{bmatrix} 4 & 2 \\ 2 & 1 \end{bmatrix} = \beta_0^2 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (4\beta_0^2)^2 - 3\left(2\beta_0^2\right)^2 = 1 \\
[y_2] &= \beta_0^3 \begin{bmatrix} 10 & 4 \\ 4 & 2 \end{bmatrix} = \beta_0^3 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (10\beta_0^3)^2 - 3\left(6\beta_0^3\right)^2 = 1 \\
[x_3] &= \beta_0^4 \begin{bmatrix} 28 & 16 \\ 16 & 6 \end{bmatrix} = \beta_0^4 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (28\beta_0^4)^2 - 3\left(16\beta_0^4\right)^2 = 1 \\
[y_3] &= \beta_0^5 \begin{bmatrix} 76 & 44 \\ 44 & 16 \end{bmatrix} = \beta_0^5 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (76\beta_0^5)^2 - 3\left(44\beta_0^5\right)^2 = 1 \\
[x_4] &= \beta_0^6 \begin{bmatrix} 210 & 136 \\ 136 & 88 \end{bmatrix} = \beta_0^6 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (210\beta_0^6)^2 - 3\left(136\beta_0^6\right)^2 = 1 \\
[y_4] &= \beta_0^7 \begin{bmatrix} 644 & 404 \\ 404 & 264 \end{bmatrix} = \beta_0^7 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (644\beta_0^7)^2 - 3\left(404\beta_0^7\right)^2 = 1 \\
[x_5] &= \beta_0^8 \begin{bmatrix} 1936 & 1252 \\ 1252 & 800 \end{bmatrix} = \beta_0^8 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (1936\beta_0^8)^2 - 3\left(1252\beta_0^8\right)^2 = 1 \\
[y_5] &= \beta_0^9 \begin{bmatrix} 6316 & 3976 \\ 3976 & 2512 \end{bmatrix} = \beta_0^9 \begin{bmatrix} 1 & 3 \\ 1 & 1 \end{bmatrix} \quad (6316\beta_0^9)^2 - 3\left(3976\beta_0^9\right)^2 = 1
\end{align*}
\]

**F.1.1 Pell’s equation for $N = 3$**

In Table F.1, Pell’s equation for $N = 3$ is given, with $\beta_0 = j/\sqrt{2}$. Perhaps try other trivial solutions such as $[-1, 0]^T$ and $[\pm j, 0]^T$, to provide clues to the proper value of $\beta_0$ for cases where $N > 3$.

**Exercise:** I suggest that you verify $E \Lambda \neq \Lambda E$ and $AE = E \Lambda$ with Matlab/Octave. Here is the Matlab/Octave program which does this:

```matlab
A = [1 2; 1 1]; % define the matrix
[E,D] = eig(A); % compute the eigenvector and eigenvalue matrices
A*E-E*D % This should be $\approx 0$, within numerical error.
E*D-D*E % This is not zero
```

\[1\] My student Kehan found the general formula for $\beta_n$.
Appendix G

Two theorems on primes

G.1 Theorem 1: Fundamental Theorem of Arithmetic

Factoring integers: Every integer \( n \in \mathbb{N} \) has a unique factorization (Stillwell, 2010, p. 43) (Eq. 2.6, p. 51).

Cofactors: Integers 2312 and 2313 are said to be coprime, since they have no common factors. Co-primes may be identified via the greatest common divisor:

\[
gcd(a, b) = 1
\]

using the Euclidean algorithm (Stillwell, 2010, p. 41).

G.2 Theorem 2: Prime Number Theorem

The primes are a random field since there is no way to predict when the next prime will occur. Thus one needs to use statistical methods to characterize their density. Based on a sample of approximately 3 million primes, Gauss showed, empirically, that the average total number of primes less than \( N \) is

\[
\sum_{n=1}^{N} \delta_n \sim \frac{N}{\ln N}.
\]  

(G.1)

These primes were obtained by manual calculations “as a pastime” in 1792-3 (Goldstein, 1973).

Define \( \delta_n = 1 \) if \( n \) is a prime, and zero otherwise.\(^1\)

It follows that the average density of primes is \( \rho_\pi(N) \sim 1/\ln N \). A Octave/Matlab program for displaying this is given in Fig. G.1

\[
\rho_\pi(N) = \frac{1}{N} \sum_{n=1}^{N} \delta_n \approx \frac{1}{N} \text{Li}(N) \approx \frac{1}{N} \int_{2}^{N} \frac{d\xi}{\ln \xi},
\]  

(G.2)

where \( \text{Li}(N) \) is the offset logarithmic integral (Stillwell, 2010, p. 585). The primes are distributed as \( 1/\ln(n) \) since the average total number of primes is proportional to the logarithmic integral \( \text{Li}(n) \) (Goldstein, 1973; Fine, 2007).

A Matlab/Octave code that tests this formula is given in Fig. G.1. A plot of cumsum(isprime(N)./(2:N)) has a slope, seemingly independent of my choice of \( N \).

From the Prime Number Theorem it is clear that the density of primes is large (they are not scarce). As best I know there are no methods to find primes other than by the sieve method (Section 2.3, p. 50). If

\[^1\text{You may display } \delta_n = \text{isprime}(1:100) \text{ for the first 100 numbers with the one-line Octave/Matlab command } \text{stem(isprime(1:100))}, \text{ and then compute } \rho_\pi(N) \text{ with } \text{cumsum(}\delta_n)\]
%Computes density of primes from average density
NP=1e6; % 10^6 primes
p=primes(NP); %compute primes
delta=zeros(1,NP); delta(p)=1; %put 1 at each prime
PI=cumsum(delta); %Number of primes vs N
rho=PI./(1:NP); %estimate of the density of primes= PI(N)./N

figure(1) %define a figure
semilogy(rho); %plot of density vs number of primes
title('Density of primes vs. N'); ylabel('rho(N)'); xlabel('N'); grid on

Figure G.1: Octave/Matlab program that computes $\rho_\pi(N)$ for the first million primes, and then plots it.

there is any good news it is that they only need to be computed once, and saved. In practical applications
this may not help much, given their large number. But I’m guessing, without any evidence, they could be
saved on a modern disk (e.g., 1 TB).

Not surprisingly, playing with primes has been a popular pastime of mathematicians. Perhaps this is
because those who have made inroads, providing improved understanding, have become famous.

G.3 RSA public-private keys

Internet security depends on a public-private key system, called RSA\textsuperscript{2} which is built on the difficulty of
factoring large primes. When a forward computation is easy, such as multiplying two primes, is easy,
and the inverse problem (factoring a product into two primes) is hard, it is called a trap door function.

What makes RSA work is a trap door. Internet security is not be as important as global warming, but
its pretty important. Global warming has no “end game.” Internet security does, redesign the internet.

Let’s consider the problem of factoring two primes, given the product $N = \pi_k \pi_l, k \neq l$. Let’s further
assume we have list of all the primes $\{\pi_1, ..., \pi_m\}$ including $N < \pi_m$. To factor $N$ we must divide $N$ by
each prime less than $N$. With intelligent sampling, on average, we would find the prime factor in $N/2$
tries. In theory, given primes $\pi_n$ up to $n = N$, the density $\rho_\pi(N)$ could help one search for a particular
prime of known size $N$, by estimating how many primes there are in the neighborhood of $N$. The cost
of factoring any integer $\in \mathbb{N}$ would be related to the magnitude of $N = \pi_k \pi_l$, where $N$ is the size of the
private key, assuming a simple product key. Worst case an exhaustive search would take $m - 1$ divides
of the form $N/\pi_k k = 1 \cdots m - 1$. If one knew approximately where the factor is $\in \mathbb{P}$ (i.e., $k$ of $\pi_k$), and
knows one of the primes, the search could be done with an exhaustive search, by addition. The number
of primes less that $N$ may be computed using Gauss’ formula for the density of primes.

So the question remains: How does internet security actually work? Unfortunately at this time I can
not give you a proper summary. But it is more complex than I have let on. The full answer requires a
proper course in number theory and internet security, beyond what can be presented.\textsuperscript{3} To save you the
trouble of looking up the method, it is quoted here\textsuperscript{4}

Setting up an RSA system involves choosing large prime numbers $p$ and $q$, computing
$n = pq$ and $k = \phi(n)$, and finding two numbers $e$ and $d$ such that $ed \equiv 1 \pmod{k}$. The
numbers $n$ and $e$ (the “encryption key”) are released to the public, and $d$ (the “decryption
key”) is kept private.

A message, represented by an integer $m$, where $0 < m < n$, is encrypted by computing
$S = me \pmod{n}$.

\textsuperscript{2}https://en.wikipedia.org/wiki/RSA_(cryptosystem)
\textsuperscript{3}https://en.wikipedia.org/wiki/RSA_(cryptosystem)#Operation
\textsuperscript{4}https://en.wikipedia.org/wiki/Euler%27s_totient_function#The_RSA_cryptosystem
It is decrypted by computing \( t = Sd \) (mod \( n \)). Euler’s Theorem can be used to show that if \( 0 < t < n \), then \( t = m \).

The security of an RSA system would be compromised if the number \( n \) could be factored or if \( \phi(n) \) could be computed without factoring \( n \).

The power of this security device is based on the relatively high density of primes \( \mathbb{P} \subset \mathbb{N} \), which is addressed by the Prime Number Theorem.

**Example:** The RSA public key is a string of characters representing a prime number \( \pi_{\text{pub}} \):

AAAAB3NzaC1yc2EAAAADAQABAAABAQCsyfp9uDXubR/ukXMpVgK2eEttQcJeEIMg6mC7qjRa2hrhFCV1+r9YSdqcKdkkefHL+

The RSA private key is a second string of characters, representing the product of prime numbers \( \pi_{\text{pri}} \):

MIIEpAIBAAKCAQEArMn6fbg17m0f7pFzKVYCTnHLbUHCKhCDIOpgu6oWto4Rldfq/W8enCn2JHNxhy/ynl1QGmk4RPetsu+

This much longer string of characters represents a second prime number \( \pi_{\text{pri}} \), the private key.

If I gave you the ASCII string that represents the product of the two prime numbers \( \pi_k \pi_l \), along with \( \pi_k \), can you find \( \pi_l \)? Yes, divide one by the other, with remainder zero. If I ask you to find \( \pi_l \) given \( \pi_k \pi_l \), you would need to call the NSA, or be some sort of expert on factoring primes. Given \( \pi_k, \pi_l \), for some large values of \( k \) and \( l \), the GCD is not helpful, nor the CF A. While the factoring can be done (it is not impossible), it is a very expensive calculation.

Why not use Matlab’s \( \text{factor}(N) \) routine to find the factors? This is where cost comes in. If the primes are large enough, even the NSA cannot do it in a lifetime. The numbers used in RSA are too large for Matlab’s routine to deliver an answer. In fact, even the largest computer in the world (such as the University of Illinois’ super computer (NCSA Water) cannot do this computation. But, for a carefully chose set of primes, not large for the NCSA to factor them, they can decrypt a message, but you cannot, because they encrypt the message. This is why they pay for these massive super-computers.

As best I know you need to try one prime at a time to see if the divisor gives you a zero remainder. There are no hints, such as \( l \approx k \). Nothing to help but to grind your way through all the known primes. And if the primes are too large to be to the list of all known all primes, you have to add the additional burden of generating a list of primes enough to contain the ones you are looking for. You can be sure that the NSA (or whoever has the fastest computer) has a longer list than you do, and its getting longer every day.

What you are given is the public key (prime \( \pi_{\text{pub}} \)) (the shorter one), and you need to guess the private key \( \pi_{\text{pri}} \) and decrypt the message I send you with the product \( \pi_{\text{pub}} \pi_{\text{pri}} \).
Appendix H

Greatest common divisor (GCD)

H.1 Division with rounding method:

We would like to show that the GCD for \( m, n, k \in \mathbb{N} \) (Eq. 2.7, p. 53) may be written in matrix as

\[
\begin{bmatrix} m \\ n \end{bmatrix}_{k+1} = \begin{bmatrix} 0 & 1 \\ -\frac{m}{n} & 1 \end{bmatrix} \begin{bmatrix} m \\ n \end{bmatrix}_k.
\]  

(H.1)

This implements \( \gcd(m,n) \) for \( m > n \).

This starts with \( k = 0, m_0 = a, n_0 = b \). With this method there is no need to test if \( n_n < m_n \), as it is built into the procedure. The method uses the floor function \( \lfloor x \rfloor \), which finds the integer part of \( x \) (\( \lfloor x \rfloor \) rounds toward \(-\infty\)). Following each step we will see that the value \( n_{k+1} < m_{k+1} \). The method terminates when \( n_{k+1} = 0 \) with \( \gcd(a,b) = m_{k+1} \).

Below is 1-line vectorized code that is much more efficient than the direct matrix method of Section H (p. 275):

```matlab
function n=gcd2(a,b)
M=[abs(a);abs(b)]; %Save (a,b) in array M(2,1)

%done when M(1) = 0
while M(1) ~= 0
    disp(sprintf('M(1)=%g, M(2)=%g ',M(1),M(2)));
    M=[M(2)-M(1)*floor(M(2)/M(1)); M(1)]; %automatically sorted
end %done

n=M(2); %GCD is M(2)

With a minor extension in the test for “end,” this code can be made to work with irrational inputs (e.g., \((n\pi, m\pi)\)).

This method calculates the number of times \( n < m \) must subtract from \( m \) using the floor function. This operation is the same as the mod function.\(^1\) Specifically

\[
n_{k+1} = m_k - \left\lfloor \frac{m}{n} \right\rfloor n_k
\]  

(H.2)

so that the output is the definition of the remainder of modular arithmetic. This would have been obvious to anyone using an abacus, which explains why it was discovered so early.

Note that the next value of \( m (M(1)) \) is always less than \( n (M(2)) \), and must remain greater or equal to zero. This one-line vector operation is then repeated until the remainder \( (M(1)) \) is 0. The gcd is then

\[^1\]https://en.wikipedia.org/wiki/Modulo_operation
n \((M(2))\). When using irrational numbers, this still works except the error is never exactly zero, due to IEEE 754 rounding. Thus the criterion must be that the error is within some small factor times the smallest number (which in Matlab is the number \(\varepsilon_{\text{FS}} = 2.220446049250313 \times 10^{-16}\), as defined in the IEEE 754 standard.)

Thus without factoring the two numbers, Eq. H.2 recursively finds the gcd. Perhaps this is best seen with some examples.

The GCD is an important and venerable method, useful in engineering and mathematics, but, as best I know, is not typically taught in the traditional engineering curriculum.

**GCD applied to polynomials:** An interesting generalization is work with polynomials rather than numbers, and apply the Euclidian algorithm.

The GCD may be generalized in several significant ways. For example what is the GCD of two polynomials? To answer this question one must factor the two polynomials to identify common roots.

### H.2 Derivation of the CFA matrix:

The CFA may be define starting from the basic definitions of the floor and remainder formulae. Starting from a decimal number \(x\) we split it into the decimal and remainder parts\(^2\) Starting with \(n = 0\) and \(x_0 = x \in \mathbb{I}\), the integer part is

\[m_0 = \lfloor x \rfloor \in \mathbb{N}\]

and the remainder is

\[r_0 = x - m_0.\]

Corresponding the the CFA, the next target \(x_1\) is for \(n = 1\) is

\[x_1 = r_0^{-1}\]

and the integer part is \(m_1 = \lfloor x_1 \rfloor.\) As in the case of \(n = 0\), the integer part is

\[m_1 = \lfloor x_1 \rfloor\]

and the remainder is

\[r_1 = x_1 - m_1.\]

The recursion for \(n = 2\) is similar.

To better appreciate what is happening it is helpful to write these recursion in a matrix format. Rewriting the case of \(n = 1\) and using the remainder formula for the ratio of two numbers \(p \geq q \in \mathbb{N}\) with \(q \neq 0\).

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} =
\begin{bmatrix}
u_1 & 1 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
r_0 \\
r_1
\end{bmatrix}
\]

From the remainder formula, \(u_1 = \lfloor p/q \rfloor\).

Continuing with \(n = 2\)

\[
\begin{bmatrix}
r_0 \\
r_1
\end{bmatrix} =
\begin{bmatrix}
u_2 & 1 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
r_1 \\
r_2
\end{bmatrix}
\]

where \(u_1 = \lfloor r_0/r_1 \rfloor\).

Continuing with \(n = 3\)

\[
\begin{bmatrix}
r_1 \\
r_2
\end{bmatrix} =
\begin{bmatrix}
u_3 & 1 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
r_2 \\
r_3
\end{bmatrix}
\]

\(^2\)The method presented here was developed by Yiming Zhang as a student project in 2019.
where \( u_2 = \lfloor r_1/r_2 \rfloor \).

For arbitrary \( n \) we find
\[
\begin{bmatrix}
    r_{n-2} \\
    r_{n-1}
\end{bmatrix} =
\begin{bmatrix}
    u_n & 1 \\
    1 & 0
\end{bmatrix}
\begin{bmatrix}
    r_{n-1} \\
    r_{n}
\end{bmatrix}
\]
(H.3)

where \( u_n = \lfloor r_{n-1}/r_n \rfloor \).

This terminates when \( r_{n} = 0 \) in the above \( n \)th step when
\[
\begin{bmatrix}
    r_{n-2} \\
    r_{n-1}
\end{bmatrix} =
\begin{bmatrix}
    u_n & 1 \\
    1 & 0
\end{bmatrix}
\begin{bmatrix}
    r_{n-1} \\
    r_{n} = 0
\end{bmatrix}.
\]

Example: Let \( p, q = 355, 113 \), which are coprime and set \( n = 1 \). Then Eq. H.3 becomes
\[
\begin{bmatrix}
    355 \\
    113
\end{bmatrix} =
\begin{bmatrix}
    3 & 1 \\
    1 & 0
\end{bmatrix}
\begin{bmatrix}
    r_0 \\
    r_1
\end{bmatrix}
\]
since \( u_1 = \lfloor 355/113 \rfloor = 3 \). Solving for the RHS gives \([r_0; r_1] = [113; 16] (355 = 113 \cdot 3 + 16)\). To find \([r_0; r_1] \), take the inverse:
\[
\begin{bmatrix}
    r_0 \\
    r_1
\end{bmatrix} =
\begin{bmatrix}
    0 & 1 \\
    1 & -3
\end{bmatrix}
\begin{bmatrix}
    355 \\
    113
\end{bmatrix}.
\]

For \( n = 2 \), with the right hand side from the previous step,
\[
\begin{bmatrix}
    113 \\
    16
\end{bmatrix} =
\begin{bmatrix}
    u_2 & 1 \\
    1 & 0
\end{bmatrix}
\begin{bmatrix}
    r_1 \\
    r_2
\end{bmatrix}
\]
since \( u_2 = \lfloor 113/16 \rfloor = 7 \). Solving for the RHS gives \([r_1; r_2] = [16; 1] (113 = 16 \cdot 7 + 1)\). It seems we are done, but lets go one more step.

For \( n = 3 \) we now have
\[
\begin{bmatrix}
    16 \\
    1
\end{bmatrix} =
\begin{bmatrix}
    u_3 & 1 \\
    1 & 0
\end{bmatrix}
\begin{bmatrix}
    r_1 \\
    r_2
\end{bmatrix}
\]
since \( u_3 = \lfloor 16/1 \rfloor = 16 \). Solving for the RHS gives \([r_1; r_2] = [1; 0] \). This confirms we are done since \( r_2 = 0 \).

Derivation of Eq. H.3: Equation Eq. H.3 is derived as follows. Starting from the target \( x \in \mathbb{R} \), define
\[
p = \lfloor x \rfloor \quad \text{and} \quad q = \frac{1}{x - p} \in \mathbb{R}.
\]

These two relations for truncation and remainder allow us to write the general matrix recursion relation for the CFA, Eq. H.3. Given \{\( p, q \)\}, continue with the above cfa method.

One slight problem with the above is that the output is on the right and the input on the left. Thus we need to take the inverse of these relationships to turn this into a composition.

H.3 Taking the inverse to get the gcd.

Variables \( p, q \) are the remainders \( r_{n-1} \) and \( r_{n} \), respectively. Using this notation with \( n = 1 \) gives Eq. H.3. Inverting this gives the formula for the GCD
\[
\begin{bmatrix}
    r_{n-1} \\
    r_{n}
\end{bmatrix} =
\begin{bmatrix}
    0 & 1 \\
    1 & -r_{n-2}/r_{n-1}
\end{bmatrix}
\begin{bmatrix}
    r_{n-2} \\
    r_{n-1}
\end{bmatrix}.
\]

This terminates when \( r_{n} = 0 \), and the \text{gcd} (\( p, q \)) is \( r_{n-1} \). Not surprisingly these equations mirror Eq H.1 (p. 275), but with different indexing scheme and interpretation of the variables.

This then explains why Gauss called the CFA the Euclidian algorithm. He was not confused. But since they have an inverse relation, they are not strictly the same.
Appendix I

Analytic continued fraction expansions

I.1 Analytic continued fractions and circuit theory

One of the most powerful generalizations of the CFA seems to be the Cauer synthesis (Cauer, 1958; Van Valkenburg, 1964b), based on the expansion of a function of a complex variable, such as the expansion of an impedance \( Z(s) \), as a function of complex frequency \( s \), as described in Fig. I.1 and Eq. I.1. This is especially interesting in that it leads to a physical interpretation of the impedance in terms of a transmission line (horn), a structure well known in acoustics as having a variable area \( A(x) \) as function of the range variable \( x \).

The CFA expansion is of great importance in circuit theory, where it is equivalent to an infinitely long segment of transmission line, composed of series and shunt impedance elements. Thus such a cascade network composed of 1 ohm resistors, has an input impedance of \( (1 + \sqrt{5})/2 \approx 1.6180 \) [ohms] Eq. 2.10 (p. 58).

The CFA may be extended to monomials in \( s \). For example consider the input impedance of a cascade L-C transmission line as shown in Fig. I.1 (p. 280). The input impedance of this transmission line is given by a continued fraction expansion of the form

\[
Z_{\text{in}} = sL + \frac{1}{sC + \frac{1}{sL + \frac{1}{sC + \cdots}}}
=: [sL, sC, sL, sC, \cdots]. \tag{I.1}
\]

In some vague way, Eq. I.1 is reminiscent of a Taylor series expansion about \( s = 0 \), yet very different. In the limit, as the frequency goes to zero \( (s \to 0) \), the impedance of the inductors go to zero, and that of the capacitors go to \( \infty \). In physical terms, the inductors become short circuits, while the capacitors become open circuits. The precise relation may be quantified by the use of composition, described in Fig. 3.5 (p. 119). Specifically

\[
\begin{bmatrix}
P_1 \\ U_1
\end{bmatrix}
= \begin{bmatrix}
1 & sL \\ 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\ sC & 1
\end{bmatrix}
\cdots
\begin{bmatrix}
1 & sL \\ 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\ sC & 1
\end{bmatrix}
\begin{bmatrix}
1 & sL \\ 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\ sC & 1
\end{bmatrix}
\begin{bmatrix}
P_2 \\ -U_2
\end{bmatrix}. \tag{I.2}
\]

It seems possible that this is the CFA generalization of the Taylor series expansion, built on composition. If we were to do the algebra we would find that \( A(s), B(s), C(s), D(s) \) (i.e., Sections 3.5 (pp. 119)) are ratios of polynomials having rational expansions as Taylor series. This seems like an important observation, that should have applications beyond the engineering literature (Campbell, 1903a; Brillouin, 1953; Ramo et al., 1965). Note that Brillouin (1953) credits Campbell (1903a).

Figure I.2 is a piece of wire having a delay determined by its velocity and the length, in units of the cells, each of length \( \Delta \). There are two basic parameters that characterize a transmission line, the
characteristic resistance $r_0 = \sqrt{sL/sC} = \sqrt{L/C}$, and wave number depends on the product of $L$ and $C$

$$\kappa = \sqrt{sL \cdot sC} = s\sqrt{LC} = s/c_0, \quad [\text{m}^{-1}] \quad (I.3)$$

thus $c_0 = 1/\sqrt{LC}$. The delay in each cell is

$$\tau_o = \Delta/c_0 = \Delta \sqrt{LC} [\text{s}].$$

The characteristic wave resistance (aka surge resistance) is given by the ratio of $L$ and $C$

$$r_0 = \sqrt{L/C} \quad [\Omega]. \quad (I.4)$$

The total delay of the line is $T = \tau_o \ [\text{s}]$, where $N$ is the number of sections. In that limit the waves travel as

$$f(t - x/c_0) = e^{-\kappa x} e^{-st},$$

as $\Delta \to 0$. When $L(x)$ and $C(x)$ depend on position, the transmission line is called a horn (Sect. 5.3.1, p.198, and described by the Webster Horn equation (Eq.5.28, p. 199).

Since the CFA has a physical representation as a transmission line, as shown in Fig. I.1, it has high utility in engineer and mathematics.\textsuperscript{1} The theory behind this will be discussed in greater detail in the exercises (Section 4.5.5, p. 180). For the advanced student, I suggest you read the classic book Brillouin (1960), Campbell (1903a, 1922), or better, the collected works of Campbell (1937).

\textsuperscript{1}Continued fraction expansions of functions are known in the circuit theory literature as a Cauer synthesis (Van Valkenburg, 1964b).

Figure I.1: This transmission line (TL) is known as a low-pass filter wave-filter (Campbell, 1922), composed of series inductors having an impedance $Z_k = sL$ and shunt admittance $Y_k = sC$. The characteristic resistance of the TL is $r_0 = \sqrt{Z_k/Y_k}$ and the wave velocity is $\kappa = \sqrt{Z_kY_k} = s/\sqrt{LC} = s/c$. Thus the wave velocity is $c = 1/\sqrt{LC}$. The length $\Delta \ [\text{m}]$ defines the physical size of each cell. For long wavelengths the wave-filter acts as a pure delay. But when the frequency increases above a cutoff frequency $f_c > c/\Delta$, the wavelength $\lambda = c/f$ is less than the size of a section $\Delta$, and the system response becomes very high-order low-pass filter.
Appendix J

The ten postulates of Systems of algebraic Networks

The 6 postulates of System (aka, Network) Theory;
The important role of the Laplace transform to impedance

Physical systems obey very important rules that follow from the physics. It is helpful to summarize these physical restrictions in terms of postulates, presented in terms of a taxonomy, or categorization method, of the fundamental properties of physical systems. Nine of these are listed below. These nine come from a recently published paper (Kim and Allen, 2013). It is possible that given time, others could be added.

A taxonomy of physical systems comes from a systematic summary of the laws of physics, which includes at least the nine basic network postulates, described in Section 3.7. To describe each of the network postulates it is helpful to begin with the 2-port transmission (aka ABCD, chain) matrix representation, discussed in Section ?? (p. ??).

As shown in Fig. J.1, the 2-port transmission matrix for an acoustic transducer (loudspeaker) is characterized by the equation

$$\begin{bmatrix}
\Phi_i \\
I_i
\end{bmatrix} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \begin{bmatrix} F_l \\
-U_l
\end{bmatrix} = \frac{1}{T} \begin{bmatrix} z_m(s) & z_m(s) + T^2 \\ z_e(s) & z_e(s) \end{bmatrix} \begin{bmatrix} F_l \\
-U_l
\end{bmatrix}, \quad (J.1)$$

shown as a product of three 2x2 matrices in the figure, with each factor representing one of the three physical elements (i.e., Hunt parameters) of the loudspeaker.

This figure represents the electromagnetic motor of the loudspeaker, consists of three elements, the electrical input impedance $Z_e(s)$, a gyrator, which is similar to a transformer, but relates current to force, and an output mechanical impedance $Z_m(s)$. This circuit describes what is needed to fully characterize it operation, from electrical input to mechanical (acoustical) output.

The input is electrical (voltage and current) $[\Phi_i, I_i]$ and the output (load) are the mechanical (force and velocity) $[F_l, U_l]$. The first matrix is the general case, expressed in terms of four unspecified func-
tions \( A(s), B(s), C(s), D(s) \), while the second matrix is for the specific example of Fig. J.1. The four entries are the electrical driving point impedance \( Z_e(s) \), the mechanical impedance \( z_m(s) \) and the transduction \( T = B_0l \) where \( B_0 \) is the magnetic flux strength and \( l \) is the length of the wire crossing the flux. Since the transmission matrix is anti-reciprocal, its determinate \( \Delta_T = -1 \), as is easily verified.

Other common transduction examples of cross-modality transduction include current–thermal (thermoelastic effect) and force–voltage (piezoelectric effect). These systems are all reciprocal, thus the transduction has the same sign.

### Impedance matrix

These nine postulates describe the properties of a system having an input and an output. For the case of an electromagnetic transducer (Loudspeaker) the system is described by the 2-port, as shown in Fig. J.1. The electrical input impedance of a loudspeaker is defined by \( Z_e(s) \), denoted

\[
Z_e(s) = \left. \frac{V(\omega)}{T(\omega)} \right|_{U=0}.
\]

Note that this driving-point impedance must be causal, thus it has a Laplace transform and therefore is a function of the complex frequency \( s = \sigma + j\omega \), whereas the Fourier transforms of the voltage \( V(\omega) \) and current \( I(\omega) \) are functions of the real radian frequency \( \omega \), since the time-domain voltage \( v(t) \leftrightarrow V(\omega) \) and the current \( i(t) \leftrightarrow I(\omega) \) are signals that may start and stop at any time (they are not typically causal).

The corresponding 2-port impedance matrix for Fig. J.1 is

\[
\begin{bmatrix} \Phi_1 \\ F_1 \end{bmatrix} = \begin{bmatrix} z_{11}(s) & z_{12}(s) \\ z_{21}(s) & z_{22}(s) \end{bmatrix} \begin{bmatrix} I_1 \\ U_1 \end{bmatrix} = \begin{bmatrix} Z_e(s) & -T(s) \\ T(s) & z_m(s) \end{bmatrix} \begin{bmatrix} I_1 \\ U_1 \end{bmatrix}. \tag{J.2}
\]

Such a description allows one to define Thévenin parameters, a very useful concept used widely in circuit analysis and other network models from other modalities.

The impedance matrix is an alternative description of the system, but with generalized forces \( [\Phi_1, F_1] \) on the left and generalized flows \( [I_1, U_1] \) on the right. A rearrangement of the equations allows one to go from the ABCD to impedance set of parameters (Van Valkenburg, 1964b). The electromagnetic transducer is anti-reciprocal (P6), \( z_{12} = -z_{21} = T = B_0l \).

### Taxonomy of algebraic networks

The postulates must go beyond postulates P1-P6 defined by Carlin and Giordano (Section 3.7, p. 130), when there are interaction of waves and a structured medium, along with other properties not covered by classic network theory. Assuming QS, the wavelength must be large relative to the medium’s lattice constants. Thus the QS property must be extended to three dimensions, and possibly to the cases of an-isotropic and random media.

#### Causality: P1
As stated above, due to causality the negative properties (e.g., negative refractive index) must be limited in bandwidth, as a result of the Cauchy-Riemann conditions. However even causality needs to be extended to include the delay, as quantified by the d’Alembert solution to the wave equation, which means that the delay is proportional to the distance. Thus we generalize P1 to include the space dependent delay. When we wish to discuss this property we denote it Einstein causality, which says that the delay must be proportional to the distance \( x \), with impulse response \( \delta(t - x/c) \).

#### Linearity: P2
The wave properties of may be non-linear. This is not restrictive as most physical systems are naturally nonlinear. For example, a capacitor is inherently nonlinear: as the charge builds up on the plates of the capacitor, a stress is applied to the intermediate dielectric due to the electrostatic force \( F = qE \). In a similar manner, an inductor is nonlinear. Two wires carrying a current are attracted
or repelled, due to the force created by the flux. The net force is the product of the two fluxes due to each current.

In summary, most physical systems are naturally nonlinear, it’s simply a matter of degree. An important counter example is a amplifier with negative feedback, with very large open-loop gain. There are, therefore, many types of non-linear, instantaneous and those with memory (e.g., hysteresis). Given the nature of P1, even an instantaneous non-linearity may be ruled out. The linear model is so critical for our analysis, providing fundamental understanding, that we frequently take P1 and P2 for granted.

**Passive/Active: P3** This postulate is about conservation of energy and Otto Brune’s positive Real (PR aka physically realizable) condition, that every passive impedance must obey. Following up on the earlier work of his primary PhD thesis advisor Wilhelm Cauer (1900-1945) and Ernst Guillemin, along with Norbert Weiner and Vannevar Bush at MIT, Otto Brune mathematically characterized the properties of every PR 1-port driving point impedance (Brune, 1931b).

When the input resistance of the impedance is real, the system is said to be passive, which means the system obeys conservation of energy. The real part of $Z(s)$ is positive if and only if the corresponding reflectance is less than 1 in magnitude. The definition of the reflectance of $Z(s)$ is defined as a bilinear transformation of the impedance, normalized by its surge resistance $r_0$ (Campbell, 1903a)

$$\Gamma(s) = \frac{Z(s) - r_0}{Z(s) + r_0} = \frac{\hat{Z} - 1}{\hat{Z} + 1}$$

where $\hat{Z} = Z/r_0$. The surge resistance is defined in terms of the inverse Laplace transform of $Z(s) \leftrightarrow z(t)$, which must have the form

$$z(t) = r_0\delta(t) + \rho(t),$$

where $\rho(t) = 0$ for $t < 0$. It naturally follows that $\gamma(t) \leftrightarrow \Gamma(s)$ is zero for negative and zero time, namely $\gamma(0) = 0, t \leq 0$.

Given any linear PR impedance $Z(s) = R(\sigma,\omega) + jX(\sigma,\omega)$, having real part $R(\sigma,\omega)$ and imaginary part $X(\sigma,\omega)$, the impedance is defined as being PR (Brune, 1931b) if and only if

$$\Re Z(s) = R(\sigma \geq 0, \omega) \geq 0.$$  \hspace{1cm} (J.3)

That is, the real part of any PR impedance is non-negative everywhere in the right half-plane ($\sigma \geq 0$). This is a very strong condition on the complex analytic function $Z(s)$ of a complex variable $s$. This condition is equivalent to any of the following statements (Van Valkenburg, 1964a):

1. There are no poles or zeros in the right half-plane ($Z(s)$ may have poles and zeros on the $\sigma = 0$ axis).
2. If $Z(s)$ is PR then its reciprocal $Y(s) = 1/Z(s)$ is PR (the poles and zeros swap).
3. If the impedance may be written as the ratio of two polynomials (a limited case, related to the quasi-statics approximation, P9) having degrees $N$ and $L$, then $|N - L| \leq 1$.
4. The angle of the impedance $\theta \equiv \angle Z$ lies between $[-\pi \leq \theta \leq \pi]$.
5. The impedance and its reciprocal are complex analytic in the right half-plane, thus they each obey the Cauchy Riemann conditions there.

**Energy and Power:** The PR (positive real or Physically realizable) condition assures that every impedance is positive-definite (PD), thus guaranteeing conservation of energy is obeyed (Schwinger and Saxon, 1968, p.17). This means that the total energy absorbed by any PR impedance must remain positive for all time, namely

$$E(t) = \int_{-\infty}^{t} v(t)i(t) \, dt = \int_{-\infty}^{t} i(t) \ast z(t) \, i(t) \, dt > 0,$$
where \( i(t) \) is any current, \( v(t) = z(t) \ast i(t) \) is the corresponding voltage and \( z(t) \) is the real causal impulse response of the impedance, e.g., \( z(t) \leftrightarrow Z(s) \) are a Laplace Transform pair. In summary, if \( Z(s) \) is PR, \( \mathcal{E}(t) \) is PD.

As discussed in detail by Van Valkenburg, any rational PR impedance can be represented as a partial fraction expansion, which can be expanded into first-order poles as

\[
Z(s) = K \prod_{n=1}^{L} (s - n_i) \prod_{k=1}^{N} (s - d_k) = \sum_{n} \rho_n \frac{e^{j(\theta_n - \theta_d)}}{s - s_n},
\]

where \( \rho_n \) is a complex scale factor (residue). Every pole in a PR function has only simple poles and zeros, requiring that \( |L - N| \leq 1 \) (Van Valkenburg, 1964b).

Whereas the PD property clearly follows P3 (conservation of energy), the physics is not so clear. Specifically what is the physical meaning of the specific constraints on \( Z(s) \)? In many ways, the impedance concept is highly artificial, as expressed by P1-P7.

When the impedance is not rational, special care must be taken. An example of this is the semi-inductor \( M/\sqrt{s} \) and semi-capacitor \( K/\sqrt{s} \) due, for example, to the skin effect in EM theory and viscous and thermal losses in acoustics, both of which are frequency dependent boundary-layer diffusion losses (Vanderkooy, 1989). They remain positive-real but have a branch cut, thus are double valued in frequency.

**Real time response: P4** The impulse response of every physical system is real vs. complex. This requires that the Laplace Transform have conjugate-symmetric symmetry \( H(s) = H^*(s^*) \), where the \( * \) indicates conjugation (e.g., \( R(\sigma, \omega) + X(\sigma, \omega) = R(\sigma, \omega) - X(\sigma, -\omega) \)).

**Time invariant: P5** The meaning of time-invariant requires that the impulse response of a system does not change over time. This requires that the system coefficients of the differential equation describing the system are constant (independent of time).

**Rayleigh Reciprocity: P6** Reciprocity is defined in terms of the unloaded output voltage that results from an input current. Specifically

\[
\begin{bmatrix}
z_{11}(s) \\
z_{12}(s) \\
z_{21}(s) \\
z_{22}(s)
\end{bmatrix} = \frac{1}{C(s)} \begin{bmatrix}
A(s) & \Delta_T \\
1 & D(s)
\end{bmatrix},
\]

where \( \Delta_T = A(s)D(s) - B(s)C(s) = \pm 1 \) for the reciprocal and anti-reciprocal systems respectively. This is best understood in term of Eq. J.2. The off-diagonal coefficients \( z_{12}(s) \) and \( z_{21}(s) \) are defined as

\[
z_{12}(s) = \frac{\Phi_2}{U_1} \bigg|_{I_1=0} \\
z_{21}(s) = \frac{F_1}{I_1} \bigg|_{U_2=0}.
\]

When these off-diagonal elements are equal \( [z_{12}(s) = z_{21}(s)] \) the system is said to obey Rayleigh reciprocity. If they are opposite in sign \( [z_{12}(s) = -z_{21}(s)] \), the system is said to be anti-reciprocal. If a network has neither of the reciprocal or anti-reciprocal characteristics, then we denote it as non-reciprocal (McMillan, 1946). The most comprehensive discussion of reciprocity, even to this day, is that of Rayleigh (1896, Vol. I). The reciprocal case may be modeled as an ideal transformer (Van Valkenburg, 1964a) while for the anti-reciprocal case the generalized force and flow are swapped across the 2-port.

An electromagnetic transducer (e.g., a moving coil loudspeaker or electrical motor) is anti-reciprocal (Kim and Allen, 2013; Beranek and Mellow, 2012), requiring a gyrator rather than a transformer, as shown in Fig. J.1.
Reversibility: P7 A second 2-port property is the reversible/non-reversible postulate. A reversible system is invariant to the input and output impedances being swapped. This property is defined by the input and output impedances being equal.

Referring to Eq. J.5, when the system is reversible \( z_{11}(s) = z_{22}(s) \) or in terms of the transmission matrix variables \( A(s) = \frac{D(s)}{C(s)} \) or simply \( A(s) = D(s) \) assuming \( C(s) \neq 0 \).

An example of a non-reversible system is a transformer where the turns ratio is not one. Also an ideal operational amplifier (when the power is turned on) is non-reversible due to the large impedance difference between the input and output. Furthermore it is active (it has a power gain, due to the current gain at constant voltage) (Van Valenkburg, 1964b).

Generalizations of this lead to group theory, and Noether’s theorem. These generalizations apply to systems with many modes whereas quasi-statics holds when operate below a cutoff frequency (Table J.1), meaning that like the case of the transmission line, there are no propagating transverse modes. While this assumption is never exact, it leads to highly accurate results because the non-propagating evanescent transverse modes are attenuated over a short distance, and thus, in practice, may be ignored (Montgomery et al., 1948; Schwinger and Saxon, 1968, Chap. 9-11).

We extend the Carlin and Giordano postulate set to include (P7) Reversibility, which was refined by Van Valenkburg (1964a). To satisfy the reversibility condition, the diagonal components in a system’s impedance matrix must be equal. In other words, the input force and the flow are proportional to the output force and flow, respectively (i.e., \( Z_e = z_m \)).

Spatial invariant: P8 The characteristic impedance and wave number \( \kappa(s, x) \) may be strongly frequency and/or spatially dependent, or even be negative over some limited frequency ranges. Due to causality, the concept of a negative group velocity must be restricted to a limited bandwidth (Brillouin, 1960). As is made clear by Einstein’s theory of relativity, all materials must be strictly causal (P1), a view that must therefore apply to acoustics, but at a very different time scale. We first discuss generalized postulates, expanding on those of Carlin and Giordano.

The QS constraint: P9 When a system is described by the wave equation, delay is introduced between two points in space, which depends on the wave speed. When the wavelength is large compared to the delay, one may successfully apply the quasi-static approximation. This method has wide-spread application, and is frequency used without mention of the assumption. This can lead to confusion, since the limitations of the approximation may not be appreciated. An example is the use of QS in Quantum Mechanics. The QS approximation has wide spread use when the signals may be accurately approximated by a band-limited signal. Examples include KCL, KVL, wave guides, transmission lines, and most importantly, impedance. The QS property is not mentioned in the six postulates of Carlin and Giordano (1964), thus they need to be extended in some fundamental ways.

When the dimensions of a cellular structure in the material are much less than the wavelength, can the QS approximation be valid. This effect can be viewed as a mode filter that suppresses unwanted (or conversely enhances the desired) modes (Ramo et al., 1965). QSs may be applied to a 3 dimensional specification, as in a semiconductor lattice. But such applications fall outside the scope of this text (Schwinger and Saxon, 1968).

Although I have never seen the point discussed in the literature, the QS approximation is applied when defining Green’s theorem. For example, Gauss’s Law is not true when the volume of the container violates QS, since changes in the distribution of the charge have not reached the boundary, when doing the integral. Thus such integral relationships assume that the system is in quasi steady-state (i.e., that QS holds).

Formally, QS is defined as \( ka < 1 \) where \( k = 2\pi/\lambda = \omega/c \) and \( a \) is the cellular dimension or the size of the object. Other ways of expressing this include \( \lambda/4 > a, \lambda/2\pi > a, \lambda > 4a \) or \( \lambda > 2\pi a \). It is not clear if it is better to normalize \( \lambda \) by 4 (quarter-wavelength constraint) or \( 2\pi \approx 6.28 > 4 \), which is more conservative by a factor of \( \pi/2 \approx 1.6 \). Also \( k \) and \( a \) can be vectors, e.g., Eq. 3.4, p. 73, Section 4.2.
Table J.1: There are several ways of indicating the quasi-static (QS) approximation. For network theory there is only one lattice constant \( a \), which must be much less than the wavelength (wavelength constraint). These three constraints are not equivalent when the object may be a larger structured medium, spanning many wavelengths, but with a cell structure size much less than the wavelength. For example, each cell could be a Helmholtz resonator, or an electromagnetic transducer (i.e., an earphone).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Domain</th>
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<tr>
<td>( k a &lt; 1 )</td>
<td>Wavenumber constraint</td>
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<tr>
<td>( \lambda &gt; 2\pi a )</td>
<td>Wavelength constraint</td>
</tr>
<tr>
<td>( f_c &lt; c/2\pi a )</td>
<td>Bandwidth constraint</td>
</tr>
</tbody>
</table>

Schelkunoff may have been the first to formalize this concept (Schelkunoff, 1943) (but not the first to use it, as exemplified by the Helmholtz resonator). George Ashley Campbell was the first to use the concept in the important application of a wave-filter, some 30 years before Schelkunoff (Campbell, 1903a). These two men were 40 years apart, and both worked for the telephone company (after 1929, called AT&T Bell Labs) (Fagen, 1975).

There are alternative definitions of the QS approximation, depending on the geometrical cell structure. The alternatives are outlined in Table J.1.

The quasi-static approximation: Since the velocity perpendicular to the walls of the horn must be zero, any radial wave propagation is exponentially attenuated (\( \kappa(s) \) is real and negative, i.e., the propagation function \( \kappa(s) \) (Sect. 4.3, p. 149) will not describe radial wave propagation), with a space constant of about 1 diameter. The assumption that these radial waves can be ignored (i.e., more than 1 diameter from their source) is called the quasi-static approximation. As the frequency is increased, once \( f \geq f_c = 2c_o/\lambda \), the radial wave can satisfy the zero normal velocity wall boundary condition, and therefore will not be attenuated. Thus above this critical frequency, radial waves (aka, higher order modes) are supported (\( \kappa \) becomes imaginary). Thus for Eq. 5.28 to describe guided wave propagation, \( f < f_c \). But even under this condition, the solution will not be precise within a diameter (or so) of any discontinuities (i.e., rapid variations) in the area.

Each horn, as determined by the area function \( A(r) \), has a distinct wave equation, and thus a distinct solution. Note that the area function determines the upper cutoff frequency via the quasi-static approximation since \( f_c = c_0/\lambda_c, \lambda_c/2 > d, A(r) = \pi(d/2)^2 \). Thus to satisfy the quasi-static approximation, the frequency \( f \) must be less than the cutoff frequency

\[
\frac{f}{f_c(r)} = \frac{c_o}{2\pi} \sqrt{\frac{\pi}{A(r)}}. \tag{J.6}
\]

We shall discuss two alternative matrix formulations of these equations: the ABCD transmission matrix, used for computation, and the impedance matrix, used when working with experimental measurements (Pierce, 1981, Chapter 7). For each formulation reciprocity and reversibility show up as different matrix symmetries, as addressed in Section 3.7 (p. 130) (Pierce, 1981, p. 195-203).

Summary

A transducer converts between modalities. We propose the general definition of the nine system postulates, that include all transduction modalities, such as electrical, mechanical, and acoustical. It is necessary to generalize the concept of the QS approximation (P9) to allow for guided waves.

Given the combination of the important QS approximation, along with these space-time, linearity, and reciprocity properties, a rigorous definition and characterization a system can thus be established. It is based on a taxonomy of such materials, formulated in terms of material and physical properties and in terms of extended network postulates.
Appendix K

Visco-thermal losses

K.1 Adiabatic approximation at low frequencies:

At very low frequencies the adiabatic approximation must break down. Above this frequency, viscous and thermal damping in air can become significant. In acoustics these two effects are typically ignored, by assuming that wave propagation is irrotational, thus is described by the scalar wave equation. However this is an approximation.

As first explained by Kirchhoff (1868) and Helmholtz (1858), these two loss mechanisms are related; but to understand why is somewhat complicated, due to both the history and the mathematics. The full theory was first worked out by Kirchhoff (1868, 1974). Both forms of damping are due to two different but coupled diffusion effects, first from viscous effects, due to shear at the container walls, and second from thermal effects, due to small deviations from adiabatic expansion (Kirchhoff, 1868, 1974). I believe ultimately Einstein was eventually involved as a result of his studies on Brownian motion (Einstein, 1905).

Newton’s early development understandably ignored viscous and thermal losses, which can be significant in a thin region called the boundary layer, at acoustic frequencies when the radius of the container (i.e., the horn) becomes less than the viscous boundary layer (e.g., much less than 1 mm) as first described in Helmholtz (1858, 1863b, 1978). Helmholtz’s analysis (Helmholtz, 1863b) was soon extended to include thermal losses by Kirchhoff (1868, 1974, English translation), as succinctly summarized by Lord Rayleigh (1896), and then experimentally verified by Warren P. Mason (Mason, 1927, 1928).

The mathematical nature of damping is that the propagation function $\kappa(s)$ (i.e, complex wave number) is extended to

$$\kappa(s) = \frac{s + \beta_0 \sqrt{s}}{c_0},$$

(K.1)

where the forwarded $P_-$ and backward $P_+$ pressure waves propagate as

$$P_{\pm}(s, x) = e^{-\kappa(s)x}, e^{-\bar{\pi}(s)x}$$

(K.2)

with $\bar{\pi}(s)$ the complex conjugate of $\kappa(s)$, and $\Re\kappa(s) > 0$. The term $\beta_0 \sqrt{s}$ effects both the real and imaginary parts of $\kappa(s)$. The real part is a frequency dependent loss and the imaginary part introduces a frequency dependent speed of sound (Mason, 1928).

K.1.1 Lossy wave-guide propagation

In the case of lossy wave propagation, the losses are due to viscous and thermal damping. The formulation of viscous loss in air transmission was first worked out by Helmholtz (1863a), and then extended

---

1 See Ch. 3 of https://www.ks.uiuc.edu/Services/Class/PHYS498/.
by Kirchhoff (1868), to include thermal damping (Rayleigh, 1896, Vol. II, p. 319). These losses are explained by a modified complex propagation function \( \kappa(s) \) (Eq. K.1). Following his review of these theories, Crandall (1926, Appendix A) noted that the “Helmholtz-Kirchhoff” theory had never been experimentally verified. Acting on this suggestion, Mason (1928) set out to experimentally verify their theory.

**Mason’s Specification of the propagation function**

Mason’s results are reproduced here in Fig. K.1 as the solid lines for tubes of fixed radius between 3.7–8.5 [mm], having a power reflectance given by

\[
|\Gamma_L(f)|^2 = \left| e^{-\kappa(f)L} \right|^2 \text{ [dB/cm].} \tag{K.3}
\]

The complex propagation function cited by Rayleigh (1896) is (Mason, 1928, Eq. 2)

\[
\kappa(\omega) = \frac{P\eta_o\sqrt{\omega}}{2c_oS\sqrt{2\rho_o}} + \frac{i\omega}{c_o} \left\{ 1 + \frac{P\eta_o}{2S\sqrt{2\omega\rho_o}} \right\}, \tag{K.4}
\]

where \( S \) is the tube area and \( P \) is its perimeter. Mason specified physical constants for air to be \( \eta_o = 1.4 \) (ratio of specific heats), \( \rho_o = 1.2 \) [kgm/m\(^3\)] (density), \( c_o = \sqrt{P_0\eta_o/\rho_o} = 341.56 \) [m/s] (lossless air velocity of sound at 23.5\(^\circ\) [C]), \( P_0 = 10^5 \) [Pa] (atmospheric pressure), \( \mu_o = 18.6 \times 10^{-6} \) [Pa-s] (viscosity). Based on these values, \( \eta'_0 \) is defined as the composite thermodynamic constant (Mason, 1928)

\[
\eta'_0 = \sqrt{\mu_o} \left[ 1 + \sqrt{5/2} \left( \eta_o^{1/2} - \eta_o^{-1/2} \right) \right] = \sqrt{18.6} \times 10^{-3} \left[ 1 + \sqrt{5/2} \left( \sqrt{1.4} - 1/\sqrt{1.4} \right) \right] = 6.618 \times 10^{-3}.
\]

**K.1.2 Impact of viscous and thermal losses**

Assuming air at 23.5\(^\circ\) [C], \( c_0 = \sqrt{\eta_0 P_0/\rho_o} \approx 344 \) [m/s] is the speed of sound, \( \eta_0 = c_p/c_v = 1.4 \) is the ratio of specific heats, \( \mu_0 = 18.5 \times 10^{-6} \) [Pa-s] is the viscosity, \( \rho_0 \approx 1.2 \) [kgm/m\(^3\)] is the density, \( P_0 = 10^5 \) [Pa] (1 atm).
Equation K.4 and the measured data are compared in Fig. K.1, reproduced from Mason’s Fig. 4, which shows that the wave speed drops from 344 [m/s] at 2.6 [kHz] to 339 [m/s] at 0.4 [kHz], a 1.5% reduction in the wave speed. At 1 [kHz] the loss is 1 [dB/m] for a 7.5 [mm] tube. Note that the loss and the speed of sound vary inversely with the radius. As the radius approaches the boundary layer thickness (the radial distance such that the loss is \( e^{-1} \)), and the effect of the damping dominates the propagation.

With some significant algebra, Eq. K.4 may be greatly simplified, as Eq. K.1. Numerically

\[
\beta_o = \frac{P \eta_o'}{2S \sqrt{\rho_o}} = \frac{P}{2S} 6.0415 \times 10^{-3}
\]

For the case of a cylindrical waveguide the radius is \( R = 2S/P \). Thus

\[
\beta_o = \frac{1}{R} \frac{\eta_o'}{\sqrt{\rho_o}} = \frac{1}{R} 6.0415 \times 10^{-3}.
\]

Here \( \beta_o = P \eta'/2S \sqrt{\rho_0} \) is a thermodynamic constant, \( P \) is the perimeter of the tube and \( S \) the area (Mason, 1928).

For a cylindrical tube having radius \( R = 2S/P \), \( \beta_o = \eta_o'/R \sqrt{\rho} \). To get a feeling for the magnitude of \( \beta_o \) consider a 7.5 [mm] tube (i.e., the average diameter of the adult ear canal). Then \( \eta' = 6.6180 \times 10^{-3} \) and \( \beta_o = 1.6110 \). Using these conditions the wave-number cutoff frequency is \( 1.6112^2/2\pi = 0.4131 \) [Hz]. At 1 kHz the ratio of the loss over the propagation is \( \beta_o/\sqrt{|s|} = 1.6011/\sqrt{2\pi10^3} \approx 2\% \). At 100 [Hz] this is a 6.4% effect.

Cut-off frequency \( s_0 \): The frequency where the loss-less part equals the lossy part is defined as \( \kappa(s_0) = 0 \), namely

\[
s_0 + \beta_0 \sqrt{s_0} = 0.
\]

Solving for \( s_0 \) gives the real, and negative, pole frequency of the system

\[
\sqrt{s_0} = -\beta_0 = -6.0415 \times 10^{-3}/R.
\]

To get a feeling for the magnitude of \( \beta_0 \) let \( R = 0.75/2 \) [cm] (i.e., the average radius of the adult ear canal). Then

\[
-\sqrt{s_0} = \beta_0 = 6.0145 \times 10^{-3}/3.75 \times 10^{-6} \approx 1.6.
\]

We conclude that the losses are insignificant in the audio range since for the case of the human ear canal \( f_0 = \beta_0^2/2\pi \approx 0.407 \) [Hz].

Note how the propagation function has a Helmholtz-Kirchhoff correction for both the real and imaginary parts. This means that both the speed of sound and the damping are dependent on frequency, proportional to \( \beta_0 \sqrt{s}/c_o \). Note also that the smaller the radius, the greater the damping.

Summary: The Helmholtz-Kirchhoff theory of viscous and thermal losses results in a frequency dependent speed of sound, having a frequency dependence proportional to \( 1/\sqrt{s} \) (Mason, 1928, Eq. 4). This corresponds to a 2% change in the sound velocity over the decade from 0.2-2 [kHz] (Mason, 1928, Fig. 5), in agreement with experiment.

---

3 The real and imaginary parts of this expression, with \( s = \text{i} \omega \), give Eq. K.4.
4/home/jba/Mimosa/2C-FindLengths.16/doc.2-c_calib.14/m/MasonKappa.m
Details For DRAFT only: Based on Mason (1927, Eq. 3)

\[ \kappa(\omega) = \frac{P\eta_o'}{2c_0S\sqrt{2\rho_o}} \cdot \sqrt{\omega} + \frac{s}{c_o} + \frac{s}{\sqrt{\omega}} \frac{P\eta_o'}{2c_0S\sqrt{2\rho_o}}, \]  

(K.5)

OR

\[ \kappa(\omega) = \frac{s}{c_o} + \frac{P\eta_o'}{2c_0S\sqrt{2\rho_o}} \beta_{1/\sqrt{2}} \left[ \sqrt{\omega} + \frac{s}{\sqrt{\omega}} \right]. \]  

(K.6)

OR

\[ \kappa(\omega) - \frac{s}{c_o} = \beta_{1/\sqrt{2}} \left[ \sqrt{\omega} + \frac{s}{\sqrt{\omega}} \right]. \]  

(K.7)

Multiply top and bottom on right by \( \sqrt{i} \)

\[ \kappa(\omega) - \frac{s}{c_o} = \beta_1 \frac{\sqrt{i\omega}}{\sqrt{i}} \left[ \frac{\sqrt{i\omega}}{\sqrt{i}} + \frac{s\sqrt{i}}{\sqrt{i\omega}} \right], \quad \text{AND SET } \sqrt{i\omega} = \sqrt{s} \]

\[ = \beta_1 \frac{\sqrt{i\omega} + s\sqrt{i}}{\sqrt{i\omega}} \left[ \sqrt{i\omega} + s\sqrt{i} \right], \quad \text{AND CROSS MULTIPLY} \]

\[ = \beta_1 \frac{s + is}{\sqrt{i\omega}} \sqrt{i\omega}, \quad \text{AND REPLACE } s/\sqrt{2i} \text{ BY } \sqrt{s} \]

\[ = \beta_1 \frac{1 + i}{\sqrt{i\omega}} \sqrt{s} \]

\[ = \beta_1 \sqrt{s} \]

Show that \( 1 + i = \sqrt{2i} \), as assumed in the second to last line, above. Square both sides gives \( 1 + 2i = 2i \).
Appendix L

Figure L.1: Page 19

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Figure L.2: Page 22

**Chronological history: 16th to 19th centuries**

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Appendix M
\[ u + jv = \tan((x+jy)) \]

\[ u + jv = \frac{(i/2) \log((1-i(x+jy))/(1+i(x+jy)))}{(i/2) \log((1-i(x+jy))/(1+i(x+jy)))} \]

\[ u + jv = s^2 \]

\[ u + jv = -\sqrt{-s} \]

\[ u + jv = \text{signal} \]
Figure M.10: Page 156

\[ u+jv = \sqrt{s} \]

Figure M.11: Page 157

\[ u+jv = \sqrt{\frac{\pi}{s}} \]

Figure M.12: Page 175

\[ u+jv = \text{besselj}(0, \pi(x+jy)) \]

\[ u+jv = \cos(\pi(x+jy)) \]
Figure M.13: Webster horn equation setup and derivation
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