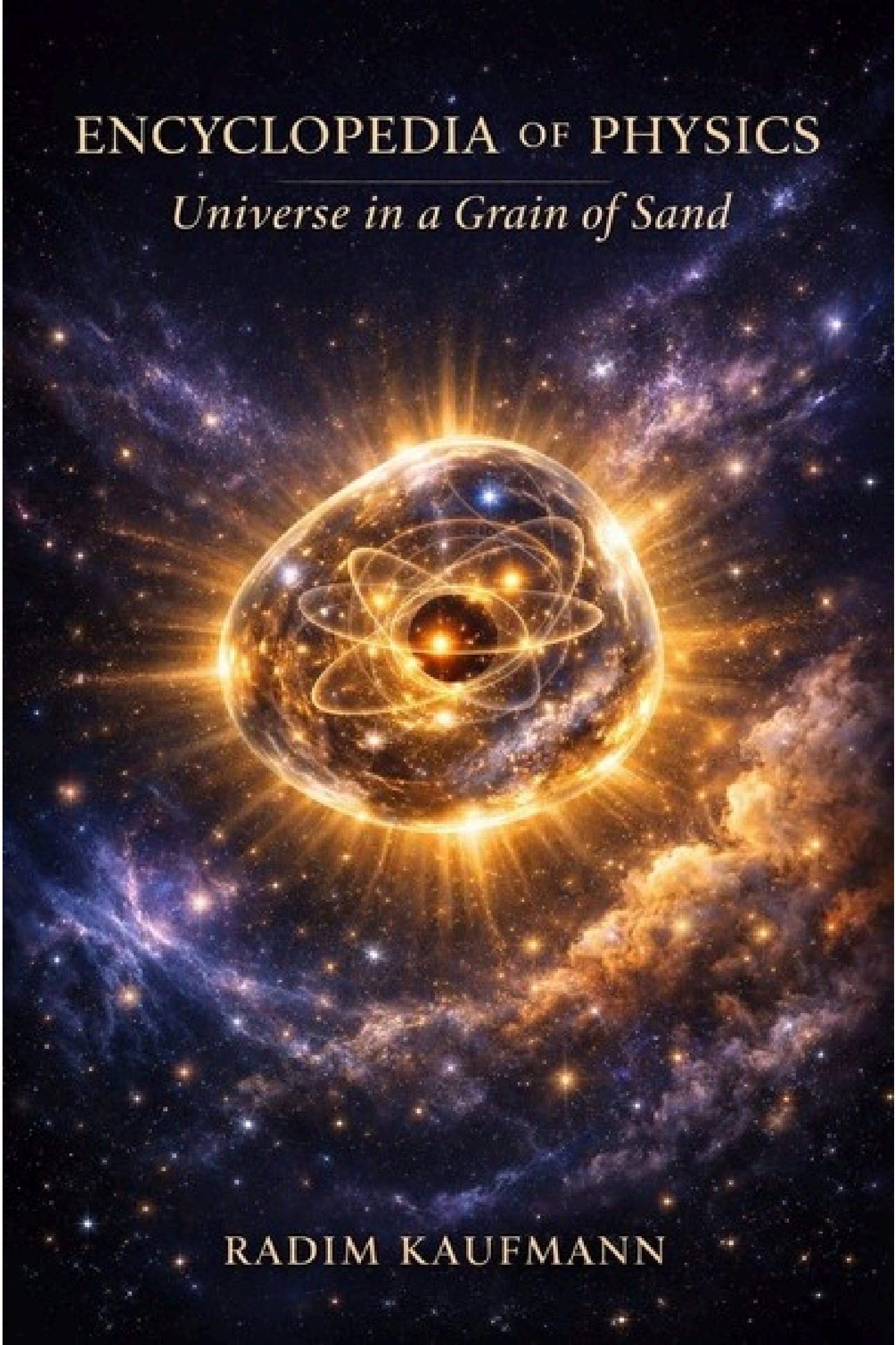
ENCYCLOPEDIA OF PHYSICS

Universe in a Grain of Sand



RADIM KAUFMANN

ENCYCLOPEDIA OF PHYSICS

Universe in a Grain of Sand

Radim Kaufmann

From Quarks to Quasars and the Frontiers of Human Knowledge

Encyclopedia of Physics: Universe in a Grain of Sand

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INTRODUCTION: WHY IS THE WORLD THE WAY IT IS?

A User's Guide to the Universe for Advanced Primates

Pick up an ordinary pebble from the ground. Or, if you happen to be at the beach, take a single grain of sand into your palm. Hold it up to the light. What do you see?

At first glance, it's just a tiny piece of matter. Insignificant debris. But if you look at that grain through the eyes of modern physics, **you hold the entire universe in your hand**.

The atoms of silicon and oxygen that make up that grain are 99.999 percent empty space. What you feel as the solidity of stone is not matter at all, but an *illusion* created by force fields that won't let your finger pass through. The nuclei of those atoms are unimaginably old. Some formed just minutes after the Big Bang; others were forged in the crushing heat of dying stars that exploded billions of years before our Solar System was born.

In that single grain of sand, the infinitely large meets the infinitely small. It is a monument to cosmic history and at the same time a gateway into the quantum world, where particles can exist in two places at once and energy emerges from nothingness.

A Bug in Our Software

So why doesn't the world seem that way to us? Why does it appear that time flows at the same rate everywhere, that space is an empty stage, and that things are simply solid?

The answer is prosaic: **Our brains did not evolve to understand quantum mechanics or the theory of relativity.** They evolved so we could hit a mammoth with a spear and not fall out of a tree. To survive on the African savanna, you didn't need to know that time at your feet flows slower than at your head (which is true), or that the electrons in your body don't actually exist in any definite place until you look at them.

Our intuition is built for the middle world—for meters, seconds, and kilograms. But the universe out there (and in there) is far wilder. It is a place where space bends, where time can freeze, where nothingness weighs more than all the stellar debris combined, and where enormous galaxies hurtle toward the unknown, pulled by a force we cannot see.

What This Book Is About

This book is an attempt to step beyond the shadow of our intuition. Together, we will venture to places where no human foot has ever trodden—and likely never will.

In Part I through V, THE PHYSICAL UNIVERSE, we trace the greatest story ever told by science. We begin with Newton's apple and end at the edge of quantum gravity. We discover that the Big Bang was not an explosion in space, but an explosion of space itself. We explore black holes that are not merely destroyers but architects of galaxies. We peer into the face of a future when the universe goes dark and time loses meaning.

Along the way, in the QUANTUM REALM, we descend beneath the surface of things. We discover that matter does not truly exist—only frozen energy. We learn that the empty vacuum is, in reality, the most vibrant place in the universe, and that without strange quantum phenomena like tunneling, the Sun would never have begun to shine.

And finally, in Part VI, THE TOOLS OF UNDERSTANDING, we turn to the language in which this book of nature is written—mathematics. We will show that infinity comes in different sizes, that the sum of positive numbers can yield a negative result, and that even the silence of the universe carries information, if you know how to listen.

Stardust That Woke Up

Some chapters may unsettle you. The notion that 95 percent of the universe consists of dark matter and dark energy, about which we know virtually nothing, is hardly comforting. The realization that our existence is the result of a chain of statistically impossible coincidences can induce vertigo.

But within that vertigo lies hope. **We are the rarest thing the universe has ever created.** We are stardust that, after billions of years, woke up, gained consciousness, and began to ask: *Where did I come from?*

The science we will discuss is not a collection of dry facts. It is the greatest adventure of our species. It is proof that even though we are small, our minds can encompass the space from quarks to quasars.

Welcome to the universe. Welcome to the real world.

Let's find out just how deep the rabbit hole really goes.

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PART I

Prologue and Foundations

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Chapter 1: The Long Road — A Brief History of Physics



The long road — from Greek philosophy to modern physics

I once heard a senior colleague remark that physics is not a body of knowledge—it is a way of being wrong, systematically and honestly, until you stumble onto something true. Having spent decades watching theories rise and fall, I think he was exactly right. The history of physics is not a triumph march; it is a long, humbling, magnificent stumble toward understanding.

Physics did not spring into existence fully formed. It grew, haltingly and sometimes painfully, from philosophical speculation through careful observation to mathematical theory. The path was never straight: wrong turns, centuries of stagnation, sudden breakthroughs, and bitter disputes all played their part. Understanding this history is not mere antiquarianism—it illuminates why physics is structured the way it is and helps us recognize which of today's questions might be tomorrow's breakthroughs.

1.1 The Greek Foundation (600 BCE – 200 CE)

The Greeks asked the right questions even when they got the wrong answers. Thales of Miletus (c. 624–546 BCE) proposed that all matter is fundamentally water—wrong in detail but revolutionary in method: he sought natural explanations rather than mythological ones. Democritus (c. 460–370 BCE) proposed that matter consists of indivisible atoms moving in void—an astonishing anticipation of modern atomic theory that would not be confirmed for over two millennia.

Aristotle (384–322 BCE) dominated physics for nearly 2,000 years with a system that was comprehensive, internally coherent, and almost entirely wrong. He taught that heavy objects fall faster than light ones, that motion requires a continuous force, and that the heavens are made of a perfect fifth element (aether) moving in perfect circles. His authority was so overwhelming that these errors persisted until Galileo demolished them experimentally in the early 1600s.

Archimedes (c. 287–212 BCE) was the great exception—a physicist in the modern sense, who combined mathematical rigor with experimental verification. His laws of buoyancy and the lever, his calculation of π, and his mechanical inventions put him centuries ahead of his time.

1.2 The Islamic Golden Age (800–1400)

While Europe languished in the Early Middle Ages, scholars in the Islamic world preserved, translated, and extended Greek knowledge. Ibn al-Haytham (Alhazen, 965–1040) wrote the *Book of Optics*, which correctly described vision as light entering the eye (not emanations leaving it) and pioneered the experimental method in optics. Al-Biruni (973–1048) measured the radius of the Earth to within 1% using trigonometry from a mountain peak. Al-Khwarizmi (c. 780–850) developed algebra—the mathematical language without which modern physics would be impossible.

1.3 The Scientific Revolution (1543–1687)

Copernicus (1543) moved the Sun to the center of the solar system. Galileo (1609) pointed a telescope at the sky and saw evidence that confirmed it—Jupiter's moons, Venus's phases, the rugged surface of the Moon. Kepler (1609–1619) discovered the mathematical laws of planetary motion. And Newton (1687) unified terrestrial and celestial mechanics in a single mathematical framework.

The transformation was not merely scientific but philosophical. The medieval worldview—a hierarchical cosmos with Earth at the center, governed by Aristotelian teleology—was replaced by a universe governed by impersonal mathematical laws. Nature became a machine, and the goal of physics became the discovery of the rules by which the machine operates.



Through the telescope — the moment astronomy became physics

1.4 Classical Physics (1687–1900)

The 18th and 19th centuries saw the systematic development of the great branches of classical physics. The Bernoulli family and Euler developed fluid mechanics and the calculus of variations. Lagrange and Hamilton reformulated mechanics in forms so general that they apply unchanged in quantum mechanics. Faraday and Maxwell unified electricity, magnetism, and light. Carnot, Clausius, and Boltzmann created thermodynamics and statistical mechanics. By 1900, physics seemed nearly complete—Lord Kelvin famously spoke of just "two clouds" on the horizon.

1.5 The Twin Revolutions (1900–1930)

Those two clouds—the failure of classical physics to explain blackbody radiation and the null result of the Michelson-Morley experiment—spawned the two greatest revolutions in the history of physics. Planck's quantum hypothesis (1900) and Einstein's special relativity (1905) shattered the classical worldview within a decade. By 1930, quantum mechanics was complete, general relativity had been confirmed, and the foundations of modern physics were in place.

The speed of this revolution was breathtaking. In 1900, atoms were still controversial. By 1930, physicists understood atomic structure, nuclear physics, quantum mechanics, and the expanding universe. The previous generation's "nearly complete" physics had been revealed as merely the low-energy, low-velocity, macroscopic limit of a far richer reality.

1.6 Modern Physics (1930–Present)

The development of quantum field theory and the Standard Model (1930s–1970s) unified three of the four fundamental forces and explained virtually all known particles. The discovery of the cosmic microwave background (1965) confirmed the Big Bang. The detection of gravitational waves (2015) opened a new window on the universe. The discovery of the Higgs boson (2012) completed the Standard Model.

Yet profound questions remain. What is dark matter? What is dark energy? How do we reconcile quantum mechanics with general relativity? Why is there more matter than antimatter? Is string theory right? What happened before the Big Bang? The history of physics teaches that such questions—seemingly unanswerable in their time—have repeatedly yielded to human ingenuity. There is no reason to believe our era is different.

1.7 Lessons from History

Several themes recur throughout the history of physics. **Unification**: the greatest advances come from recognizing that apparently different phenomena are aspects of the same underlying physics (electricity + magnetism → electromagnetism; space + time → spacetime). **Symmetry**: the deepest laws are those with the most symmetry (Noether's theorem, gauge invariance). **Reductionism tempered by emergence**: while fundamental laws are simple, the phenomena they produce can be astonishingly complex—superconductivity, life, consciousness. **The unreasonable effectiveness of mathematics**: again and again, mathematical structures developed for purely abstract reasons turn out to describe physical reality with uncanny precision.

And perhaps the most important lesson: the universe is not obligated to be intuitive. Quantum mechanics violates common sense. General relativity warps time. The vacuum of empty space seethes with virtual particles. The greatest physicist is not the one with the best intuition but the one willing to follow the mathematics and the experiments wherever they lead, even when the destination seems absurd.

Chapter 2: The Language of Nature — Physical Quantities, Units, and Measurement



The tools of measurement — precision instruments of science

Lord Kelvin said: "When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind." Physics begins and ends with measurement. Every theory, no matter how elegant, must ultimately be tested against numbers obtained from careful experiments. This chapter is about the system of measurement that makes modern physics—and modern civilization—possible.

What does it actually mean to "measure" something?

2.1 What Physics Is

> *"When you can measure what you are speaking about and express it in numbers, you know something about it." — Lord Kelvin*

Physics is the science of matter, energy, space, and time—and the laws that govern their interactions. It is the most fundamental of the natural sciences: chemistry is applied physics; biology is applied chemistry; and geology, meteorology, and astronomy all rest on physical foundations.

The method of physics is the interplay between **theory** (mathematical models of nature) and **experiment** (quantitative observations designed to test those models). A theory that makes no testable predictions is not physics—it is philosophy. An experiment without a theoretical framework to interpret it is just data collection. The power of physics comes from the dynamic tension between the two.

2.2 Physical Quantities and Dimensions

Every physical quantity can be expressed as a combination of a small number of **base dimensions**. The International System of Units (SI) uses seven:

> SI Base Quantities:
>
> Length [L] — meter (m)
>
> Mass [M] — kilogram (kg)
>
> Time [T] — second (s)
>
> Electric current [I] — ampere (A)
>
> Temperature [Θ] — kelvin (K)
>
> Amount of substance [N] — mole (mol)
>
> Luminous intensity [J] — candela (cd)

All other units are derived from these seven. Force is $kg \cdot m/s^2$ (newton); energy is $kg \cdot m^2/s^2$ (joule); pressure is $kg/(m \cdot s^2)$ (pascal); voltage is $kg \cdot m^2/(A \cdot s^3)$ (volt). **Dimensional analysis**—checking that the dimensions of both sides of an equation match—is one of the most powerful sanity checks in physics. An equation that claims force equals mass times velocity *must* be wrong, because $[M][L/T] \neq [M][L/T^2]$.

2.3 The 2019 SI Redefinition

Until 2019, the kilogram was defined by a physical artifact—a platinum-iridium cylinder stored in a vault near Paris. This was profoundly unsatisfying: the mass of the *entire system of measurement* depended on one lump of metal that could be damaged, contaminated, or simply drift in mass over time (as it apparently did).

On May 20, 2019, all seven base units were redefined in terms of fundamental constants of nature:

> Second: defined by the cesium-133 hyperfine transition ($\Delta\nu = 9{,}192{,}631{,}770$ Hz)
>
> Meter: defined by the speed of light ($c = 299{,}792{,}458$ m/s exactly)
>
> Kilogram: defined by Planck's constant ($h = 6.62607015 \times 10^{-34}$ J·s exactly)
>
> Ampere: defined by the elementary charge ($e = 1.602176634 \times 10^{-19}$ C exactly)
>
> Kelvin: defined by Boltzmann's constant ($k_B = 1.380649 \times 10^{-23}$ J/K exactly)
>
> Mole: defined by the Avogadro constant ($N_A = 6.02214076 \times 10^{23}$ mol^{-1} exactly)

This is a conceptual revolution: the units of measurement are now built on the laws of physics themselves, not on human artifacts. The kilogram is defined by quantum mechanics (via Planck's constant), the meter by special relativity (via the speed of light), and the kelvin by statistical mechanics (via Boltzmann's constant). The system of measurement is now as permanent as the laws of nature.

2.4 Orders of Magnitude

One of the first skills a physicist learns is thinking in **orders of magnitude**—powers of ten. The universe spans roughly 60 orders of magnitude in length:

> Planck length: ~10^{-35} m
>
> Proton diameter: ~10^{-15} m
>
> Atom diameter: ~10^{-10} m
>
> Human height: ~10^{0} m
>
> Earth diameter: ~10^{7} m
>
> Sun-Earth distance: ~10^{11} m
>
> Milky Way diameter: ~10^{21} m
>
> Observable universe: ~10^{26} m

And roughly 80 orders of magnitude in mass, from the electron (10^{-30} kg) to the observable universe (10^{53} kg). Understanding where any quantity falls on this vast scale—and being able to estimate it quickly—is an essential physicist's skill that Enrico Fermi elevated to an art form.

2.5 Measurement Uncertainty

No measurement is exact. Every experimental result has an associated **uncertainty** that must be honestly reported. The result of a measurement is not a single number but an interval: 9.81 ± 0.02 m/s² means we are confident the true value lies between 9.79 and 9.83.

Uncertainties propagate through calculations: when you add two quantities, their absolute uncertainties add; when you multiply, their *relative* uncertainties add in quadrature. Understanding uncertainty is not merely a technical detail—it is the essence of scientific honesty. A physicist who reports a result without an uncertainty has, in an important sense, reported nothing at all.

The history of physics is, in many ways, a history of improving measurement precision. Tycho Brahe's naked-eye observations of Mars (accurate to about 2 arcminutes) were precise enough for Kepler to deduce the elliptical orbits. Michelson's interferometric measurements of the speed of light (accurate to parts per million) were precise enough to reveal the failure of the ether hypothesis. The LIGO gravitational wave detectors measure displacements of 10^{-18} meters—one-thousandth the diameter of a proton. Each leap in measurement precision has opened new windows onto nature.

Chapter 3: Thinking Like a Physicist — Dimensional Analysis



Thinking like a physicist — dimensional analysis and scaling

Enrico Fermi could estimate the number of piano tuners in Chicago, the energy of an atomic bomb from the displacement of scraps of paper, and the answer to almost any quantitative question within an order of magnitude—using nothing more than physical reasoning and basic arithmetic. This skill—the ability to extract approximate answers from minimal data—is arguably the most important practical ability a physicist can develop. It separates those who understand physics from those who merely calculate.

3.1 Dimensional Analysis

Every physical equation must be **dimensionally consistent**—the dimensions on both sides must match. This simple requirement is a powerful tool for both checking equations and *deriving* them.

Suppose you want to know how the period T of a simple pendulum depends on its length L, mass m, and gravitational acceleration g. The dimensions are: [T] = T, [L] = L, [m] = M, [g] = L/T². The only dimensionless combination of L, m, and g that gives dimension T is:

$$T \propto \sqrt{(L/g)}$$

Dimensional analysis tells us the answer must be of this form—the only unknown is a dimensionless numerical constant (which turns out to be 2π). Notice that mass cannot appear in the formula, because there is no way to combine L, m, and g to get dimension T if m appears—a result that many students find surprising but that dimensional analysis delivers effortlessly.

The **Buckingham π theorem** formalizes this approach: if a physical problem involves n variables containing k independent dimensions, the solution can be expressed in terms of (n − k) dimensionless groups. This principle is why wind tunnels work—a scale model airplane at appropriately chosen speed and air density produces the same dimensionless aerodynamic coefficients as the full-size aircraft.

3.2 Natural Units and the Planck Scale

By combining the fundamental constants G, $\hbar$, and c, we can construct quantities with dimensions of length, time, mass, and temperature—the **Planck units**:

$$\text{Planck length: } l_P = \sqrt{(\hbar G/c^3)} \approx 1.6 \times 10^{-35} \text{ m}$$

$$\text{Planck time: } t_P = \sqrt{(\hbar G/c^5)} \approx 5.4 \times 10^{-44} \text{ s}$$

$$\text{Planck mass: } m_P = \sqrt{(\hbar c/G)} \approx 2.2 \times 10^{-8} \text{ kg}$$

$$\text{Planck temperature: } T_P = \sqrt{(\hbar c^5/(G k_B^2))} \approx 1.4 \times 10^{32} \text{ K}$$

The Planck scale marks the boundary where both quantum mechanics and general relativity are simultaneously important—where our current theories break down. At the Planck length, spacetime itself may become granular or foamy. At the Planck time, the universe was so young that our notions of space and time may not apply. The quest for a theory of quantum gravity is, in essence, a quest to understand physics at the Planck scale.

3.3 Fermi Estimation

A **Fermi estimation** (or "back-of-the-envelope calculation") breaks a complex question into simpler subproblems, estimates each, and combines them. The art lies in choosing the right decomposition and in knowing when precision matters and when it doesn't.

Example: How many molecules of Caesar's last breath are in every breath you take? Assume Caesar's last breath (~2 L at STP, containing ~5×10^{22} molecules) has been uniformly mixed into the atmosphere (~4×10^{44} molecules total). The fraction of the atmosphere that was in Caesar's breath is about $5 \times 10^{22} / 4 \times 10^{44} = 1.25 \times 10^{-22}$. Each breath you take contains ~2.5×10^{22} molecules, so the expected number of "Caesar molecules" per breath is ~$2.5 \times 10^{22} \times 1.25 \times 10^{-22} \approx 3$. You inhale about three molecules from Caesar's dying breath in every breath you take.

Fermi estimations work because errors tend to cancel: overestimates of some factors compensate underestimates of others. The goal is never exact answers but the correct order of magnitude—10^1 versus 10^3 versus 10^6. Being within a factor of 3 of the true answer is considered excellent.

> **Enrico Fermi (1901–1954)**
>
> The Italian-born physicist was the last great master of both theoretical and experimental physics. He developed the theory of beta decay, built the first nuclear reactor (Chicago, 1942), and was legendary for his ability to solve problems with minimal calculation. His "Fermi questions" are still used in physics education and job interviews. When the Trinity test was detonated, Fermi dropped scraps of paper and estimated the bomb's yield from their displacement at 10 kilotons—remarkably close to the measured 20 kilotons.

3.4 Scaling Laws

Scaling laws describe how physical quantities change with size. An ant can carry 50 times its own weight; a human cannot—because muscle strength scales as cross-sectional area (L^2) while weight scales as volume (L^3). Doubling an animal's linear dimensions increases its weight eightfold but only quadruples its muscle strength. This is why elephants have proportionally thicker legs than mice, why insects can walk on water but humans cannot, and why Godzilla is physically impossible.

The **surface-to-volume ratio** ($\propto 1/L$) explains why small organisms lose heat rapidly (and must eat constantly), why nanoparticles are so chemically reactive (most atoms are on the surface), and why a lump of coal burns slowly but coal dust can explode. The entire field of nanotechnology is built on the fact that at small scales, surface effects dominate volume effects.

PART II

Mathematical Foundations

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Chapter 4: The Imaginary World — Complex Numbers



The complex number plane and Euler's identity

How an "Impossible" Number Became the Alphabet of the Universe

When you were little and learning to count on your fingers, the world was simple. Two blocks plus three blocks equals five. But then came the question: "What is two minus three?" Your childhood answer might have been: "That's impossible—there's nothing left." And you were right—in the world of apples and blocks, negative numbers don't exist. Yet we accepted them because they're useful for describing debts or temperatures below zero.

A few years later in school came another prohibition: "You cannot take the square root of a negative number." The square root of minus one? Nonsense. What number multiplied by itself gives minus? None. Positive times positive is plus, negative times negative is also plus.

For a long time, it seemed that mathematics ended here. That there was nothing beyond this wall. But then it turned out that precisely beyond this wall hides the language through which the very essence of reality speaks to us.

4.1 The Duel in Venice

> **GEROLAMO CARDANO (1501–1576)**
>
> "I was too clever to be happy."
>
> Italian polymath—mathematician, physician, astrologer, gambler, and perhaps the greatest scoundrel in the history of mathematics. He wrote over 200 books on everything from algebra to dream interpretation.
>
> Born illegitimate, he fought for recognition his whole life. He became a famous physician (treating archbishops and popes), but his son was executed for poisoning his wife, and another son robbed him.
>
> Tartaglia revealed the solution to cubic equations to him under oath of secrecy. Cardano broke the oath and published the formulas in his *Ars Magna* (1545). Tartaglia was furious, but Cardano's betrayal paradoxically ensured the discoveries reached future generations.
>
> In the same book, square roots of negative numbers first appeared—"so subtle they are useless," Cardano wrote. Four centuries later, they turned out to be the foundation of quantum mechanics.
>
> According to legend, he predicted the date of his own death using astrology. When the day came and he was still alive, he allegedly committed suicide so as not to be wrong.

The story of the number that "doesn't exist" begins as a Renaissance thriller full of intrigue, betrayal, and duels. In 16th-century Italy, mathematicians didn't publish their discoveries in journals. They guarded them like trade secrets. They had to defend their positions and salaries in public mathematical duels, where they posed problems for each other to solve. Losing meant public humiliation and often loss of employment.

In 1535, a famous duel took place in Venice. On one side stood Antonio Fiore, on the other Niccolò Tartaglia—a self-taught genius whose face had been slashed by a soldier's sword as a child, leaving him with a stutter for life (Tartaglia means "Stutterer").

The subject of the duel was cubic equations (e.g., $x^3 = 15x + 4$). Until then, no one could reliably solve them. Tartaglia discovered the general procedure the night before the duel and crushed Fiore. He wanted to keep his secret, but eventually revealed it under oath of secrecy to another mathematician, Gerolamo Cardano.

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