Lesson 1: What is Physics? Theories, Models, and Prediction

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Prerequisites

None.

Learning goals

By the end of this lesson, you will be able to:

- Explain what physics is as a human activity and distinguish it from related fields like mathematics, philosophy, and engineering.
- Describe the roles of observation, experiment, and measurement in physics.
- Define what a physical theory is and what makes one successful.
- Explain the central importance of quantitative prediction in physics.
- Distinguish between a model and the underlying reality it describes.
- Recognize that physical theories are human constructions built from evidence, always provisional, and tested against experiment.
- Identify common ways that ideas about physics can become detached from evidence and experiment.

The story and motivation

We are starting at the very beginning because many people arrive at physics with strong preconceptions. Some view it as a collection of strange facts about the universe. Others treat it as a source of ultimate truths or mystical insights. Still others dismiss parts of it as impossible because they conflict with everyday intuition.

None of those views capture what physics actually is.

Physics is a specific human enterprise. It is the systematic attempt to describe the behavior of the natural world in terms of precise, quantitative rules that can be tested by experiment. We observe patterns in nature, propose mathematical models that account for those patterns, make new predictions from the models, and then perform experiments to check whether those predictions hold.

If the predictions match the experiments (within measurement accuracy), the model survives and gains credibility. If they do not match, the model must be modified or replaced. This process has no endpoint. Every theory remains open to revision in light of new evidence.

This disciplined reliance on experiment and measurement is what separates physics from speculation, philosophy, or personal intuition. A statement about the physical world may be interesting, profound, or intuitively appealing, but unless it leads to testable quantitative predictions that can be confirmed or falsified by measurement, it is not part of physics.

We begin here because everything that follows in this curriculum rests on this foundation. Later topics will involve sophisticated mathematics and abstract concepts, but they all serve the same goal: to build models that predict the outcomes of experiments accurately and consistently.

Definitions and notation

We introduce a few key terms carefully. Each definition includes the formal statement, a plain-English explanation, two examples, and one non-example.

Definition 1: Observation Formal: An observation is the recording of a phenomenon in the natural world using human senses or instruments. Plain English: Noticing something that happens without controlling how it happens. Example 1: Seeing that the Sun rises in the east every morning. Example 2: Detecting cosmic microwave background radiation with a radio telescope. Non-example: Imagining what the inside of a black hole looks like without any data.

Definition 2: Experiment Formal: An experiment is a controlled procedure carried out to test a specific prediction, where variables are deliberately manipulated and outcomes measured. Plain English: Setting up a situation on purpose to see if something happens as expected. Example 1: Dropping objects of different masses in a vacuum chamber to measure their acceleration. Example 2: Colliding protons at the LHC to search for new particles. Non-example: Watching leaves fall from a tree and drawing conclusions without measuring times or distances.

Definition 3: Measurement Formal: A measurement is the assignment of a numerical value and unit to a physical quantity obtained through an experiment or standardized procedure. Plain English: Putting a number and unit on something we observe in a repeatable way. Example 1: Timing how long a ball takes to fall 10 meters (result: 1.43 seconds). Example 2: Determining the wavelength of light emitted by hydrogen (result: 656.3 nanometers). Non-example: Describing light as "vibrating energy" without specifying any measurable quantity.

Definition 4: Physical theory Formal: A physical theory is a mathematical model together with rules for its application that accounts for a wide range of observations and enables quantitative predictions about future experiments. Plain English: A precise mathematical description that explains many measurements and correctly forecasts new ones. Example 1: Newtonian mechanics (predicts planetary orbits and falling objects). Example 2: Special relativity (predicts time dilation in GPS satellites). Non-example: A verbal claim that "everything is connected" without equations or testable predictions.

Definition 5: Model (in physics) Formal: A model is a simplified representation of reality used within a theory to calculate outcomes. Plain English: We never claim the model is reality itself; it is a tool that works well in certain domains. Example 1: Treating Earth as a point mass when calculating orbits. Example 2: Describing electrons as point particles in quantum electrodynamics. Non-example: Insisting that the mathematical description is the ultimate metaphysical truth rather than a useful approximation.

Main development

Physics begins with observation. We notice regularities in nature: objects fall, seasons repeat, magnets attract iron. These regularities invite questions.

Early humans explained them with stories involving gods or spirits. Those stories were meaningful culturally but did not allow precise prediction. If you needed to know exactly when an eclipse would occur, mythology was useless.

The pivotal shift occurred when people began demanding quantitative agreement with measurement. Galileo measured falling bodies and rolling balls. Newton proposed mathematical laws that matched Galileo's numbers and predicted new phenomena, such as planetary motion.

The theory succeeded because anyone could perform the experiments and obtain the same numbers (within measurement error). The theory failed in other regimes (very high speeds, very strong gravity), leading Einstein to propose better models.

This cycle (observation → mathematical model → prediction → experiment → refinement or replacement) defines physics.

A crucial point: physical theories are always provisional. They are never proven true in an absolute sense. They are only confirmed by all experiments performed so far. A single reproducible contradiction forces revision.

Another crucial point: the mathematical structure of a theory is chosen because it matches measurements, not because it feels profound or matches personal intuition. Many successful theories violate everyday intuition (quantum mechanics, relativity), yet they predict experimental results with extraordinary accuracy.

When people detach claims from experimental testing and instead appeal to intuition, philosophical preference, or alleged deeper meaning, those claims cease to be physics. They may be interesting in other contexts, but they do not belong to the discipline we are studying.

Physics advances precisely by refusing to accept ideas, no matter how attractive, that cannot be tested quantitatively.

Let us now clear up three misconceptions that frequently arise when people first encounter physics.

First misconception: the phrase "it's just a theory." You will often hear this dismissively applied to well-established ideas such as evolution or the Big Bang. The complaint sometimes continues with "Why hasn't it become a law if it is true?"

This confusion comes from everyday language. In ordinary speech, a theory means a hunch or guess. In physics, the word has a precise technical meaning. A physical theory is a comprehensive mathematical framework that explains a broad class of phenomena and makes detailed, quantitative predictions that have been repeatedly confirmed by experiment.

A physical law, by contrast, is usually a single mathematical relation that describes a specific regularity (for example, Newton's law of gravitation or the ideal gas law). Laws are often components within a larger theory. Newton's laws of motion are part of Newtonian mechanics, which is a theory. Einstein's general relativity is a theory that contains the Einstein field equations (sometimes loosely called laws).

Well-tested theories do not "graduate" into laws. They remain theories because they are broad explanatory structures. The theory of general relativity is far more firmly established than many individual laws, yet it is still called a theory. The label reflects scope, not uncertainty.

Second misconception: the worry that modern theoretical physics, especially areas like string theory or quantum gravity, consists of untestable ideas detached from experiment.

Every serious proposal in theoretical physics begins with the requirement that it must, in principle, make testable predictions. Sometimes those tests are currently beyond our technological reach (for example, probing Planck-scale physics requires energies far higher than any existing accelerator). Theorists therefore look for indirect consequences, consistency conditions, or predictions in related domains such as cosmology or condensed-matter analogues.

Ideas that make no testable predictions at all, even in principle, are not considered part of physics proper. They may be interesting mathematical structures, but they do not qualify as physical theories under the definition we are using. The field continually refines proposals to bring them closer to experimental scrutiny. Progress comes precisely from maintaining the link to measurement, however distant it may currently appear.

Third misconception: the complaint that physics involves "too much math" or that the mathematics obscures simple underlying truths.

Mathematics is not an optional decoration in physics. It is the language that allows us to state relationships with the precision required for quantitative prediction. Verbal descriptions are inevitably vague or ambiguous when applied to extreme regimes (high speeds, strong gravity, microscopic scales). Mathematics removes that ambiguity.

Every successful physical theory has been mathematical at its core. Newton did not merely say "objects attract"; he wrote $F = Gm_1m_2/r^2$ and showed how to derive observable consequences. Einstein did not merely say "gravity curves space"; he wrote ten coupled nonlinear partial differential equations and predicted the bending of starlight during a solar eclipse.

The mathematics is there because nature, when probed carefully, exhibits patterns that demand precise description. As we proceed, you will see that the mathematical structures are chosen not for elegance alone, but because they match detailed measurements better than any alternative.

These clarifications reinforce the central point: physics is defined by its commitment to quantitative, testable prediction. Anything that deviates from that commitment, no matter how philosophically appealing or mathematically beautiful, lies outside the discipline.

Summary

Physics is the construction and testing of mathematical models that make precise, quantitative predictions about the outcomes of experiments. Observations and measurements provide the raw material. Experiments provide the test. Successful theories are those whose predictions consistently match measurements across many different situations.

All theories are provisional and limited in scope. They are tools, not ultimate truths. The power of physics lies in its insistence on experimental verification and its willingness to discard or modify ideas that fail that test.

No idea enters physics without surviving rigorous quantitative comparison with reality.

Practice set

Checkpoint questions

1. State in your own words the difference between an observation and an experiment.
2. Why can a physical theory never be proven absolutely true?
3. Give an example (not from the lesson) of a claim about nature that is not part of physics and explain why.

Core exercises

1. Describe how Newtonian gravity and general relativity differ in their status as physical theories. Which aspects make one more successful in certain regimes?
2. Explain why a model that perfectly matches all existing data but makes no new testable predictions is considered incomplete in physics.

Deepening problems

1. Consider the historical shift from Ptolemaic to Copernican models of the solar system. Both could be made to match observations at the time. What eventually distinguished the Copernican/Keplerian approach as better physics?

2. Reflect on why some people find quantum mechanics or relativity counterintuitive yet accept their predictions in technology (lasers, GPS). How does this illustrate the role of evidence over intuition in physics?

Lesson 2: Measurement, Units, and Dimensional Analysis

Prerequisites

Lesson 1 (What is Physics? Theories, Models, and Prediction).

Learning goals

By the end of this lesson, you will be able to:

- Explain why measurement is the foundation of quantitative physics.
- Distinguish between fundamental and derived quantities.
- Describe the role of units and the importance of standardized systems (especially SI).
- Perform basic unit conversions confidently.
- Use dimensional analysis to check equations and derive relationships.
- Estimate orders of magnitude and recognize the practical limits of measurement precision.
- Understand how experimental uncertainty arises and why no measurement is exact.
- Appreciate why physics insists on repeatable, numerical results rather than qualitative impressions.

The story and motivation

In Lesson 1 we established that physics lives or dies by quantitative prediction tested against experiment. But for a prediction to be quantitative, we must be able to assign numbers to physical quantities in a consistent, repeatable way. That process is measurement.

Without reliable measurement, there is no way to compare a theoretical prediction with reality. You cannot say "the model predicts the ball falls faster" and call it science; you must say "the model predicts the ball reaches the ground in 1.43 seconds from a height of 10 meters" and then measure whether it actually takes 1.43 seconds (or 1.43 ± 0.02 seconds).

Measurement requires agreed-upon standards: units. If I measure a length in feet and you measure it in cubits, we cannot compare results. Modern physics uses the International System of Units (SI) precisely because it provides universal standards that anyone, anywhere, can reproduce.

We also need tools to reason about quantities before we even perform calculations. Dimensional analysis lets us check whether an equation makes sense by looking only at the units involved. It can even guide us toward the correct form of a physical relation when we do not know all the details.

Finally, every measurement has limitations. No ruler is infinitely precise, no clock is perfect. Understanding uncertainty keeps us honest and prevents us from claiming more than the data support.

This lesson builds the practical foundation that every later calculation will rest upon. We will go slowly and carefully because errors here propagate through the entire subject.

Definitions and notation

We define key terms with the usual structure: formal definition, plain-English explanation, two examples, and one non-example.

Definition 1: Physical quantity Formal: A physical quantity is a property of a system that can be measured and expressed as a number multiplied by a unit. Plain English: Something we can assign a numerical value to in a repeatable way. Example 1: Length of a table (2.15 meters). Example 2: Mass of an electron (9.11×10^{-31} kilograms). Non-example: Beauty of a sunset (cannot be quantified repeatably).

Definition 2: Unit Formal: A unit is a standardized reference quantity used to express the magnitude of a physical quantity. Plain English: An agreed-upon "ruler" for comparison. Example 1: Meter for length. Example 2: Second for time. Non-example: "Handful" for volume (not standardized).

Definition 3: Fundamental quantity Formal: A fundamental quantity is one that is defined independently and not derived from other quantities. Plain English: Basic building block chosen by convention. Example 1: Length, time, mass in SI. Example 2: Electric current (ampere). Non-example: Velocity (derived from length and time).

Definition 4: Derived quantity Formal: A derived quantity is one defined in terms of fundamental quantities. Plain English: Built from the basic ones. Example 1: Area (length^2). Example 2: Force ($\text{mass} \times \text{acceleration} = \text{kg}\cdot\text{m/s}^2$). Non-example: Length itself.

Definition 5: Dimensional analysis Formal: Dimensional analysis is the examination of the dimensions (units) of physical quantities to check consistency or derive relationships. Plain English: Checking whether the units on both sides of an equation match, or using units to guess the form of a formula. Example 1: Verifying that energy ($\text{kg}\cdot\text{m}^2/\text{s}^2$) matches force $\times$ distance. Example 2: Deducing that period of a pendulum depends on $\sqrt{\text{length/gravity}}$. Non-example: Calculating numerical values without units.

Main development

We begin with the seven SI base units, because every measurement in modern physics traces back to them.

The current SI base units are:

- Meter (m) for length
- Kilogram (kg) for mass
- Second (s) for time
- Ampere (A) for electric current
- Kelvin (K) for thermodynamic temperature
- Mole (mol) for amount of substance

- Candela (cd) for luminous intensity

Each is defined by a precise physical procedure or constant (for example, the meter is defined via the speed of light, the second via cesium atom oscillations). This makes them reproducible anywhere in the universe.

All other units are derived. Velocity has dimensions [L][T]$^{-1}$, written as m/s. Acceleration is m/s^2. Force (newton) is kg·m/s^2.

We use bracket notation [ ] for dimensions to separate them from numerical values.

Why does this matter? Suppose you claim an equation for the speed v of an object falling distance d under gravity g: $v = \sqrt{dg}$. Check dimensions: $[v] =$[L][T]$^{-1}$ $[\sqrt{dg}] = \sqrt{[L][L][T]^{-2}} = \sqrt{[L]^2[T]^{-2}} = [L][T]^{-1}$

The dimensions match. The equation is dimensionally consistent. If you had written $v = dg$, dimensions would be [L]^2 [T]$^{-2}$, which does not match velocity. The equation would be dimensionally wrong, and you would know immediately to fix it.

Dimensional analysis often goes further. For a simple pendulum, the period T might depend on length l, mass m, gravity g, and perhaps amplitude θ (for small angles we ignore θ). We write $T \propto l^a m^b g^c$ and match dimensions: $[T] = [L]^a[M]^b([L][T]^{-2})^c$

This gives three equations for a, b, c. Solving shows $b = 0$ (mass does not matter) and $T \propto \sqrt{l/g}$. Dimensional reasoning alone reveals the correct dependence.

Next, uncertainty. Every measurement has error. If I measure a length with a ruler marked in millimeters, I might report 137.4 ± 0.5 mm. The ± 0.5 mm reflects the precision limit of the instrument and my reading.

In calculations, uncertainties propagate. Physics demands we track them so claims stay honest.

Finally, orders of magnitude. Physics spans enormous scales: from 10^{-35} m (Planck length) to 10^{26} m (observable universe radius). Estimating orders of magnitude quickly reveals whether a calculation is sensible. If a result comes out 10^{20} meters for the height of a building, you know something went wrong.

Summary

Measurement assigns numbers and units to physical phenomena. Standardized units (SI) ensure reproducibility. Dimensional analysis provides a powerful consistency check and discovery tool. All measurements carry uncertainty, and responsible physics accounts for it.

These tools turn qualitative impressions into the quantitative predictions that define the discipline.

Practice set

Checkpoint questions

1. State the SI base units for length, mass, and time.
2. What are the dimensions of energy in terms of length L, mass M, and time T?
3. If an equation has meters on the left side and seconds on the right, is it dimensionally consistent? Explain.

Core exercises

1. Express the unit of pressure (pascal) in terms of base SI units.

2. Use dimensional analysis to find possible dependence of kinetic energy on mass m and speed v (assume no other variables).

3. Convert 65 miles per hour to meters per second (use 1 mile $\approx$ 1.609 km).

Deepening problems

1. The range of a projectile depends on initial speed v, launch angle θ, and gravity g. Use dimensional analysis to show that range $\propto v^2/g$ (angle dependence cannot be found this way).

2. Estimate the order of magnitude of the number of atoms in a grain of sand (make reasonable assumptions and state them).

Lesson 3: The Role of Mathematics in Physics: Describing Structure and Making Predictions

Prerequisites

Lesson 1 (What is Physics? Theories, Models, and Prediction) and Lesson 2 (Measurement, Units, Dimensional Analysis, and Experimental Reality).

Learning goals

By the end of this lesson, you will be able to:

- Explain why mathematics is indispensable for quantitative physics rather than an optional tool.
- Distinguish between using mathematics for mere calculation and using it to describe structural relationships.
- Recognize that physical laws are expressed as precise relations between measurable quantities.
- Understand how mathematical idealization simplifies reality while preserving predictive power.
- Appreciate that the choice of mathematical framework is guided by experimental success, not prior philosophical preference.
- Identify why verbal or purely qualitative descriptions cannot substitute for mathematical ones in physics.
- Prepare yourself for the gradual introduction of increasingly sophisticated mathematical tools in later lessons.

The story and motivation

We have seen that physics demands quantitative predictions that can be checked against measurement. Measurement gives us numbers attached to units. To connect those numbers across different experiments and make new predictions, we need a language capable of expressing exact relationships.

That language is mathematics.

Many students arrive believing mathematics in physics is mostly about "plugging numbers into formulas" or performing tedious calculations. That view misses the deeper point. Mathematics is not primarily a computational device here. It is the tool that lets us state structural relationships between physical quantities with complete precision.

A verbal statement like "force causes acceleration" is too vague. How much acceleration? Does it depend on mass? On anything else? Mathematics removes the ambiguity: $F = ma$.

As we move to more complex phenomena (curved spacetime, quantum states, fields permeating space), verbal description becomes entirely inadequate. Only mathematical structures can capture the patterns observed in experiments and extrapolate them reliably.

We are not claiming that the universe "is" mathematics in some metaphysical sense. We are saying that the patterns nature exhibits, when probed quantitatively, match certain mathematical relations extraordinarily well. Those relations allow predictions of unprecedented accuracy.

This lesson bridges the conceptual foundation of Lessons 1 and 2 to the mathematical development that begins in earnest next. We will not yet introduce new technical machinery. Instead, we will clarify why that machinery is necessary and how it will be used.

Definitions and notation

We define a few central ideas.

Definition 1: Mathematical model (refined) Formal: A mathematical model in physics is a set of mathematical objects (numbers, functions, vectors, operators, geometries, etc.) together with rules that relate them, assigned to physical quantities in such a way that measurable predictions follow. Plain English: A precise mathematical description we map onto reality to compute numbers we can compare with experiment. Example 1: Newtonian mechanics models position as a vector $\mathbf{r}(t)$ satisfying $m\frac{d^2\mathbf{r}}{dt^2} = \mathbf{F}(\mathbf{r}, \mathbf{v}, t)$. Example 2: Quantum mechanics models the state of a particle with a wave function $\psi(x,t)$ satisfying the Schrödinger equation. Non-example: A vague analogy like "the atom is like a solar system" without equations.

Definition 2: Idealization Formal: An idealization is the deliberate simplification or approximation of a physical system within a model to make exact mathematical treatment possible. Plain English: Ignoring complicating factors that are small in the regime of interest. Example 1: Treating a planet as a point mass with no internal structure. Example 2: Modeling air resistance as zero for short falls. Non-example: Ignoring gravity entirely when calculating the motion of a thrown ball.

Definition 3: Physical law (mathematical form) Formal: A physical law is a mathematical relation between physical quantities that has been confirmed to hold (within specified accuracy and domain) across a wide range of experiments. Plain English: A precise equation that nature reliably obeys in the situations we have tested. Example 1: Conservation of energy: $\Delta E = 0$ for isolated systems. Example 2: Coulomb's law for electrostatic force between point charges. Non-example: A statement like "opposites attract" without the $1/r^2$ dependence and constant k.

Main development

Consider a simple example: free fall near Earth's surface.

Observation shows objects fall faster and faster. Measurement reveals the distance fallen d is proportional to the square of time t: $d \propto t^2$.

We express this mathematically as $d = \frac{1}{2}gt^2$, where g is a constant we measure (approximately 9.8 $\mathrm{m/s^2}$).

The equation is not arbitrary. It matches thousands of measurements. From it we predict: if you drop an object from 19.6 meters, it will take exactly 2 seconds to hit the ground (ignoring air). Anyone can test this.

A purely verbal description cannot achieve that precision. Words like "quickly" or "steadily increasing speed" do not tell you exactly when the object will hit the ground.

As phenomena grow more complex, the need for mathematics becomes more acute. In electromagnetism, electric and magnetic fields at a point influence charges elsewhere instantaneously in certain frames, but with specific strengths and directions. Maxwell's four equations (plus Lorentz force) capture all classical electromagnetic phenomena with a handful of mathematical statements.

In general relativity, gravity is described as curvature of four-dimensional spacetime. The mathematics is more sophisticated (tensors, differential geometry), but the principle is the same: the mathematical structure is chosen because its consequences match detailed measurements (light bending, orbital precession, gravitational waves).

We idealize constantly. Real objects are never perfect spheres, real vacuums never perfect, real measurements never infinitely precise. Yet the idealized mathematical models predict outcomes to many decimal places.

The mathematics is not imposed on nature because it is elegant or because we like it. It is selected because it works: it matches existing data and correctly predicts new data no one had measured before.

When a better mathematical description is found (quantum mechanics replacing classical for atomic scales, general relativity replacing Newtonian for strong gravity), we adopt it without sentiment.

This curriculum will introduce mathematical tools gradually and deliberately. We begin with basic notation, numbers, and sets, then build algebra, geometry, calculus, and beyond. Every tool will be motivated by the physical structures it describes, not introduced for its own sake.

Summary

Mathematics provides the precise language that connects measurements across experiments and enables quantitative prediction. Physical theories are mathematical models mapped onto reality. Idealizations simplify while preserving predictive power. The choice of mathematical framework is dictated solely by agreement with experiment.

Physics without mathematics would be limited to vague qualitative impressions. With mathematics, it becomes the extraordinarily successful enterprise we know.

Practice set

Checkpoint questions

1. Why is a purely verbal description of a physical law insufficient for physics as we have defined it?
2. Give an example of an idealization in everyday physics calculations.
3. What criterion determines whether a particular mathematical structure is adopted in a physical theory?

Core exercises

1. Explain how the mathematical form of Newton's second law ($F = ma$) eliminates ambiguity present in the verbal statement "force causes acceleration."
2. Consider the ideal gas law $PV = nRT$. Identify which quantities are idealized and why the equation remains useful despite those idealizations.

Deepening problems

1. Reflect on why Einstein's general relativity, despite its much greater mathematical complexity, replaced Newtonian gravity. Focus on predictive success rather than philosophical appeal.
2. Imagine trying to describe the double-slit experiment in quantum mechanics using only words and no equations or diagrams. What essential predictive content would be lost?

We will begin introducing concrete mathematical notation and tools in the next lesson.