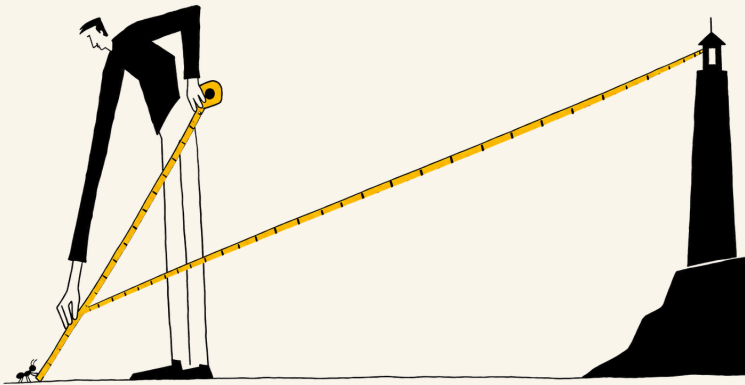


College Physics



Paul Peter Urone, Roger Hinrichs · 2022

Illustrated audio lectures

Lecturized

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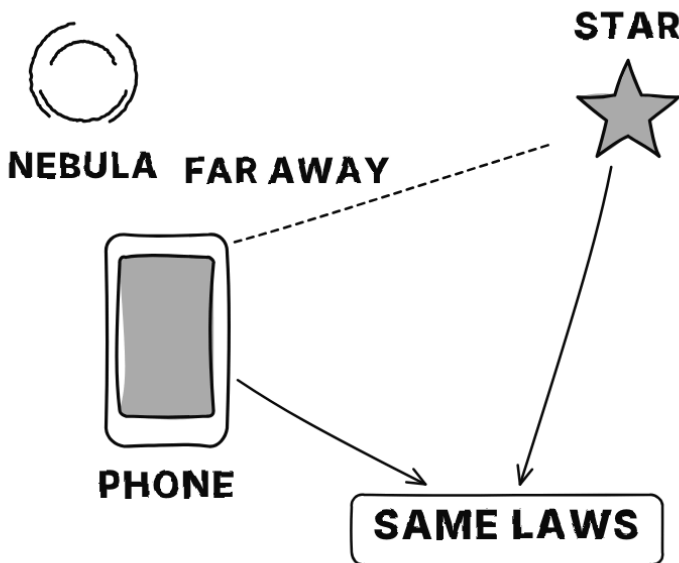
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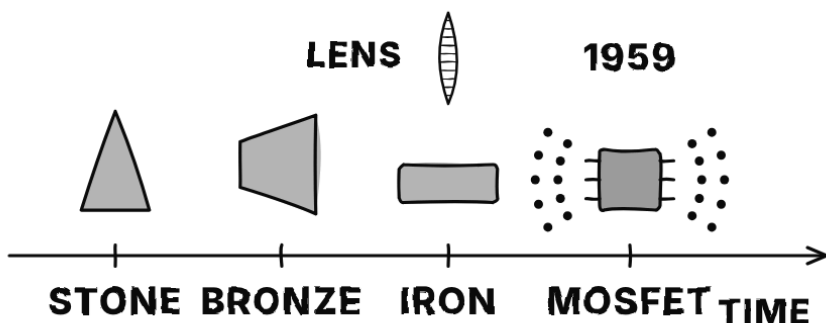
Tonight, if the sky is clear, step outside and find one bright star. Hold your phone up beside it, so that the glowing screen and the distant point of light sit in the same view. You would expect the two to have nothing in common: one is a slab of glass and metal in your hand, the other a furnace of gas more than a lifetime of light-years away. And yet the light from both comes from the same handful of rules, the same ones that make a kettle boil and a dropped key fall. That surprise is where this book begins, and it is the main line of everything that follows.



Phone and star, one set of rules

The first picture in the book is the Veil Nebula, a vast cloud of glowing gas about two thousand four hundred light-years from Earth. A light-year is the distance light covers in a year, roughly nine and a half trillion kilometers, so the cloud is unimaginably far and unimaginably large. It is what is left of a star that exploded about eight thousand years ago, and its blast wave is still ploughing into the gas around it, drawing thin glowing threads and sheets. Astronomers compare new photographs of it with ones the Hubble telescope took in 1997, and from the change they learn how such clouds spread. The point the book makes is plain: the forces at work out there are the same forces engineers deal with when they launch a rocket or heat a house. Its colours are the familiar glows of hydrogen, sulfur and oxygen, the same elements that make up everything around us.

The book then turns from the sky to human history. Each great age of technology, the Stone Age, the Bronze Age, the Iron Age, was marked by what people knew about materials and how to work them. How a stone flakes into a spear point, how carbon mixed into iron in the furnaces of South India and Sri Lanka gave the earliest fine steel, how polished glass makes a lens: all of that is physics, learned by hand long before it was written down. Our own age has its hero too, a tiny switch called the MOSFET, invented in 1959 in New Jersey by Mohamed Atalla, born in Egypt, and Dawon Kahng, born in Korea. More of these switches have been made than any other object in human history. Billions of them sit inside the phone you just held up to the star, and others steer the controls of a car and the electronics of a microwave oven.

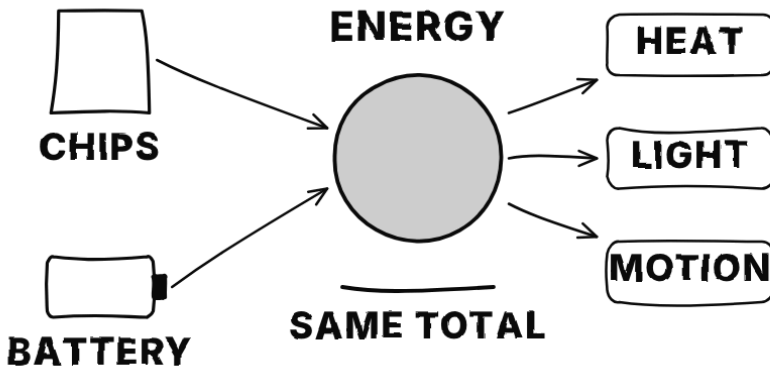


Ages built on materials

Physics also lives inside many jobs that do not have the word in their title. A pilot has to understand how the wind pushes on a plane and bends its path, and a physical therapist has to understand the forces on muscles as a body bends and moves. Engineers, electricians, doctors and programmers lean on the same ideas every working day. The book adds the newest wonders from the news, trains that float above their tracks, cloaks that bend light around themselves, tiny robots that hunt cancer cells, and says that they too rest on these same principles.

Here is the heart of the matter. The world is enormously varied: birds flying in formation, flowers of every colour, lightning, gravity, the smallest particles and the largest clusters of galaxies. Over centuries

people have gathered mountains of facts about all of it. And the striking discovery is that a surprisingly small set of laws explains what we see; nature turns out to be orderly and, underneath, simple. The book gives one example of such a law: energy can change its form, but it is never lost. A bag of chips and a car battery look like strangers, yet both store energy that can be turned into other forms, and the same law ties together food, batteries, heat, light and a wound-up spring. The calories printed on a snack packet and the charge in your phone's battery are two entries in the same account. Said another way, physics is not a list of facts to memorize; it is a short list of rules that lets you connect things which seemed to have nothing to do with each other.



Energy changes form

That is why the book promises more than a tour of topics. Learning to apply a few laws trains a way of thinking, an analytical habit that carries far beyond any one book, into study and into whatever work you choose. Ahead lie a short history of how natural philosophy grew into physics, from ancient thinkers of the Middle East and the Mediterranean up to Newton, and then the common system of units that lets scientists everywhere speak one mathematical language. Last comes the honest part: how accurate and how precise a measurement can be, and why scientists take such care to say exactly what they do not know. The details of each of these, from what physics studies to how laws, theories and models differ, are left for the parts that follow.

Remember

Nature is wildly varied in its details, but a small set of physical laws explains a great deal of it. The same forces act in a distant exploding star and on a kitchen table. Every age of technology, from stone tools to the transistors in a phone, grew out of knowing how materials behave. The law that energy changes form but is never lost links things as different as food, batteries and light. What physics really teaches is a way of thinking that connects instead of memorizing.

Questions

1. Why can scientists learn something useful for Earth by watching a cloud like the Veil Nebula?

- a. Because the forces that shape the cloud are the same forces at work on Earth
 - b. Because the cloud is close enough to be visited and sampled
 - c. Because the cloud is made of materials that are found nowhere on Earth
 - d. Because space follows its own rules that happen to resemble ours
2. What does the law that energy changes form but is never lost let you do?
- a. Treat food, batteries and light as separate subjects with separate rules
 - b. Connect things as different as a bag of chips and a car battery
 - c. Store energy forever without it ever being used
 - d. Avoid having to measure anything at all
3. According to the book, what is the most valuable thing studying physics gives you?
- a. A long list of facts about nature to memorize
 - b. A collection of formulas for the classroom
 - c. A way of thinking that applies a few laws far beyond one book
 - d. A detailed history of every invention
4. Why are the great ages of history named after materials such as stone, bronze and iron?
- a. Because those were the only materials people had at all
 - b. Because the names were chosen at random by historians
 - c. Because each material was discovered in a single year

- d. Because each age rested on knowing how a material behaves and how to work it

Answers

1. **a)** The same forces act out there and here, whether in an exploding star or when we launch a rocket or heat a house.
2. **b)** Both a snack and a battery store energy that can turn into other forms, and one law ties them together.
3. **c)** Learning to apply a few laws trains an analytical habit that carries into study and into any work you choose.
4. **d)** Each age was marked by what people knew about a material and how to shape it, and that knowledge is physics.

Practice

1. The book says nature is enormously varied, yet a small set of laws explains much of it. Pick two everyday things that seem unrelated and explain, using the law of conservation of energy, what they have in common.

Hint: Ask where the energy in each thing is stored and what it can turn into.

Answer: For example, a sandwich and a phone battery: both store energy, the sandwich as food calories and the battery as electrical charge. The law that energy changes form but is never lost says each can be turned into other forms, such as heat or motion, so the same rule describes both.

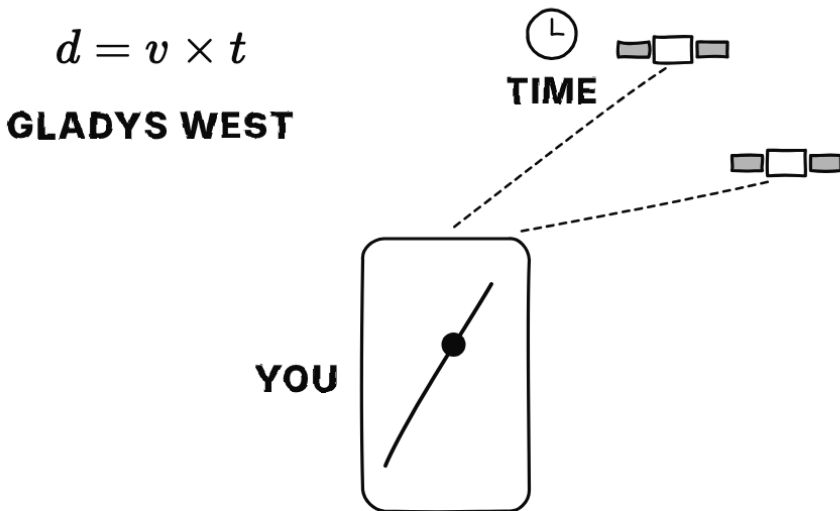
2. Explain in your own words why the book chose a tiny switch, the MOSFET, as the hero of the Information Age.

Hint: Think about how many have been made and where they are used.

Answer: Few people have heard of it, yet more MOSFETs have been made than any other object in history, and they sit inside computers, phones, cars, microwave ovens and medical instruments. Modern electronics is built on it, just as earlier ages were built on stone, bronze or iron.

What physics covers

Open the map on your phone and watch the little blue dot. Walk a few steps and it follows you, though nothing in your pocket can see the street. How does a device know where you are, to within a few steps? The answer, the book says, is physics, and the blue dot is a good way into what physics actually is.



Physics behind the blue dot

Physics is the study of how matter, energy, space and time act on one another, and above all of the basic mechanisms underneath every happening in nature. That is its whole territory, and it is huge: from

tiny charged particles to people, cars and spaceships, almost everything around you can be described quite accurately by its laws. Inside a smartphone, physics describes how electricity moves through the circuits, and that knowledge lets engineers choose the right materials and layout. The map on your phone rests on one of the simplest relations in physics, the link between how far something goes, how fast, and how long it takes. To work, the system has to account for the shape of the land, the exact distances to the satellites overhead, and even a subtle effect in which time itself runs slightly differently up there. Most of these calculations grew from the work of the mathematician Gladys West, who programmed the first computers able to pin down positions on Earth with high accuracy.

You do not need to be a scientist to use physics. It explains how a microwave oven heats food and why metal should never go inside one. It explains why a black car radiator helps carry heat away from an engine, and why a white roof keeps a house cooler. It also helps you judge the hazards of radiation calmly instead of by fear. The same thinking explains a car's ignition and the electrical signals that travel along your own nerves.

Physics is also the ground other sciences stand on. Chemistry deals with atoms and molecules, so it is rooted in the physics of atoms; most engineering is physics put to work; architecture needs it for sturdy buildings and for their sound, heating, lighting and cooling. Geologists use it to date rocks and to study earthquakes, and whole fields such as biophysics and geophysics are half physics by birth. In medicine it gives us x-rays, magnetic resonance scans and ultrasound measurements of blood flow, and radiotherapy against cancer. The book points out a quiet kinship here: a microwave oven and a brain

scanner both work with the same kind of waves, one to heat food, the other to find a tumour.

The book's conclusion is that nobody needs to study every application. What matters is to know the basic laws and to be skilled at applying them. Said in other words, physics keeps the most basic parts of science, so every other science uses it, and learning it makes them all easier. The details, such as how each of these devices works and how the many examples from biology and sensing play out, are left to the rest of the book.

Remember

Physics studies how matter, energy, space and time interact, and the basic mechanisms behind every happening in nature. Almost everything around you, from a phone's circuits to its map, can be described by its laws. You use it without being a scientist: in a microwave oven, a white roof, a car radiator. Chemistry, engineering, architecture, geology and medicine all stand on it. What counts most is knowing the basic laws and how to apply them, not memorizing every use.

Questions

1. Which relation from physics does the map on a phone rest on?
 - a. The link between how far something goes, how fast, and how long it takes
 - b. The link between the colour of light and its temperature

- c. The link between the weight of a phone and its battery
 - d. The link between the size of a screen and its brightness
2. Why can chemistry be said to be rooted in physics?
- a. Because chemists use the same laboratory glassware
 - b. Because chemistry deals with atoms and molecules, which atomic physics describes
 - c. Because chemistry was invented after physics
 - d. Because physics and chemistry use the same units only
3. What do a microwave oven and a brain scanner have in common?
- a. Both are used only in hospitals
 - b. Both work by heating whatever is inside them
 - c. Both work with the same kind of waves, put to different uses
 - d. Both were invented by Gladys West
4. According to the book, what is most worth learning about physics?
- a. Every one of its applications in detail
 - b. The history of each device
 - c. The names of the sciences that use it
 - d. The basic laws and the skill of applying them

Answers

1. a) Positioning comes down to one of the simplest relations in physics, distance, speed and time.

2. b) Chemistry studies how atoms and molecules interact, and that rests on the physics of atoms.

3. c) One uses the waves to heat food, the other to make an image and find a tumour.

4. d) Nobody needs to study every use; knowing the basic laws and how to apply them is what counts.

Practice

1. The book says physics is useful even if you are not a scientist. Pick one of its everyday examples, such as the white roof or the black car radiator, and explain in your own words what kind of question physics answers about it.

Hint: Ask what happens to heat in each case.

Answer: Both are about heat. Physics explains why a white roof helps keep a house cool and why a black radiator helps carry heat away from a car engine; the colour of a surface affects how it deals with heat, and physics gives the reason.

2. Name two fields besides physics that the book says rely on it, and say for each what physics gives it.

Hint: Look at geology, architecture or medicine.

Answer: For example, geology uses physics to date rocks and study earthquakes, and medicine uses it for x-rays, magnetic resonance scans, ultrasound measurements of blood flow and cancer radiotherapy.

Models, theories and laws

You turn the key in your car one morning, and nothing happens. You do not just stare at it; you start to guess. Maybe it is out of oil, so you open the bonnet and check the dipstick, and the oil is fine. So that guess was wrong, and you try the next one. Without noticing, you have just run the method that the whole of science rests on.

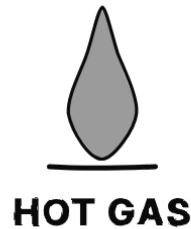
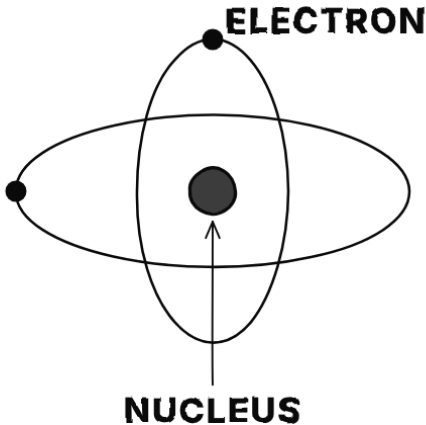
The book begins with where the laws of nature come from. They are built into the universe: people did not make them and cannot change them, only discover them and come to understand them. What we write down as a law is a human statement of a rule that every natural process already follows. Finding those rules is a very human adventure, full of imagination, struggle, triumph and disappointment. Isaac Newton had to be persuaded to publish his great work, and Marie Curie paid for her early research with her own money and her health, and became the only person to win Nobel Prizes in both physics and chemistry. Underneath it all lies one firm rule of the game: observation comes first, and science must describe the world as it is, not as we would like it to be.

It starts with ordinary curiosity, like wondering whether a certain kind of cloud means rain. When we get serious, we collect and study facts with care, measure more exactly, run controlled experiments where we can, and look for ways the facts fit together. From that work come three kinds of summary: models, theories and laws.

MODEL

THEORY

LAW



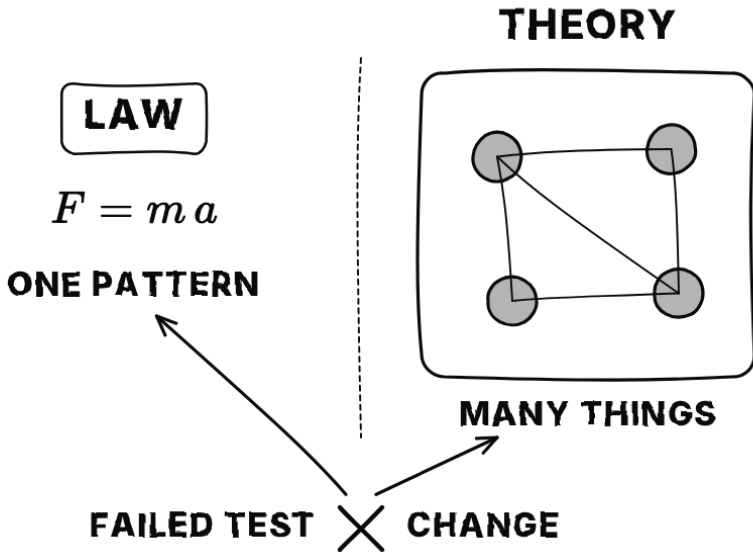
A model of the atom

A model is a picture of something we cannot show directly. The famous one is the atom drawn as a tiny solar system, with electrons circling the centre like planets round the Sun. Nobody can watch an electron go round, but the picture helps explain what we can see, such as the particular colours of light given off by a hot gas. A model is backed by evidence, yet it only works within certain limits; physicists use models to think through a situation, to calculate, or to build a simulation on a computer. A weather forecast on your phone comes from such a model: the computer pictures an atmosphere no one can see whole, in order to say what it will do next.

A theory, to a scientist, is not a guess, which is why the phrase "it's just a theory" sounds silly to them. A theory is a testable explanation

for patterns in nature, backed by evidence and confirmed many times by different groups of researchers. Where a model describes only some features of a thing, a theory should account for everything within its reach, and every consequence of it that can be tested should hold up. If an experiment ever shows one of those consequences to be false, the theory is either thrown out or adjusted, for instance by narrowing the range of cases it claims to cover. Some theories need a mental picture and some do not: Newton's theory of gravity needs none, since we can watch falling and orbiting bodies directly, while the theory of gases pictures a gas as countless tiny atoms and molecules too small to see.

A law is the shortest of the three: a brief, very general statement of a pattern in nature, backed by evidence and repeated experiments, often written as a single equation. The law that energy is conserved in any process is one; Newton's second law, which ties together force, mass and acceleration, is another. A theory, by contrast, is too large and too rich to squeeze into one line, as with the theory of evolution or the theory of relativity. Put simply, a law describes one kind of action, while a theory explains a whole family of related happenings; a law stands at the start of scientific reasoning, a theory is where it arrives. Narrower rules that hold only in special settings are usually called principles, though the line between laws and principles is often not drawn carefully.

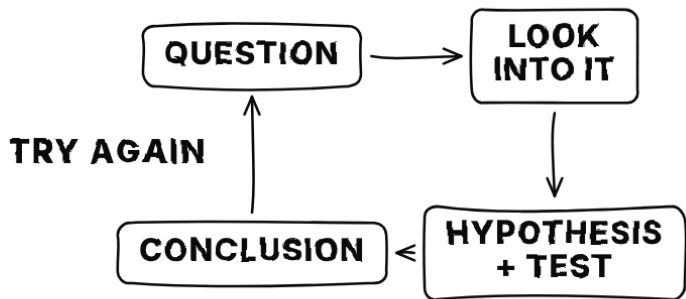
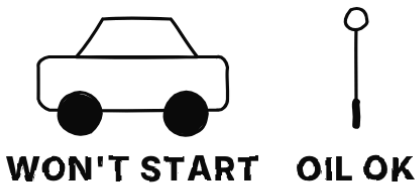


Law versus theory

These ideas do more than tidy up old facts. Often a model, theory or law points scientists toward things nobody has seen yet, and such predictions are among the great triumphs of science, possible only because the universe is orderly. But if experiment does not confirm a prediction, the theory or law is wrong, however elegant or convenient it may be. No law can be known with absolute certainty, because no one can try every possible experiment; physicists treat laws as valid until a solid, repeatable experiment contradicts them, and then the law must be changed or overthrown.

The way of working behind all this has a long history. A thousand years ago in Cairo, Ibn al-Haytham, who greatly advanced the study of light and vision, told scientists to be the enemy of everything they

read, to trust only objective evidence, and to test again and again, knowing that the senses and our own expectations can mislead us. His approach led toward what we now call the scientific method: notice something and ask a question, look into it, propose an explanation, test it by experiment, then study the result and draw a conclusion. That is exactly what you did with the car that would not start: the oil hypothesis failed the test, so you made a new one and went round again. The method works far beyond science, and it can be bent to suit the problem. This part leaves out how these ideas grew historically from natural philosophy into modern physics; that story comes next.



The method as a loop

Remember

The laws of nature are discovered, not invented, and observation of the world as it really is comes first. A model is a picture of something we cannot see directly, useful only within limits. A theory is a well-tested explanation of a whole family of happenings; a law is a short, general statement of one pattern, often a single equation. Every theory and law stays valid only until a reliable experiment contradicts it. The scientific method, observe, guess, test, conclude and try again, is what you already do when a car will not start.

Questions

1. Why does it sound silly to a scientist when someone says "it's just a theory"?
 - a. Because scientists never use the word theory
 - b. Because to a scientist a theory is a well-tested explanation, not a guess
 - c. Because every theory is already a law
 - d. Because theories cannot be tested
2. What happens to a well-established law if a solid, repeatable experiment contradicts it?
 - a. The law must be changed or overthrown
 - b. The experiment is ignored because the law is older
 - c. The law becomes a model instead

- d. Nothing, because laws are known with absolute certainty
3. Why do we need a model of the atom, but not of a falling apple?
- a. Because apples do not obey physical laws
 - b. Because the atom follows no theory at all
 - c. Because the atom is too small to see directly, while a falling body can be watched
 - d. Because models are only used for living things
4. Which is the main difference between a law and a theory?
- a. A law is a guess, a theory is proven
 - b. A law is older than any theory
 - c. A theory always comes with an equation, a law never does
 - d. A law states one pattern briefly; a theory explains a whole family of related happenings

Answers

1. **b)** A theory is a testable explanation for patterns in nature, backed by evidence and confirmed many times by different researchers.
2. **a)** No law can be known with absolute certainty; laws hold only until a reliable experiment contradicts them.
3. **c)** A model pictures what we cannot see; Newton's gravity needs no picture because we can watch the bodies themselves.
4. **d)** A law describes one kind of action, often as a single equation, while a theory is too rich to fit in one line.

Worked examples

The car that will not start You turn the key and the car will not start. Follow the scientific method to look for the reason, testing the idea that it has no engine oil.

Observe and ask: the car does not start, so the question is why.

Look into it: find out the various reasons a car may fail to start.

Propose a hypothesis: perhaps the car has no engine oil.

Test it: open the bonnet and check the oil level; it is at an acceptable level.

Conclude: the oil is not the cause, so form a new hypothesis and go round the cycle again.

Answer: The oil hypothesis is rejected by the test, and the search continues with a new hypothesis.

Practice

1. Sort these into model, theory or law, and say why: (a) energy is conserved in any process; (b) the atom pictured as a tiny solar system; (c) the theory of evolution.

Hint: Ask of each: is it a picture of something unseen, a brief general statement, or a large explanation of many related happenings?

Answer: (a) is a law: a short, very general statement of one pattern. (b) is a model: a picture of something too small to see, useful within limits. (c) is a theory: an explanation of a whole family of happenings, too rich to state in one line.

2. Why can no law of physics ever be known with absolute certainty? Explain in a few sentences.

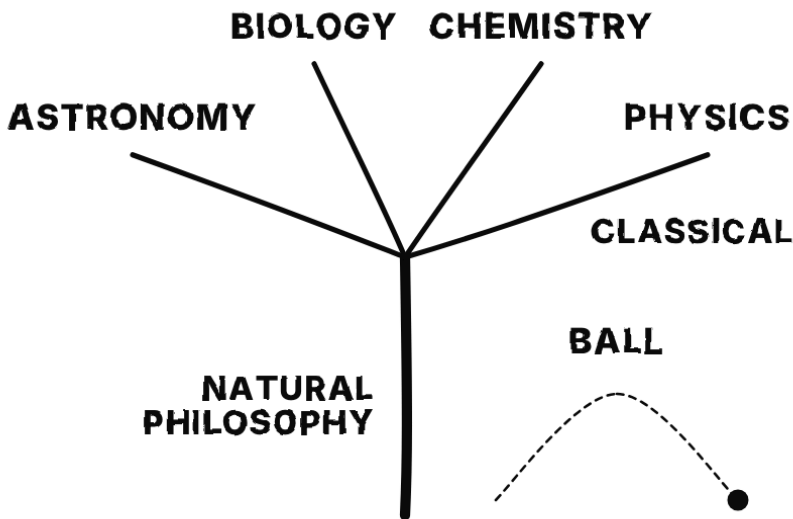
Hint: Think about how many experiments it would take to check a law in every possible case.

Answer: To be completely sure, one would have to test a law in every imaginable situation, which is impossible. So physicists treat a law as

valid until a good, repeatable experiment contradicts it, and then the law is changed or overthrown.

From natural philosophy to modern physics

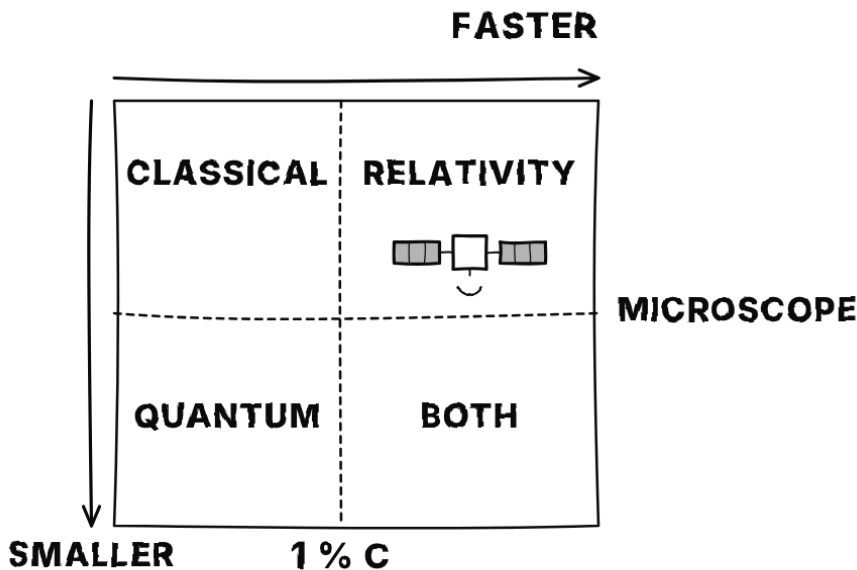
Throw a ball across a room and you can predict its path almost perfectly with rules that are three hundred years old. Now ask the same rules about an electron inside an atom, or a spacecraft racing near the Sun, and they begin to give wrong answers. Why should good rules suddenly fail? The answer comes from the history of physics itself.



Natural philosophy branches out

Physics was not always a separate subject. The word comes from the Greek for nature, and for a long time the study of nature was called natural philosophy, one broad field that held astronomy, biology, chemistry, physics, mathematics and medicine together. Aristotle wrote about physics, animals, the soul, politics and poetry all at once. Over the last few centuries knowledge grew so large that natural philosophy split into separate branches, and physics kept the most basic part. Ibn al-Haytham and Galileo stood at the turning points; much later, Niels Bohr helped build one of the pillars of the new physics of the twentieth century.

Physics from the Renaissance to the end of the nineteenth century is called classical physics, and the revolutionary discoveries that began around 1900 turned it into modern physics. Classical physics is not an exact account of the universe, but it is an excellent approximation under three conditions: things move slower than about one percent of the speed of light, they are large enough to be seen with a microscope, and gravity is weak, like the Earth's. Since we live in exactly those conditions, classical physics feels natural to us, while much of modern physics feels strange. That is why models matter so much in modern physics: they let us picture what we never experience, such as very fast motion or things too small to see. New instruments help too; a special microscope can now show the separate atoms in a sheet of gold.



Which theory where

Modern physics rests on two revolutionary theories. Relativity deals with the very fast and with strong gravity, and quantum mechanics deals with the very small. Joined together they make relativistic quantum mechanics, the most universally valid theory we have, but it is so mathematically demanding that it is used only when nothing simpler will do. The satellites behind your phone's map are a real case where everyday rules are not quite enough, which is why the system has to correct for the subtle effect on time mentioned earlier.

So why does most of the book stay with classical physics? For two reasons: it describes everyday life extremely well, and you cannot understand modern physics without it. The book also offers a quick test of the earlier ideas: if a friend has learned a new law, you already

know it will be a brief statement of a rule nature always follows; if it is a theory, you know it will be a broad explanation of a whole family of happenings. How physics measures things, with its agreed units and standards, is left for the next parts.

Remember

Physics grew out of natural philosophy, a single study of nature that split into separate sciences, with physics keeping the most basic part. Classical physics works superbly as long as things are slow, large enough to see with a microscope, and in weak gravity. Outside those limits we need modern physics: relativity for the very fast and strong gravity, quantum mechanics for the very small. Classical physics stays the core of the book because it describes everyday life so well and modern physics is built on it.

Questions

1. Why does classical physics feel natural to us, while modern physics often seems strange?
 - a. Because classical physics is exact and modern physics is only a guess
 - b. Because we live where things are slow, large enough to see and in weak gravity, exactly where classical physics works
 - c. Because modern physics was invented by philosophers rather than scientists
 - d. Because classical physics is newer and better tested

2. Which theory must be used for a spacecraft passing very close to the Sun at high speed?
 - a. Relativity, because of the strong gravity and the great speed
 - b. Quantum mechanics, because the spacecraft is very small
 - c. Classical physics, because the spacecraft can be seen
 - d. None, because no theory covers the Sun
3. Why does most of the book stay with classical physics even though modern physics is more exact?
 - a. Because modern physics has been proved wrong
 - b. Because modern physics is only about science fiction
 - c. Because it describes everyday life extremely well and modern physics cannot be understood without it
 - d. Because relativistic quantum mechanics is too new to be taught
4. What happened to natural philosophy as knowledge grew?
 - a. It was abandoned and replaced entirely by mathematics
 - b. It merged with medicine into a single science
 - c. It stayed one field that still covers everything
 - d. It split into separate sciences, with physics keeping the most basic part

Answers

1. **b)** Classical physics is an excellent approximation under the very conditions of everyday life, so it fits our experience.
2. **a)** Relativity deals with the very fast and with strong gravity such as that near the Sun.

- 3. c)** Classical physics is accurate for everyday circumstances, and knowing it is needed to understand modern physics.
- 4. d)** Over the last few centuries natural philosophy branched into separate fields, and physics kept the most basic facets.

Worked examples

A friend's new law A friend says they have learned about a new law of nature. What can you know about it before they describe it, and what would be different if they had learned a theory instead?

Recall what every law is: a brief statement of a rule that all natural processes follow.

So, without the details, you know the friend's law will be a short description of how nature always behaves.

Recall what a theory is: a broad explanation of a whole family of related happenings.

So if it were a theory, you would expect a large-scale, broadly applicable explanation rather than a single brief rule.

Answer: A law will be a concise statement of a rule nature always follows; a theory would be a broad explanation covering a whole group of related happenings.

Practice

1. For each case, say whether classical physics is enough or which part of modern physics is needed, and why: (a) a ball thrown across a room; (b) an electron inside an atom; (c) an object moving at a tenth of the speed of light.

Hint: Check the three conditions: slower than about one percent of the speed of light, large enough to see with a microscope, weak gravity.

Answer: (a) Classical physics: the ball is slow, visible and in Earth's weak gravity. (b) Quantum mechanics: the electron is far too small to see with a microscope. (c) Relativity: a tenth of the speed of light is well above one percent of it.

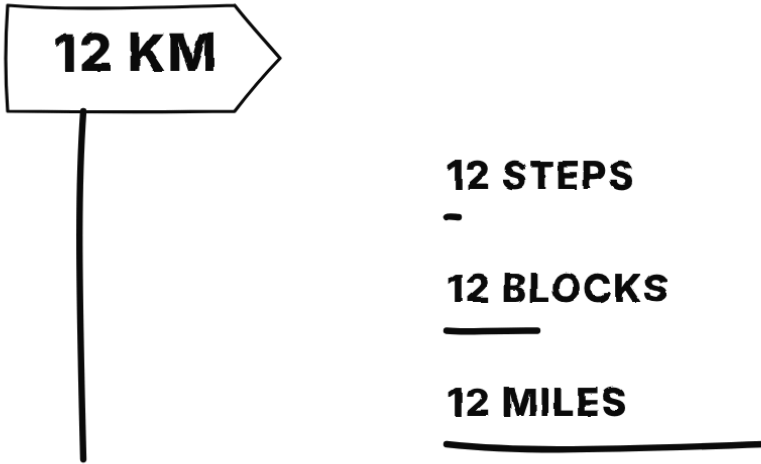
2. Why are models especially useful in modern physics? Explain in a few sentences.

Hint: Think about what modern physics deals with and whether we ever experience it directly.

Answer: Modern physics deals with things we never meet in daily life, such as very fast motion or objects too small to see. Models let us picture those things in human terms, as when we imagine an atom we have never seen with our eyes.

Why we need agreed units

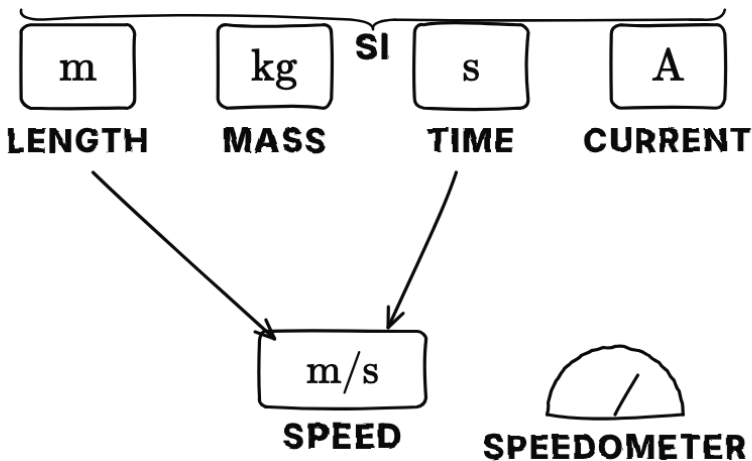
Imagine a road sign that reads simply: "Town, 12." Twelve what? Miles, kilometers, minutes of walking? Without the unit, the number is useless, and the book even shows a cartoon making exactly that point. This part is about why physics cannot work without units everyone agrees on, and where the two most basic ones come from.



Twelve what?

Physics deals with an enormous spread of sizes and times: from the fleeting life of an atomic nucleus to the age of the Earth, from particles smaller than a nucleus to the edge of the known universe,

from the push of a jumping flea to the pull between Earth and Sun. Putting numbers on these things, rather than only describing them in words, lets us understand nature far more deeply. But numbers only mean something if they come with accepted units. And here nature shows its simplicity again: almost every quantity in physics can be built from just four basic ones, length, mass, time and electric current.

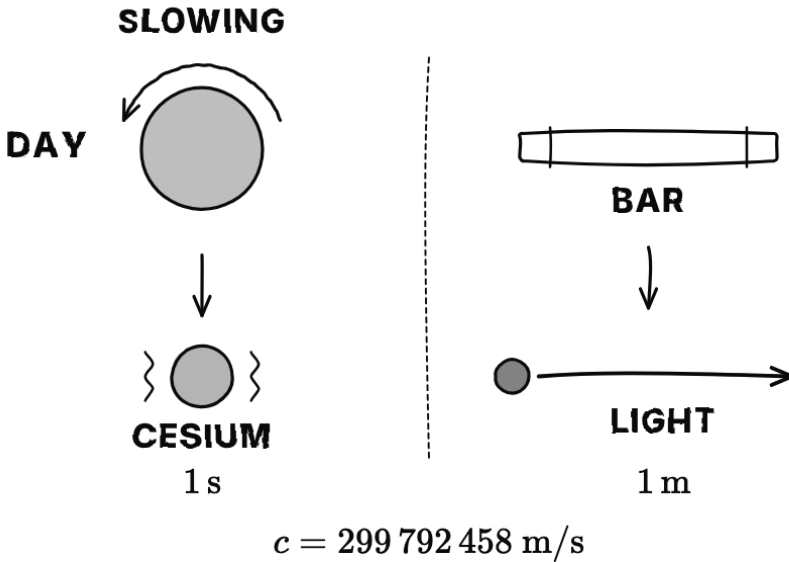


Four base units, many derived

A physical quantity is defined in one of two ways: either by saying how to measure it, as with distance and time, or by saying how to calculate it from other measurements, as with average speed, which is distance travelled divided by the time taken. Each measurement is then given in units, standard amounts, such as meters for a sprint or kilometers for a long-distance race. Two systems are in use in the world: the

international metric system, called SI after its French name, and the older English or imperial units, still common in the United States. Almost every other country, and scientists everywhere, use SI. The four basic SI units are the meter for length, the kilogram for mass, the second for time and the ampere for electric current; every other unit, for speed or force or electric charge, is built from these and is called a derived unit.

The second used to be a fraction of an average day, but the Earth's spin is slowly getting slower, so the day is getting longer and is no good as a fixed standard. Since 1967 the second has been tied instead to the steady vibrations of cesium atoms, counted by atomic clocks that drift by less than a millionth of a second in a year. Your phone quietly sets its clock from networks that in turn rely on such atomic time. The meter has a similar story: first a fraction of the distance from the equator to the North Pole, then the gap between two marks on a metal bar kept near Paris, then a count of wavelengths of light, and since 1983 the distance light travels in a vacuum in a tiny, fixed fraction of a second. That last choice fixes the speed of light at an exact number of meters per second.



Second and meter, made exact

Why all this care? Because every measurement in physics is in the end expressed through these basic units, and no measurement can be more accurate than the units themselves. The kilogram, the prefixes that stretch units over many powers of ten, and how to convert from one unit to another are left for the next parts.

Remember

A number without an agreed unit tells you nothing. Almost all of physics is built from four basic quantities: length, mass, time and electric current, measured in meters, kilograms, seconds and amperes. Every other unit is derived from these four. The second is now set by atomic clocks, and the meter by how far light travels in a fixed fraction of a second. Measurements can never be more accurate than the basic units they rest on.

Questions

1. Why was the second no longer defined as a fraction of the average day?
 - a. Because the day is slowly getting longer as the Earth's spin slows, so it is not a fixed standard
 - b. Because days are different lengths in different countries
 - c. Because clocks could not count that many parts of a day
 - d. Because the day was found to be exactly one hour shorter than believed
2. Why can no measurement be more accurate than the fundamental units?
 - a. Because fundamental units are only rough guesses
 - b. Because every measurement is in the end expressed through those units
 - c. Because measuring tools are always faulty

- d. Because derived units are more accurate than fundamental ones
3. Which of these is a derived unit rather than a fundamental one?
- a. The meter
 - b. The second
 - c. The unit of speed
 - d. The ampere
4. Since 1983, what is the meter based on?
- a. A fraction of the distance from the equator to the North Pole
 - b. The gap between two marks on a metal bar near Paris
 - c. The vibrations of cesium atoms
 - d. The distance light travels in a vacuum in a tiny, fixed fraction of a second

Answers

1. **a)** A standard must not change, and the solar day is gradually lengthening, so the second was tied to steady cesium vibrations instead.
2. **b)** All measurements rest on the basic units, so their accuracy sets the limit for everything built on them.
3. **c)** Speed is built from length and time, so its unit is derived; the meter, second, kilogram and ampere are the four fundamental units.
4. **d)** The meter is now the distance light covers in a vacuum in one part in 299,792,458 of a second, which fixes the speed of light exactly.

Worked examples

How far light goes in a millionth of a second The meter is defined so that light in a vacuum travels exactly 299,792,458 meters in one second. How far does light travel in one millionth of a second?

Distance travelled is speed multiplied by time, as the book's figure on the meter says.

The speed is 299,792,458 meters per second and the time is one millionth of a second.

Multiplying by one millionth moves the decimal point six places:
299,792,458 becomes 299.792458.

So the distance is about 300 meters.

Answer: About 300 meters (299.79 meters).

Practice

1. Average speed is defined as distance travelled divided by time of travel. A runner covers 10 kilometers in 50 minutes. What is the average speed in kilometers per minute?

Hint: Divide the distance by the time, and keep the units together.

Answer: 0.2 kilometers per minute: 10 kilometers divided by 50 minutes.

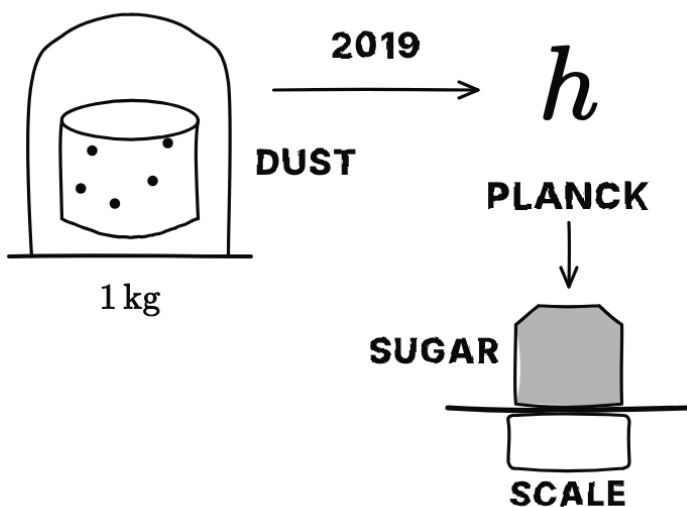
2. Before 1967 the second was $\frac{1}{86,400}$ of an average day. How many seconds are there in a day, and why does it make sense that a day has that many? (There are 24 hours in a day and 60 minutes in an hour.)

Hint: Count the seconds in an hour first.

Answer: 86,400 seconds: an hour has $60 \times 60 = 3,600$ seconds, and $24 \times 3,600 = 86,400$.

The kilogram and the prefixes

Put a bag of sugar on a kitchen scale and it reads one kilogram. But how does the scale know what a kilogram is? Somewhere at the end of a long chain of comparisons there has to be one master kilogram, and for more than a century that master was a small metal cylinder kept in a vault near Paris. Every bathroom scale and every pharmacy balance was, in the end, being compared with that single lump of metal.



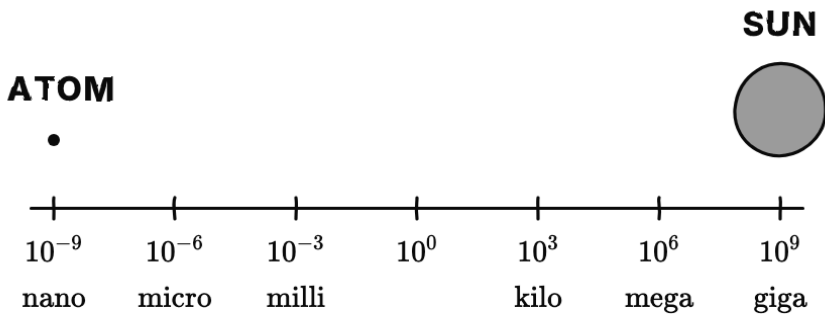
The kilogram leaves its cylinder

The cylinder was made of platinum and iridium, kept with the old meter bar at the international bureau of weights and measures, with

exact copies in places such as the American standards institute near Washington. It resisted rust, yet tiny traces of dirt from the air still settled on its surface and changed its mass very slightly over the years. A standard that drifts is a poor standard, so in May 2019 scientists adopted a new, steadier definition. The kilogram is now defined through the second, the meter and a fixed constant of nature from quantum physics, Planck's constant, which links the energy of a particle of light to its frequency.

Behind this lies a wider wish that the book describes. Physicists would like every basic unit to rest on the smallest building blocks of nature and on fixed features of the universe such as the speed of light, rather than on objects in a vault. Time already does, through the steady vibrations of cesium atoms, and length now rests on the speed of light. Electric current, the fourth basic quantity, will come much later in the book; the early chapters on motion, fluids, heat and waves need only length, mass and time.

The second half of the part is about the great convenience of the metric system: its units step up and down in factors of ten. There are a hundred centimeters in a meter and a thousand meters in a kilometer, whereas the older system has twelve inches to a foot and five thousand two hundred and eighty feet to a mile. A short prefix in front of a unit tells you the factor: kilo means a thousand, milli a thousandth, micro a millionth, nano a billionth, and so on, from things as huge as the distance light travels in a century down to the time light takes to cross an atom. So one unit serves every scale: meters for building, kilometers for air travel, nanometers for designing lenses, with no need to invent new units. The same idea is at work when your phone's storage is counted in gigabytes or a medicine dose in milligrams.



Prefixes along powers of ten

Thinking in powers of ten also gives a quick way to judge size, called the order of magnitude: a ballpark sense of scale. Eight hundred and four hundred and fifty are different numbers, but both are "hundreds", so they share an order of magnitude. An atom is roughly a ten-billionth of a meter across, while the Sun is roughly a billion meters across, and the gap between those orders of magnitude says more than any long list of digits. The full table of prefixes and the details of converting between units are left for the next parts.

Remember

The kilogram used to be a metal cylinder near Paris, but dirt from the air slowly changed its mass. Since 2019 the kilogram has been defined through the second, the meter and Planck's constant, a fixed number of nature. Physicists want every basic unit to rest on nature's smallest parts and unchanging constants. Metric units step in factors of ten, and a prefix such as kilo, milli or nano tells you which factor. The order of magnitude is a quick, ballpark sense of how big something is.

Questions

1. Why was the old metal kilogram replaced as the standard?
 - a. Because it was lost in a move from Paris
 - b. Because tiny traces of dirt from the air settled on it and slowly changed its mass
 - c. Because it rusted away
 - d. Because it was too heavy to use
2. What makes metric conversions easier than conversions in the older system?
 - a. Metric units are always smaller
 - b. Metric units have no names
 - c. Metric units change only by factors of ten
 - d. Metric units are used only by scientists

3. Why are 800 and 450 said to have the same order of magnitude?
- a. Because both are in the hundreds, the same power of ten
 - b. Because they differ by less than ten
 - c. Because both are even numbers
 - d. Because both can be divided by fifty
4. What do physicists hope to base every basic unit on?
- a. Objects kept in a vault near Paris
 - b. The length of a day
 - c. The size of the Earth
 - d. The smallest building blocks of nature and its unchanging constants

Answers

1. **b)** Though it resisted rust, airborne dirt stuck to its surface, so the standard drifted and a steadier definition was needed.
2. **c)** A hundred centimeters make a meter and a thousand meters a kilometer, whereas the old system uses twelve inches to a foot and 5,280 feet to a mile.
3. **a)** Order of magnitude is the ballpark scale, the power of ten, and both numbers are hundreds.
4. **d)** They want standards that rest on nature's smallest parts and fixed features such as the speed of light, as time and length now do.

Worked examples

Same order of magnitude Show that 800 and 450 are of the same order of magnitude.

Order of magnitude means the power of ten that sets the scale of a number.

800 is 8 times a hundred, that is 8×10^2 .

450 is 4.5 times a hundred, that is 4.5×10^2 .

Both carry the same power of ten, a hundred, so they share the order of magnitude 10^2 .

Answer: Both are of order 10^2 , that is, hundreds.

Practice

1. How many meters are in 3 kilometers, and how many inches are in one mile? Compare how easy each conversion is.

Hint: Use 1,000 meters in a kilometer; for the mile use 12 inches in a foot and 5,280 feet in a mile.

Answer: 3 kilometers is 3,000 meters, just a shift by a power of ten. One mile is $12 \times 5,280 = 63,360$ inches, which needs real multiplication. That is why metric conversions are simpler.

2. An atom is about a ten-billionth of a meter across, and the Sun about a billion meters across. By how many powers of ten do these orders of magnitude differ?

Hint: Write each as a power of ten: a ten-billionth is 10 to the minus ten, a billion is 10 to the nine.

Answer: Nineteen powers of ten: from 10 to the minus ten up to 10 to the nine is $9 + 10 = 19$ steps.

From a proton to the universe, and back to meters

Hold a single grain of sand on your fingertip. It is about a millimeter across, a thousandth of a meter. Now think of a proton, the core of a hydrogen atom: it is a trillion times smaller still. And think of the edge of the known universe, which lies at a distance written as a one followed by twenty-six zeros, in meters. The book's point in this part is simple and dizzying: physics has to talk about all of these with the same small set of units.

To give a feel for that range, the book sets out a long table of known lengths, masses and times, each given only by its order of magnitude. For length, it climbs from the smallest detail experiments can see, through the size of a proton and of an atom, the thickness of a cell's membrane, a grain of sand, a small child, a football field, the deepest ocean, the Earth, the distance to the Sun, a light-year, our galaxy, and finally the edges of the known universe. For mass, it runs from the electron, through a hydrogen atom, a bacterium, a mosquito, a hummingbird, a liter of water at about one kilogram, a person, a car, a ship, an iceberg, the Moon, the Earth, the Sun, our galaxy and the whole known universe. For time, it starts with the moment it takes light to cross a proton and goes through the swing of a light wave, a nerve impulse lasting about a thousandth of a second, a heartbeat of about one second, a day, a year, a human life, recorded history, the age of the Earth and the age of the universe. Two photographs frame the table: tiny sea plankton among ice crystals, a few micrometers to two millimeters long, and two galaxies colliding more than two billion

light-years away. The range, the book says, challenges the imagination.

With so many sizes, we constantly have to switch from one unit to another. A European recipe gives milk in liters and you want cups; a map gives a walk in feet and you want miles; a medicine label gives a dose in milligrams and you want to know how much that is in grams. The method the book teaches is called unit conversion, and it rests on one idea, the conversion factor. A conversion factor is just a ratio saying how many of one unit make another: twelve inches in a foot, a hundred centimeters in a meter, sixty seconds in a minute, a thousand meters in a kilometer. You write down what you have, multiply by the conversion factor arranged so that the unwanted unit cancels out, and the unit you want is left behind. The book's first example turns eighty meters into kilometers: the meters cancel and you are left with eight hundredths of a kilometer.

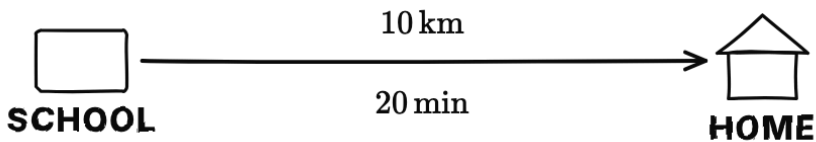
$$\frac{1 \text{ km}}{1000 \text{ m}}$$

CONVERSION FACTOR

$$80 \cancel{\text{ m}} \times \frac{1 \text{ km}}{1000 \cancel{\text{ m}}} = 0.080 \text{ km}$$

A conversion factor cancels units

Then it works a fuller example, a short drive home. You drive ten kilometers from school to home in twenty minutes, and you want your average speed, first in kilometers per hour and then in meters per second. Dividing distance by time gives half a kilometer every minute, and since an hour has sixty minutes, that becomes thirty kilometers per hour. That is the same kind of number your car's speedometer shows, a city speed, which is a good sign the answer is reasonable. Turning it into meters per second needs two factors at once, one swapping hours for seconds and one swapping kilometers for meters, and gives about eight and a third meters every second.



$$\frac{10 \text{ km}}{20 \text{ min}} = 0.500 \text{ km/min}$$

$$\times \frac{60 \text{ min}}{1 \text{ h}} = 30.0 \text{ km/h}$$

$$= 8.33 \text{ m/s}$$



Ten kilometres in twenty minutes

The worked example also teaches how to check yourself, and this is the heart of what is called dimensional analysis: letting the units guide and police the calculation. If you put a conversion factor in upside down, the units refuse to cancel and you end up with nonsense, something like kilometer-hours per minute squared, which is plainly not a speed. So you check that the units cancelled, that the answer is in the units asked for, and that the result makes sense: ten kilometers in a third of an hour means thirty in a full hour. The book also notes that the answer was given to three digits, and asks why; that question belongs to the next part.

A few side notes round it off. There are odd old units, such as the firkin, about thirty-four liters, once used for beer, and the barleycorn,

and each can be tied to SI. A hummingbird that beats its wings fifty times a second takes about twenty thousandths of a second per beat, so a scientist timing it would measure in seconds but write the result in milliseconds. And a cubic centimeter is exactly a milliliter, which shows how SI builds its unit of volume straight out of its unit of length. What this part leaves out is how exact any of these numbers really is, and how many digits we are entitled to write; accuracy, precision and uncertainty come next.

Remember

Physics spans an enormous range, from the size of a proton to the edges of the universe and from the time light takes to cross a proton to the age of the universe. Unit conversion uses conversion factors, ratios such as a thousand meters to a kilometer, arranged so that the unwanted unit cancels.

Dimensional analysis means letting the units check the work: if they do not cancel to the units you want, something is upside down. Ten kilometers in twenty minutes is thirty kilometers per hour, or about eight and a third meters per second. Always check that an answer is in the right units and is reasonable.

Questions

1. When you convert units, how should the conversion factor be arranged?
 - a. So that the unwanted unit cancels and the wanted unit is left

- b. So that the bigger number is always on top
 - c. So that both units stay in the answer
 - d. It does not matter which way round it goes
2. You converted a speed and ended up with units of kilometer-hours per minute squared. What does that tell you?
- a. That the answer is correct but unusual
 - b. That the speed is very high
 - c. That a conversion factor was put in upside down
 - d. That the distance was in miles
3. Why is thirty kilometers per hour a reasonable answer for ten kilometers in twenty minutes?
- a. Because any answer with the right units is reasonable
 - b. Because twenty minutes is a third of an hour, so in a full hour you would go three times as far
 - c. Because thirty is larger than ten
 - d. Because all city speeds are exactly thirty
4. What does the fact that a cubic centimeter equals a milliliter show?
- a. That volume is a fundamental quantity
 - b. That the liter is older than the meter
 - c. That milliliters and centimeters measure the same thing
 - d. That SI builds its unit of volume out of its unit of length

Answers

1. a) You multiply by the factor arranged so the unit you have cancels out, leaving the unit you want.

- 2. c)** If the factor is upside down, the units do not cancel and give nonsense instead of a speed.
- 3. b)** Ten kilometers in a third of an hour means thirty in a whole hour, which matches the result.
- 4. d)** The milliliter depends on the centimeter, so the unit of volume is derived from the meter.

Worked examples

A short drive home You drive the 10.0 km from school to home in 20.0 min. Find your average speed in kilometers per hour and in meters per second.

Average speed is distance divided by time: 10.0 km divided by 20.0 min gives 0.500 km per minute.

To get kilometers per hour, multiply by 60 minutes per hour, so that minutes cancel: $0.500 \times 60 = 30.0$ km/h.

Check: twenty minutes is a third of an hour, so in a full hour you would go three times 10 km, which is 30 km.

To get meters per second, multiply 30.0 km/h by 1,000 meters per kilometer and by one hour per 3,600 seconds.

$30.0 \times 1,000 \div 3,600 = 8.33$ meters per second.

Answer: 30.0 km/h, which is 8.33 m/s.

Practice

- 1.** Convert 80 meters to kilometers using a conversion factor.

Hint: There are 1,000 meters in 1 kilometer; arrange the factor so meters cancel.

Answer: 0.080 km: 80 m multiplied by 1 km per 1,000 m leaves $80 \div 1,000 = 0.080$ km.

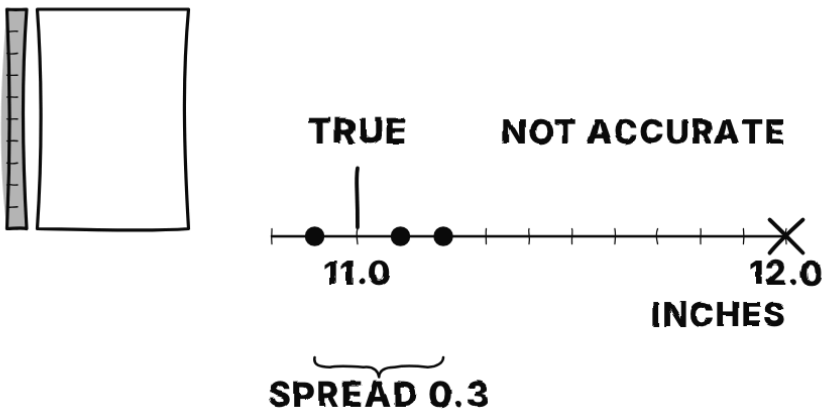
2. Some hummingbirds beat their wings more than 50 times per second. Which fundamental unit should a scientist use to time one wing beat, and which metric prefix suits the result?

Hint: Work out how long one beat lasts if there are 50 in a second.

Answer: The second is the fundamental unit. One beat lasts a fiftieth of a second, 0.02 s, which is 20 milliseconds, so the prefix milli, a thousandth, is the natural choice.

Accurate, precise, and how sure

Take a sheet of ordinary printer paper and measure its length with a ruler three times. The packet says eleven inches, and you read eleven point one, eleven point two, and ten point nine. Are you right? Close, but not exactly, and each try came out a little different. That small puzzle holds the three ideas of this part: accuracy, precision and uncertainty.



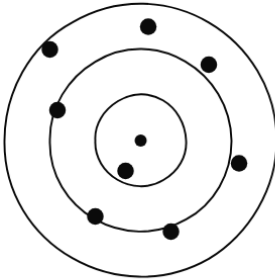
Three readings of 11 inches

Accuracy is how close a measurement comes to the true value. Your three readings all sit near eleven inches, so they are accurate; a

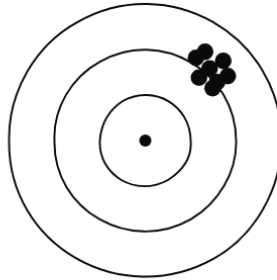
reading of twelve would not be. Precision is something else: how closely repeated measurements, made the same way, agree with one another. Your readings spread over only three tenths of an inch, so they are fairly precise; readings of ten point nine, eleven point one and eleven point nine would not be.

The two can come apart, and the book shows it with a dartboard picture. Imagine a GPS trying to find a restaurant at the centre of a target, each attempt marked as a dot. In one picture the dots are scattered widely but grouped around the centre: low precision, high accuracy. In the other they sit in a tight little cluster, but well away from the restaurant: high precision, low accuracy. That second case is like a phone map that keeps placing you, very confidently and always in the same spot, across the street from where you really stand.

$45\,000 \pm 500$ miles



**HIGH ACCURACY
LOW PRECISION**

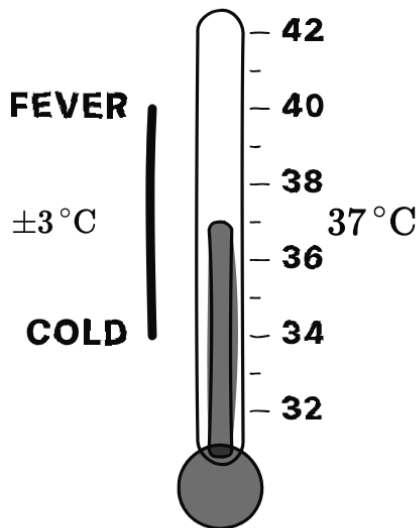


**HIGH PRECISION
LOW ACCURACY**

Accurate or precise

Uncertainty ties the two together: it is a number saying how far your measurement may be from the true or expected value. The book calls it a kind of disclaimer. Asked how far your car has gone, you might say forty-five thousand miles, give or take five hundred, meaning anywhere from forty-four and a half to forty-five and a half thousand. Every measurement has some uncertainty, and the paper might honestly be reported as eleven inches, give or take two tenths. It comes from the limits of the measuring tool, the skill of the person measuring, unevenness in the thing measured, and whatever else the situation brings: a ruler marked only in tenths of an inch, poor eyesight, a sheet cut slightly crooked. Instruments matter here; the book shows an old double-pan balance that reads to a tenth of a gram, beside a digital scale that reads to a thousandth.

Why should anyone care? The book's answer is a sick child and a thermometer. If the thermometer could be off by three degrees Celsius, a normal reading of thirty-seven might really mean anything from a dangerously cold thirty-four to a dangerous fever of forty. A thermometer like that would be useless, which is why a medical one has to be far more certain than that. Said simply, a measurement is only as useful as its uncertainty is small. How to write uncertainty as a percentage, and how many digits a result is entitled to, are left for the next parts.



A thermometer three degrees off

Remember

Accuracy is how close a measurement is to the true value.

Precision is how closely repeated measurements agree with one another, and a result can have one without the other.

Uncertainty says how far a measurement may be from the true value, and every measurement has some. It comes from the tool, the person, the object and the circumstances. A measurement with too much uncertainty, like a thermometer that may be three degrees off, is useless.

Questions

1. A GPS gives a tight cluster of positions, all well away from the restaurant. How would you describe it?
 - a. High accuracy, low precision
 - b. Low accuracy, low precision
 - c. High precision, low accuracy
 - d. High precision, high accuracy
2. Why are the readings 11.1, 11.2 and 10.9 inches called fairly precise?
 - a. Because they spread over only three tenths of an inch
 - b. Because one of them is exactly right
 - c. Because they were taken with a digital scale
 - d. Because their average is twelve

3. Why would a thermometer with an uncertainty of three degrees be useless for a sick child?
 - a. Because it would always read too high
 - b. Because three degrees is too small to notice
 - c. Because thermometers never have any uncertainty
 - d. Because a normal reading could really mean anything from dangerously cold to a dangerous fever
4. Which of these is NOT one of the sources of uncertainty the book lists?
 - a. The limits of the measuring tool
 - b. The price of the measuring tool
 - c. The skill of the person measuring
 - d. Unevenness in the object being measured

Answers

1. **c)** The dots agree closely with each other, which is precision, but miss the true spot, which is poor accuracy.
2. **a)** Precision is how closely repeated measurements agree, and these differ by at most three tenths of an inch.
3. **d)** A reading of 37 could mean anywhere from 34 to 40 degrees, which tells you nothing you can act on.
4. **b)** The book names the tool's limits, the person's skill, irregularities in the object, and other factors of the situation.

Worked examples

Reading an uncertainty Asked for your car's mileage, you say 45,000 miles, give or take 500 miles. What range does this statement

allow?

The give-or-take amount, 500 miles, is the uncertainty.

The lowest value is 45,000 minus 500, which is 44,500 miles.

The highest value is 45,000 plus 500, which is 45,500 miles.

The true mileage could be anywhere between these two.

Answer: From 44,500 to 45,500 miles.

Practice

1. You measure printer paper three times and get 11.1, 11.2 and 10.9 inches; the packet says 11.0 inches. How large is the spread of your readings, and are they accurate?

Hint: Subtract the lowest reading from the highest, then compare all of them with 11.0.

Answer: The spread is $11.2 - 10.9 = 0.3$ inches, so they are fairly precise. All are close to 11.0 inches, so they are also accurate.

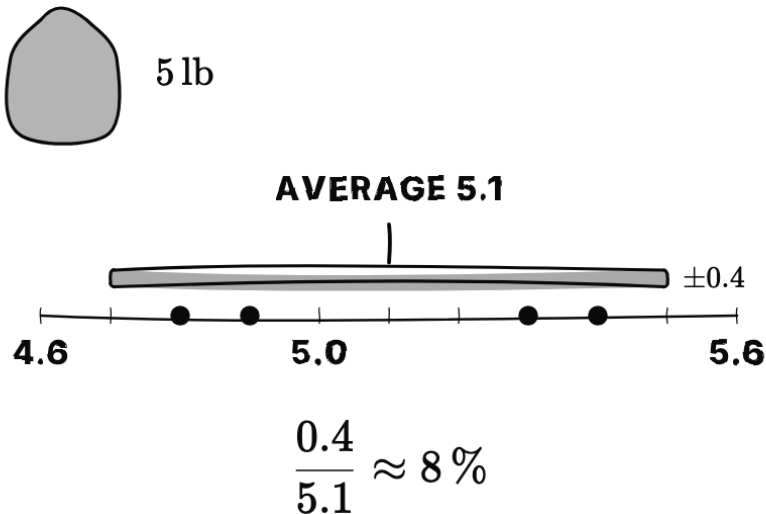
2. A thermometer reads 37.0 °C but could be off by 3.0 °C. Between which two temperatures could the true value lie, and why does that make the thermometer useless?

Hint: Subtract and add the uncertainty.

Answer: Between 34.0 °C and 40.0 °C. That range runs from dangerously cold to a dangerous fever, so the reading cannot tell you whether the child is ill.

How big is the doubt, and how many digits

Buy a bag of apples marked five pounds, four weeks running, and weigh each one at home. You might get four point eight, five point three, four point nine and five point four. None is exactly five, so is the shop cheating you? Not if the numbers stay within the honest give or take, and this part is about saying how big that give or take is, and how many digits a measurement deserves.



Five pounds, give or take

The book's first tool is the percent uncertainty: the give or take expressed as a share of the measured value. In the apple example the average of the four weighings is five point one pounds, and earlier measurements showed the bag's weight is uncertain by about four tenths of a pound. Four tenths out of five point one is about eight percent, so the bag weighs five pounds, give or take eight percent, and the shop is within the honest range. The book adds a reminder: if the same give or take sat on a bag half as heavy, the percent uncertainty would be twice as big.

Anything you calculate from measurements carries their doubt with it. If you work out the area of a floor from its length and width, both of which are a little uncertain, the area is uncertain too. For multiplying or dividing measurements with small uncertainties, the book gives a simple rule: add their percent uncertainties. A floor four meters long and three meters wide, with doubts of two and one percent, has an area of twelve square meters, uncertain by about three percent. And sometimes the doubt decides the answer outright: a stopwatch that may be off by five hundredths of a second cannot tell you whether a sprinter's eleven point nine six really beat last week's twelve point zero four.



$$4 \text{ m} \pm 2 \%$$

$$3 \text{ m} \pm 1 \%$$

$$2 \% + 1 \% = 3 \%$$

$$A = 12 \text{ m}^2 \pm 3 \%$$

Percent uncertainties add

The doubt also depends on the tool. A ruler measures to the nearest millimeter, a caliper to the nearest hundredth of a millimeter, so the caliper is the more precise tool. A kitchen scale that shows whole grams cannot honestly report a medicine dose to a tenth of a gram, however carefully you read it. That is the idea behind significant figures: you write only as many digits as your tool really measured, and the last one is already partly a guess. A stick read off a ruler as thirty-six point seven centimeters has three significant figures; writing thirty-six point seven one would claim a precision the ruler does not have.

Zeros need care. Zeros that only mark where the decimal point is, as in zero point zero five three, do not count. Zeros between other digits,

or at the end after a decimal point, do count, because they record a real measurement. A round number like thirteen hundred is ambiguous, since its zeros may or may not have been measured, and the book advises writing such numbers in powers of ten to make it clear. How to carry significant figures through additions and multiplications, and how to make good rough estimates, are left for the last part.

Remember

Percent uncertainty is the give or take written as a share of the measured value, like five pounds plus or minus eight percent. When measurements are multiplied or divided, their small percent uncertainties add. If the uncertainty is larger than the difference you want to see, as with the sprinter and the stopwatch, you cannot tell the results apart. Significant figures record only the digits a tool really measured, with the last one partly estimated. Zeros count when they were measured, not when they only hold the decimal point.

Questions

1. If a bag of apples were half as heavy but its weight had the same give or take, what would happen to its percent uncertainty?
 - a. It would stay the same
 - b. It would be twice as big
 - c. It would be half as big

- d. It would disappear
2. A floor's length is uncertain by 2% and its width by 1%. How uncertain is its area?
- a. About 3%, the sum of the two
 - b. About 2%, the larger of the two
 - c. About 1%, the smaller of the two
 - d. About 2%, the product of the two
3. Why can't the coach say the sprinter got faster, from 12.04 s to 11.96 s, with a stopwatch good to ± 0.05 s?
- a. Because sprint times always get slower
 - b. Because the stopwatch measures only whole seconds
 - c. Because 100 meters is too short a race
 - d. Because the stopwatch's uncertainty is too large to tell such close times apart
4. How many significant figures does 0.053 have?
- a. Four
 - b. Three
 - c. Two
 - d. One

Answers

1. **b)** The same uncertainty on half the value is twice as large a share of it.
2. **a)** When measurements with small uncertainties are multiplied, their percent uncertainties add.

- 3. d)** When the give or take is as big as the difference you want to see, the results cannot be told apart.
- 4. c)** The zeros in front only mark where the decimal point is, so only the 5 and the 3 count.

Worked examples

A bag of apples A 5-lb bag of apples weighs 4.8, 5.3, 4.9 and 5.4 lb in four weeks. The uncertainty in its average weight is ± 0.4 lb. Find the average weight and the percent uncertainty.

Add the four weights: $4.8 + 5.3 + 4.9 + 5.4 = 20.4$ lb.

Divide by four to get the average: $20.4 \div 4 = 5.1$ lb.

Percent uncertainty is the uncertainty divided by the value, times 100%:
 $0.4 \div 5.1 \times 100\%$.

That comes to about 8%, and the average 5.1 lb agrees with the label's 5 lb within the 0.4 lb uncertainty.

Answer: Average 5.1 lb; the bag weighs 5 lb $\pm$ 8%.

Practice

- 1.** A floor is 4.00 m long and 3.00 m wide, with uncertainties of 2% and 1%. What is its area and the uncertainty of the area, in percent and in square meters?

Hint: Multiply to get the area, add the percentages, then take that percentage of the area.

Answer: The area is 12.0 m² with an uncertainty of 3%. Three percent of 12.0 m² is 0.36 m², rounded to 0.4 m².

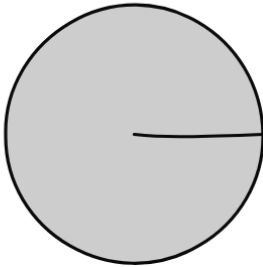
- 2.** How many significant figures are in each: 0.0009; 15,450.0; 87.990; 30.42?

Hint: Leading zeros only place the decimal point; zeros after a decimal point or between digits were measured.

Answer: 0.0009 has 1; 15,450.0 has 6; 87.990 has 5; 30.42 has 4.

Honest answers and good guesses

Type the area of a small round table into a calculator and it might hand you eight digits: four point five two three eight nine three four square meters. Every one of those digits looks confident. But if you measured the table's radius as one point two meters, only two of them mean anything. This last part is about how many digits an answer has earned, and then about the opposite skill: making a good rough guess with almost no digits at all.



$$r = 1.2 \text{ m}$$

$$4.5238934 \text{ m}^2$$

$$A = \pi r^2 \approx 4.5 \text{ m}^2$$

2 SIG FIGS

Digits the radius allows

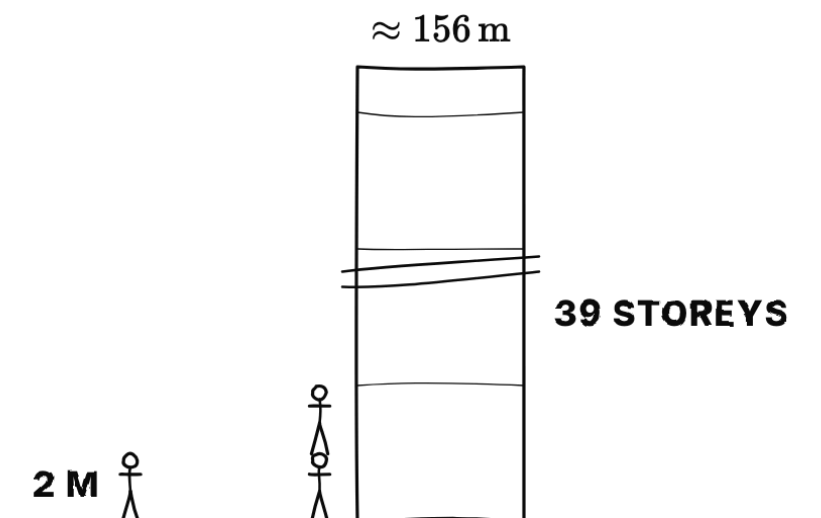
The ground rule is simple: an answer can never be more precise than the least precise measurement that went into it. For multiplying and dividing, the book's rule is to keep as many significant figures as the measurement that has the fewest. The table's radius had two, so the area is four point five square meters, even though the number pi is known to far more digits. It is like a medicine dose worked out from a weight read on a bathroom scale: the dose cannot be more exact than the scale reading it came from.

For adding and subtracting, the rule is about decimal places instead. The book's example follows a load of potatoes: seven point five six kilograms bought on a shop scale that reads to hundredths, six point zero five two kilograms dropped off at a laboratory on a scale that reads to thousandths, and thirteen point seven kilograms added at home on a bathroom scale that reads only to tenths. Do the sums and you get fifteen point two zero eight, but the bathroom scale knew only tenths, so the honest answer is fifteen point two kilograms. Exact numbers, such as the two bags counted in a total or the two in the formula for a circle's circumference, never limit the digits, because they carry no uncertainty at all. The book itself mostly works with three significant figures, using more only where a subject such as optics needs them.

$$\begin{array}{r}
 7.56 \text{ kg} \\
 - 6.052 \text{ kg} \\
 + 13.7 \text{ kg} \quad \textbf{TENTHS ONLY} \\
 \hline
 15.208 \text{ kg} \longrightarrow 15.2 \text{ kg}
 \end{array}$$

Adding: keep the fewest decimals

Then the book turns the question around. Often scientists and engineers do not need many digits at all; they need a quick, sensible estimate, which the book calls a guesstimate. How far is it to a certain place, how dense is a certain object, roughly how much current flows in a circuit? Such approximations rule out impossible answers, let you challenge other people's claims, and guide your thinking. The skill grows with practice, with a feel for units, and with the courage to commit to a number.

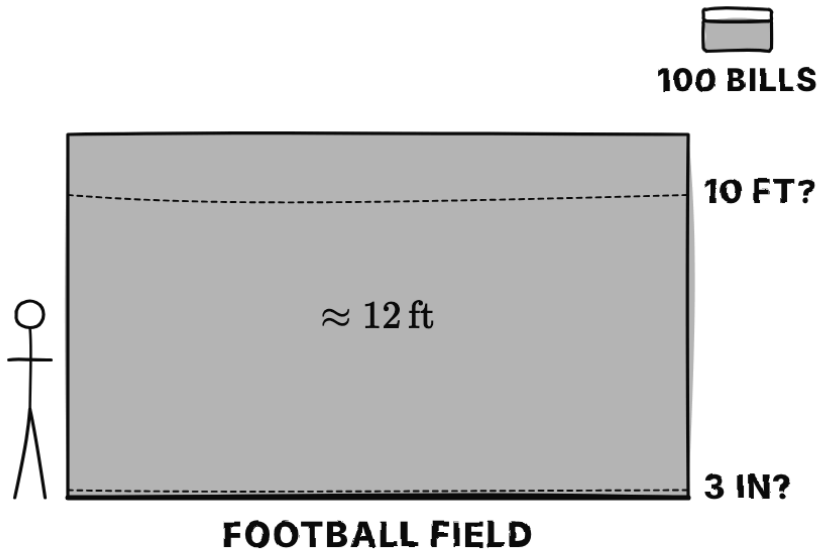


A building in people

The first example estimates a thirty-nine-storey building by scaling up from a person. The book takes a person as about two meters tall and a storey as about two people high, so the building comes out at roughly a hundred and fifty-six meters. You can do the same from your own body: if your hand is about ten centimeters across, a few hand-widths tell you the width of your desk without a tape measure.

The second example tackles a number almost nobody can picture: a trillion dollars. Imagine a trillion dollars in hundred-dollar bills, bundled into bank stacks of a hundred bills each, and spread evenly over a football field. One friend guesses the pile would be three inches high, another guesses ten feet. Working it through in rough steps, using one significant figure, the book finds about a hundred million

stacks, each about the size of a small paperback, and a field of about six million square inches; dividing one by the other gives a pile around a hundred and fifty inches high, about twelve feet. So the ten-foot guess was close and the three-inch guess was far too small, and the careful estimate beats both gut feelings.



A trillion dollars on a field

The book ends the chapter with one more invitation: estimate a basketball court with mental arithmetic alone. Lay imaginary people of about two meters end to end, some fifteen along it and seven across, and the area comes out at roughly four hundred and twenty square meters. That closes the first chapter: physics as a search for simple laws, built on agreed units, honest about its uncertainty, and comfortable both with careful digits and with bold, sensible estimates.

Remember

An answer is never more precise than the least precise measurement behind it. When multiplying or dividing, keep as many significant figures as the input with the fewest; when adding or subtracting, keep as many decimal places as the least precise input. Exact numbers, such as counted items, never limit the digits. A good approximation, scaled up from familiar things like a person's height, rules out impossible answers fast. A trillion dollars in hundred-dollar bills would cover a football field about twelve feet deep.

Questions

1. A circle's radius is measured as 1.2 m. Why should its area be given as 4.5 square meters and not 4.5238934?
 - a. Because pi is only known to two digits
 - b. Because calculators make mistakes after two digits
 - c. Because the radius has only two significant figures, which limits the result
 - d. Because areas are always rounded to one decimal place
2. Potatoes measured as 7.56 kg, 6.052 kg and 13.7 kg are combined. Why is the answer given to tenths?
 - a. Because the least precise measurement, 13.7 kg, was known only to tenths
 - b. Because the laboratory scale was the most precise

- c. Because potatoes cannot be weighed more exactly
 - d. Because adding always removes two decimal places
3. Why does counting the number of bags never limit the significant figures of a total?
- a. Because counts are always large numbers
 - b. Because counted numbers are rounded away
 - c. Because bags are never weighed
 - d. Because a counted or exact number carries no uncertainty
4. What is the main use of a rough approximation, or guesstimate?
- a. To replace all careful measurements
 - b. To rule out impossible answers and guide your thinking quickly
 - c. To get the exact answer without any work
 - d. To avoid using units altogether

Answers

1. **c)** In multiplication the answer keeps as many significant figures as the input with the fewest, here the radius with two.
2. **a)** In addition and subtraction the answer keeps no more decimal places than the least precise measurement.
3. **d)** Exact numbers, like counted items or the two in a circle's circumference, have no uncertainty.
4. **b)** Approximations rule out unrealistic numbers, let you challenge claims, and guide your approach.

Worked examples

Height of a 39-storey building Estimate the height of a 39-storey building, taking a person as about 2 m tall and one storey as about two people high.

One storey is about two people, and each person is about 2 m, so one storey is about 4 m.

There are 39 storeys.

Multiply: $39 \times 4 \text{ m} = 156 \text{ m}$.

Answer: About 156 m.

Practice

1. A woman has three bags: two weigh 13.5 pounds each and one weighs 10.2 pounds. What is the total weight, with the right number of digits?

Hint: The count of two bags is exact; look at the decimal places of the weights.

Answer: 37.2 pounds: $13.5 + 13.5 + 10.2 = 37.2$. The number of bags is exact and does not limit the digits.

2. A wagon of mass 55 kg accelerates at 0.0255 m/s^2 . The force is mass times acceleration. What is the force, with the right number of significant figures?

Hint: Multiply, then keep as many significant figures as the input with the fewest.

Answer: 1.4 N: $55 \times 0.0255 = 1.4025$, and since 55 kg has only two significant figures, the answer is rounded to two.