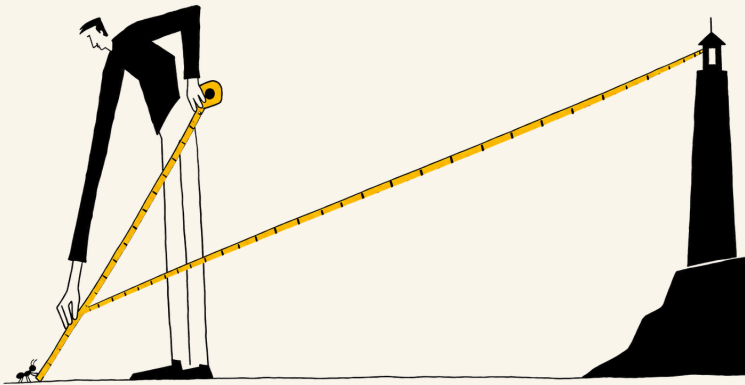


College Physics



Paul Peter Urone, Roger Hinrichs · 2022

Illustrated audio lectures

Lecturized

College Physics

Illustrated audio lectures

Paul Peter Urone, Roger Hinrichs · 2022

Retold as illustrated lectures by Lecturized
lecturized.com

From the original: College Physics 2e, OpenStax (CC BY 4.0 edition, osbooks-college-physics-bundle@f98d7a792138)

Contents

Introduction: The Nature of Science and Physics

Physics: An Introduction

Applications of Physics

Models, Theories, and Laws; The Role of Experimentation

The Scientific Method and the Rise of Modern Physics

Physical Quantities and Units

The Second, the Meter, and the Kilogram

Metric Prefixes

Known Ranges and Unit Conversion

Finishing the Drive Home

Accuracy, Precision, and Uncertainty

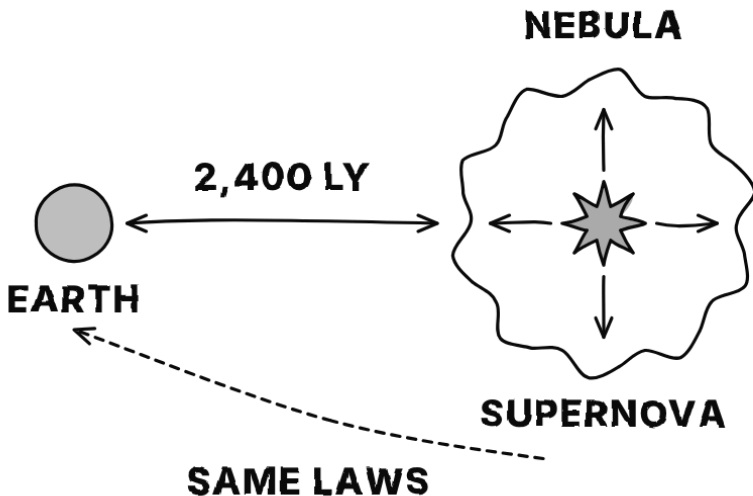
Percent Uncertainty and Significant Figures

Zeros and Significant Figures in Calculations

Approximation

Introduction: The Nature of Science and Physics

What is your first reaction when you hear the word “physics”? Did you imagine working through difficult equations or memorizing formulas that seem to have no real use in life outside the physics classroom? Many people come to the subject of physics with a bit of fear. But as you begin your exploration of this broad-ranging subject, you may soon come to realize that physics plays a much larger role in your life than you first thought, no matter your life goals or career choice.

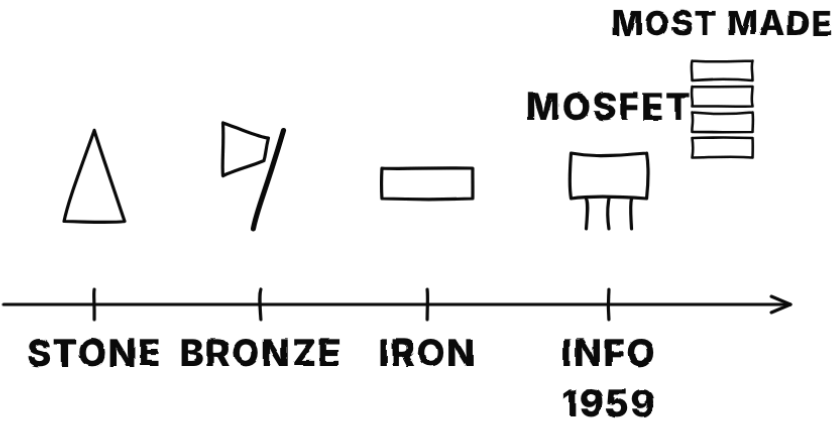


The Veil Nebula is far away

Consider the Veil Nebula, a cloud of heated dust and gas located about 2,400 light years from Earth (a light year is the distance light travels in one year, or approximately 9.5 trillion kilometers). The unique structure is the ongoing result of a supernova that occurred 8,000 years ago. The shock wave from the explosion is colliding with a cloud of gas and dust, creating the rope-like filaments and sheet-like appearance. Scientists compare newer images with detailed images taken by the Hubble Space Telescope in 1997 in order to understand nebula expansion and other properties of astronomical objects. The forces that cause the supernova remnant to act as it does are the same forces we contend with here on Earth, whether we are planning to send a rocket into space or simply heating a new home. Although the scale is much different, the interaction of gasses in the Veil Nebula resembles those on Earth; and the vibrant color combinations are created by the familiar glows of hydrogen, sulfur, oxygen, and similar elements that make up everything we know. Tonight, take a moment to look up at the stars. The forces out there are the same as the ones here on Earth. Through a study of physics, you may gain a greater understanding of the interconnectedness of everything we can see and know in this universe.

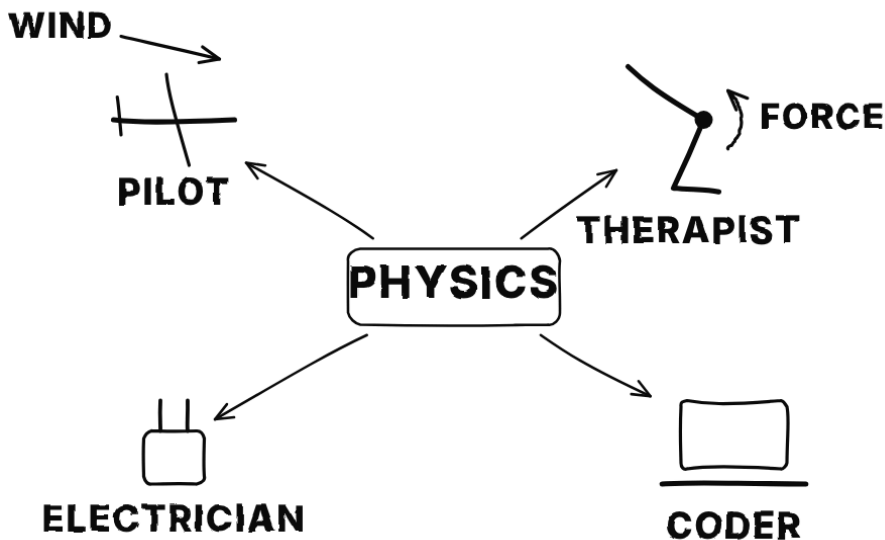
Humans have created and manufactured millions of different objects over the history of our species. Successive technological periods (often referred to as the Stone Age, the Bronze Age, the Iron Age, and so on) were marked by our knowledge of the physical properties of certain materials and our ability to manipulate them. This knowledge all stems from physics, whether it's the way a rock would flake when constructing a spear point, the effect of integrating carbon with iron in South Indian and Sri Lankan furnaces to create the earliest high-quality steel, or the proper way to combine perfectly ground and

polished pieces of glass to create optical instruments. Our current technological age, the Information Age, builds on all that knowledge and can be traced to critical innovations made by people from all backgrounds working together. Mohamed M. Atalla and Dawon Kahng, for example, invented the MOSFET (metal-oxide-semiconductor field-effect transistor). Although unknown to most people, this tiny device, created in 1959 by an Egyptian-born scientist and Korean-born scientist working in a lab in New Jersey, is the basis for modern electronics. More MOSFETs have been produced than any other object in human history. They are used in computers, smart phones, microwave ovens, automotive controls, medical instruments, and nearly every other electronic device.



Ages of materials

Next, think about the most exciting modern technologies that you have heard about in the news, such as trains that levitate above tracks, “invisibility cloaks” that bend light around them, and microscopic robots that fight cancer cells in our bodies. All of these groundbreaking advancements, commonplace or unbelievable, rely on the principles of physics. Aside from playing a significant role in technology, professionals such as engineers, pilots, physicians, physical therapists, electricians, and computer programmers apply physics concepts in their daily work. For example, a pilot must understand how wind forces affect a flight path and a physical therapist must understand how the muscles in the body experience forces as they move and bend. As you will learn in this text, physics principles are propelling new, exciting technologies, and these principles are applied in a wide range of careers.



Careers that use physics

In this text, you will begin to explore the history of the formal study of physics, beginning with natural philosophy and the ancient thinkers from the Middle East and the Mediterranean, and leading up through a review of Sir Isaac Newton and the laws of physics that bear his name. You will also be introduced to the standards scientists use when they study physical quantities and the interrelated system of measurements most of the scientific community uses to communicate in a single mathematical language. Finally, you will study the limits of our ability to be accurate and precise, and the reasons scientists go to painstaking lengths to be as clear as possible regarding their own limitations.

Questions

1. Why does the text bring in the Veil Nebula at the very start of a physics course?
 - a. To show that the forces shaping a far-off cloud are the same ones we deal with on Earth
 - b. To show that astronomy is the hardest branch of physics
 - c. To show that physics is mainly about very distant objects
 - d. To show that supernovas are common near the Earth
2. How do scientists learn how the nebula is expanding?
 - a. By sending probes into the cloud of gas
 - b. By measuring its colours once and comparing them with the Sun
 - c. By comparing newer images with detailed Hubble images taken in 1997
 - d. By calculating when the supernova happened
3. What, according to the text, marked each technological age such as the Bronze Age or the Iron Age?
 - a. The number of people who used the new tools
 - b. Knowledge of the physical properties of certain materials and the ability to work them
 - c. The discovery of a new law of motion
 - d. The invention of measuring instruments

Answers

1. **a)** The forces that make the supernova remnant act as it does are the same forces we contend with here on Earth, from rockets to heating a home.
2. **c)** The still-moving wave is observed again and again; laying newer images beside those of 1997 shows how the nebula expands.
3. **b)** Successive technological periods were marked by our knowledge of the physical properties of materials and our ability to manipulate them, and that knowledge stems from physics.

Practice

1. The text says a pilot and a physical therapist both use physics in their daily work. Explain in your own words what physics each of them needs.

Hint: Think about which forces each one has to deal with: on the aircraft, and in the patient's body.

Answer: A pilot must understand how the forces of the wind push the aircraft and change its flight path. A physical therapist must understand the forces the muscles feel as the body moves and bends. Both use the same physical ideas about forces, in very different jobs.

2. The MOSFET is unknown to most people, yet the text calls it the basis of modern electronics. Explain why both statements can be true at once.

Hint: Ask where the device is and whether anyone sees it.

Answer: The MOSFET is a tiny device hidden inside computers, smart phones, microwave ovens, car controls and medical instruments, so people use it constantly without ever seeing it. More of them have been made than any other object in history, which is why the whole Information Age rests on it.

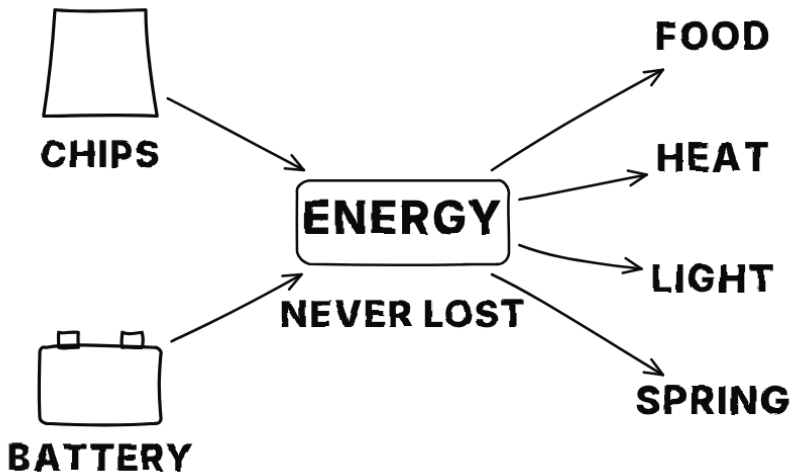
3. The colours of the Veil Nebula come from glowing hydrogen, sulfur and oxygen. Why does the text think this fact matters for someone on Earth?

Hint: Compare those elements with what things around you are made of.

Answer: These are the same familiar elements that make up everything we know. So the cloud, though vastly larger and far away, is made of the same stuff and follows the same rules as gases on Earth, which is the text's point about the interconnectedness of everything.

Physics: An Introduction

The physical universe is enormously complex in its detail. Every day, each of us observes a great variety of objects and phenomena. Over the centuries, the curiosity of the human race has led us collectively to explore and catalog a tremendous wealth of information. From the flight of birds to the colors of flowers, from lightning to gravity, from quarks to clusters of galaxies, from the flow of time to the mystery of the creation of the universe, we have asked questions and assembled huge arrays of facts. In the face of all these details, we have discovered that a surprisingly small and unified set of physical laws can explain what we observe. As humans, we make generalizations and seek order. We have found that nature is remarkably cooperative: it exhibits the underlying order and simplicity we so value.

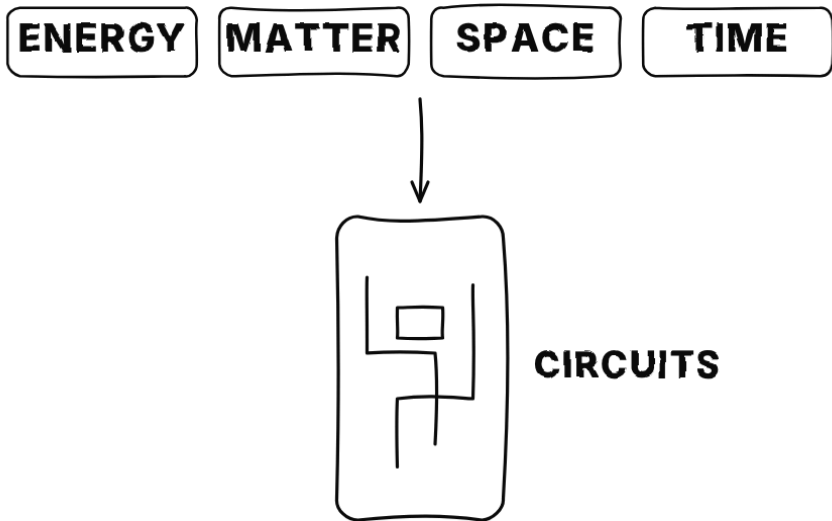


One law ties energy together

It is the underlying order of nature that makes science in general, and physics in particular, so enjoyable to study. For example, what do a bag of chips and a car battery have in common? Both contain energy that can be converted to other forms. The law of conservation of energy (which says that energy can change form but is never lost) ties together such topics as food calories, batteries, heat, light, and watch springs. Understanding this law makes it easier to learn about the various forms energy takes and how they relate to one another. Apparently unrelated topics are connected through broadly applicable physical laws, permitting an understanding beyond just the memorization of lists of facts.

The unifying aspect of physical laws and the basic simplicity of nature form the underlying themes of this text. In learning to apply these laws, you will, of course, study the most important topics in physics. More importantly, you will gain analytical abilities that will enable you to apply these laws far beyond the scope of what can be included in a single book. These analytical skills will help you to excel academically, and they will also help you to think critically in any professional career you choose to pursue. This module discusses the realm of physics (to define what physics is), some applications of physics (to illustrate its relevance to other disciplines), and more precisely what constitutes a physical law (to illuminate the importance of experimentation to theory).

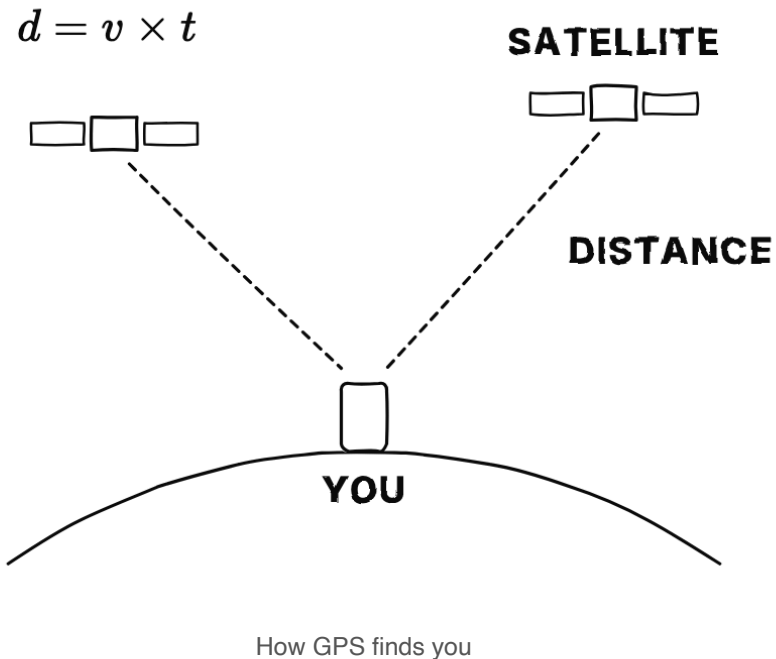
Science consists of the theories and laws that are the general truths of nature as well as the body of knowledge they encompass. Scientists are continually trying to expand this body of knowledge and to perfect the expression of the laws that describe it. Physics is concerned with describing the interactions of energy, matter, space, and time, and it is especially interested in what fundamental mechanisms underlie every phenomenon. The concern for describing the basic phenomena in nature essentially defines the realm of physics.



What physics describes

Physics aims to describe the function of everything around us, from the movement of tiny charged particles to the motion of people, cars, and spaceships. In fact, almost everything around you can be described quite accurately by the laws of physics. Consider a smart phone. Physics describes how electricity interacts with the various circuits inside the device. This knowledge helps engineers select the appropriate materials and circuit layout when building the smart phone. Next, consider a GPS system. Physics describes the relationship between the speed of an object, the distance over which it travels, and the time it takes to travel that distance. GPS relies on precise calculations that account for variations in the Earth's landscapes, the exact distance between orbiting satellites, and even the effect of a complex occurrence of time dilation. Most of these

calculations are founded on algorithms developed by Gladys West, a mathematician and computer scientist who programmed the first computers capable of highly accurate remote sensing and positioning. When you use a GPS device, it utilizes these algorithms to recognize where you are and how your position relates to other objects on Earth.



Questions

1. What do a bag of chips and a car battery have in common, according to the text?
 - a. Both are made of the same chemical elements

- b. Both contain energy that can be converted to other forms
 - c. Both lose their energy completely when used
 - d. Both store energy only as heat
2. What does the law of conservation of energy say?
- a. Energy can change form but is never lost
 - b. Energy is used up whenever something moves
 - c. Energy can be created by machines
 - d. Each form of energy obeys its own separate law
3. Why does the text say understanding physical laws is better than memorizing lists of facts?
- a. Because lists of facts are often wrong
 - b. Because laws are shorter to write down
 - c. Because broadly applicable laws connect apparently unrelated topics
 - d. Because facts change every year
4. Which relationship from physics does a GPS system rely on, according to the text?
- a. Between the mass of an object and its color
 - b. Between temperature and pressure
 - c. Between electricity and light
 - d. Between the speed of an object, the distance it travels and the time it takes

Answers

1. **b)** Both contain energy that can be converted to other forms, and the law of conservation of energy ties such topics together.

- 2. a)** The law says energy can change form but is never lost, which links food calories, batteries, heat, light and watch springs.
- 3. c)** Apparently unrelated topics are connected through broadly applicable physical laws, permitting an understanding beyond memorization.
- 4. d)** Physics describes the relationship between speed, distance and time, and GPS relies on precise calculations built on it.

Practice

- 1.** In your own words, explain what makes physics different from simply collecting facts about nature.

Hint: Think about how many laws the text says explain what we observe.

Answer: We have gathered huge arrays of facts, from birds to galaxies, but a surprisingly small and unified set of physical laws explains them.

Physics looks for that underlying order and the fundamental mechanisms behind each phenomenon, rather than memorizing the facts one by one.

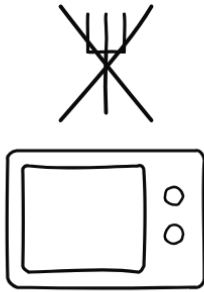
- 2.** Food calories, batteries, heat, light and watch springs seem unrelated. Explain what single idea ties them together.

Hint: Ask what all of them contain and what can happen to it.

Answer: All of them involve energy, which can change from one form into another but is never lost. The law of conservation of energy links them, so learning it makes each of these topics easier to understand.

Applications of Physics

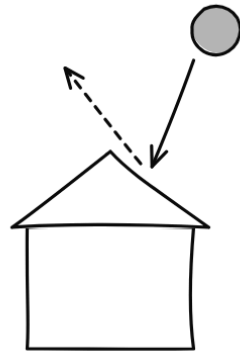
You need not be a scientist to use physics. On the contrary, knowledge of physics is useful in everyday situations as well as in nonscientific professions. It can help you understand how microwave ovens work, why metals should not be put into them, and why they might affect pacemakers. Physics allows you to understand the hazards of radiation and rationally evaluate these hazards more easily. Physics also explains the reason why a black car radiator helps remove heat in a car engine, and it explains why a white roof helps keep the inside of a house cool. Similarly, the operation of a car's ignition system as well as the transmission of electrical signals through our body's nervous system are much easier to understand when you think about them in terms of basic physics.



MICROWAVE



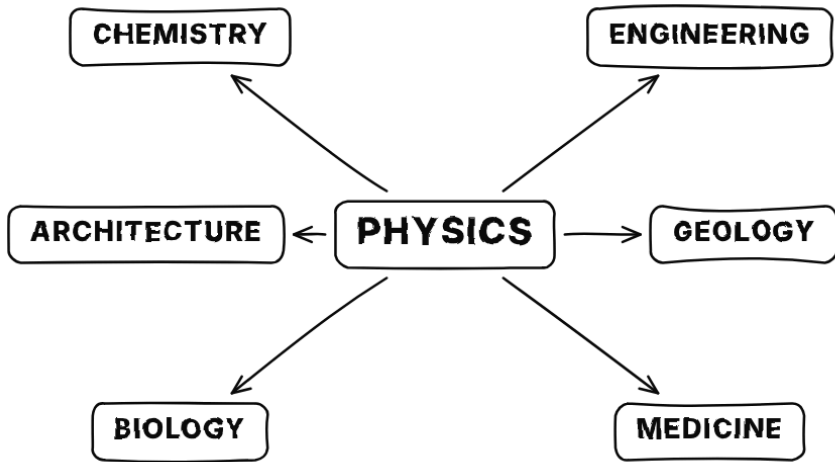
RADIATOR



WHITE ROOF

Physics in a house and a car

Physics is the foundation of many important disciplines and contributes directly to others. Chemistry, for example, since it deals with the interactions of atoms and molecules, is rooted in atomic and molecular physics. Most branches of engineering are applied physics. In architecture, physics is at the heart of structural stability, and is involved in the acoustics, heating, lighting, and cooling of buildings. Parts of geology rely heavily on physics, such as radioactive dating of rocks, earthquake analysis, and heat transfer in the Earth. Some disciplines, such as biophysics and geophysics, are hybrids of physics and other disciplines.



Fields built on physics

Physics has many applications in the biological sciences. On the microscopic level, it helps describe the properties of cell walls and cell membranes. On the macroscopic level, it can explain the heat, work, and power associated with the human body. Physics is involved in medical diagnostics, such as x-rays, magnetic resonance imaging (MRI), and ultrasonic blood flow measurements. Medical therapy sometimes directly involves physics; for example, cancer radiotherapy uses ionizing radiation. Physics can also explain sensory phenomena, such as how musical instruments make sound, how the eye detects color, and how lasers can transmit information.

It is not necessary to formally study all applications of physics. What is most useful is knowledge of the basic laws of physics and a skill in

the analytical methods for applying them. The study of physics also can improve your problem-solving skills. Furthermore, physics has retained the most basic aspects of science, so it is used by all of the sciences, and the study of physics makes other sciences easier to understand.

Questions

1. Why is chemistry described as rooted in physics?
 - a. Because chemists use the same laboratories as physicists
 - b. Because chemistry deals with interactions of atoms and molecules, the subject of atomic and molecular physics
 - c. Because chemistry was invented after physics
 - d. Because every chemical is radioactive
2. According to the text, what is most useful to take from a physics course?
 - a. A complete list of all the applications of physics
 - b. The ability to build medical machines
 - c. Knowledge of the basic laws and skill in the analytical methods for applying them
 - d. Memorized values of physical constants
3. Which pair below are both given in the text as examples of physics in medicine?
 - a. Magnetic resonance imaging and cancer radiotherapy
 - b. Vaccines and antibiotics

- c. Blood types and genetics
 - d. Diets and vitamins
4. Why does studying physics make other sciences easier to understand?
- a. Because other sciences copy their textbooks from physics
 - b. Because physics avoids mathematics
 - c. Because physics is the oldest science
 - d. Because physics has retained the most basic aspects of science, so all the sciences use it

Answers

- 1. **b)** Chemistry deals with the interactions of atoms and molecules, so it is rooted in atomic and molecular physics.
- 2. **c)** It is not necessary to study every application; the basic laws and the skill of applying them are what matter most.
- 3. **a)** Physics is involved in diagnostics such as MRI, and cancer radiotherapy uses ionizing radiation.
- 4. **d)** Physics keeps the most basic aspects of science, so it is used by all the sciences.

Practice

1. Name three disciplines outside physics that the text says depend on it, and say for each what physics contributes.

Hint: Look at chemistry, engineering, architecture and geology.

Answer: Chemistry rests on atomic and molecular physics because it deals with atoms and molecules. In architecture, physics underlies structural stability and the acoustics, heating, lighting and cooling of

buildings. Geology uses physics for radioactive dating of rocks, earthquake analysis and heat transfer in the Earth.

2. The text says you need not be a scientist to use physics. Give two everyday examples from the text and explain what physics helps you understand in each.

Hint: Think of the kitchen and of a house or car.

Answer: Physics helps you understand how a microwave oven works and why metal should not be put into it. It also explains why a white roof keeps a house cool and why a black radiator helps remove heat from a car engine.

Models, Theories, and Laws; The Role of Experimentation

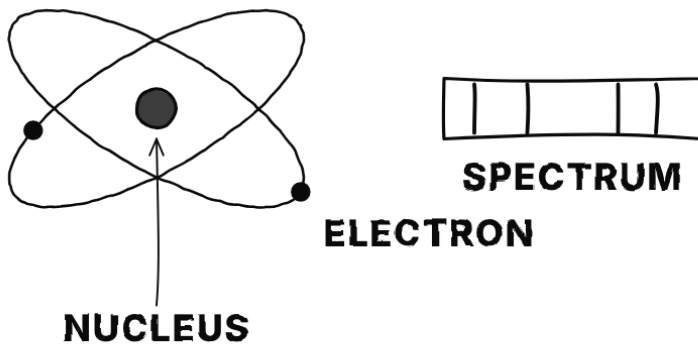
The laws of nature are concise descriptions of the universe around us; they are human statements of the underlying laws or rules that all natural processes follow. Such laws are intrinsic to the universe; humans did not create them and so cannot change them. We can only discover and understand them. Their discovery is a very human endeavor, with all the elements of mystery, imagination, struggle, triumph, and disappointment inherent in any creative effort. The cornerstone of discovering natural laws is observation; science must describe the universe as it is, not as we may imagine it to be.

We all are curious to some extent. We look around, make generalizations, and try to understand what we see; for example, we look up and wonder whether one type of cloud signals an oncoming storm. As we become serious about exploring nature, we become more organized and formal in collecting and analyzing data. We attempt greater precision, perform controlled experiments (if we can), and write down ideas about how the data may be organized and unified. We then formulate models, theories, and laws based on the data we have collected and analyzed to generalize and communicate the results of these experiments.

A model is a representation of something that is often too difficult (or impossible) to display directly. While a model is justified with experimental proof, it is only accurate under limited situations. An example is the planetary model of the atom in which electrons are pictured as orbiting the nucleus, analogous to the way planets orbit

the Sun. We cannot observe electron orbits directly, but the mental image helps explain the observations we can make, such as the emission of light from hot gases (atomic spectra). Physicists use models for a variety of purposes. For example, models can help physicists analyze a scenario and perform a calculation, or they can be used to represent a situation in the form of a computer simulation.

MODEL LIMITED

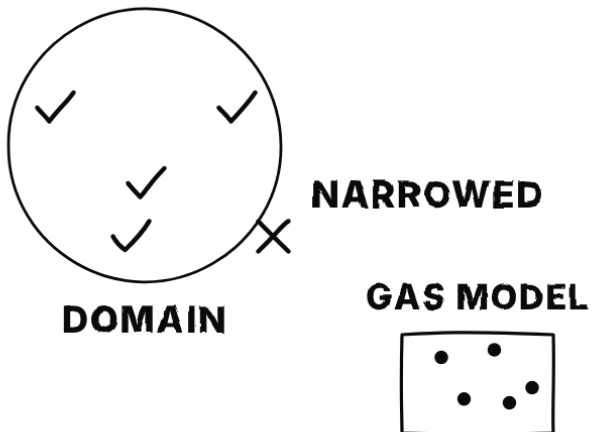


The planetary model of the atom

The word theory means something different to scientists than what is often meant when the word is used in everyday conversation. In particular, to a scientist a theory is not the same as a “guess” or an “idea” or even a “hypothesis.” The phrase “it’s just a theory” seems meaningless and silly to scientists because science is founded on the notion of theories. To a scientist, a theory is a testable explanation for

patterns in nature supported by scientific evidence and verified multiple times by various groups of researchers. Some theories include models to help visualize phenomena whereas others do not. Newton's theory of gravity, for example, does not require a model or mental image, because we can observe the objects directly with our own senses. Although models are meant only to describe certain aspects of a physical system accurately, a theory should describe all aspects of any system that falls within its domain of applicability. In particular, any experimentally testable implication of a theory should be verified. If an experiment ever shows an implication of a theory to be false, then the theory is either thrown out or modified suitably (for example, by limiting its domain of applicability).

THEORY

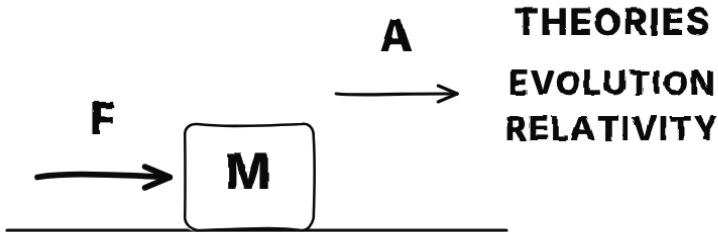


A theory is tested in its domain

Some theories include models to help visualize phenomena, whereas others do not. Newton's theory of gravity, for example, does not require a model or mental image, because we can observe the objects directly with our own senses. The kinetic theory of gases, on the other hand, is a model in which a gas is viewed as being composed of atoms and molecules. Atoms and molecules are too small to be observed directly with our senses; thus, we picture them mentally to understand what our instruments tell us about the behavior of gases.

A law uses concise language to describe a generalized pattern in nature that is supported by scientific evidence and repeated experiments. Often, a law can be expressed in the form of a single mathematical equation. Laws and theories are similar in that they are both scientific statements that result from a tested hypothesis and are supported by scientific evidence. However, the designation law is reserved for a concise and very general statement that describes phenomena in nature, such as the law that energy is conserved during any process, or Newton's second law of motion, which relates force, mass, and acceleration by the simple equation $F = ma$. A theory, in contrast, is a less concise statement of observed phenomena. For example, the Theory of Evolution and the Theory of Relativity cannot be expressed concisely enough to be considered a law. The biggest difference between a law and a theory is that a theory is much more complex and dynamic. A law describes a single action, whereas a theory explains an entire group of related phenomena. And, whereas a law is a postulate that forms the foundation of the scientific method, a theory is the end result of that process.

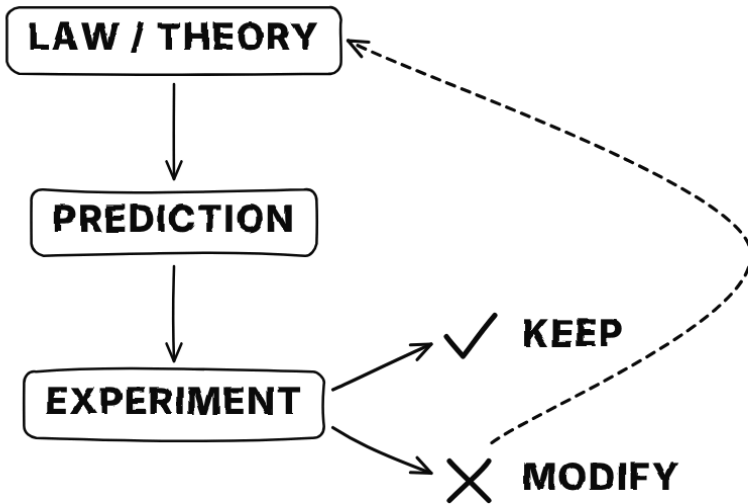
$$F = m a$$



A law in one equation

Less broadly applicable statements are usually called principles (such as Pascal's principle, which is applicable only in fluids), but the distinction between laws and principles often is not carefully made.

Models, theories, and laws are used to help scientists analyze the data they have already collected. However, often after a model, theory, or law has been developed, it points scientists toward new discoveries they would not otherwise have made.



Prediction meets experiment

The models, theories, and laws we devise sometimes imply the existence of objects or phenomena as yet unobserved. These predictions are remarkable triumphs and tributes to the power of science. It is the underlying order in the universe that enables scientists to make such spectacular predictions. However, if experiment does not verify our predictions, then the theory or law is wrong, no matter how elegant or convenient it is. Laws can never be known with absolute certainty because it is impossible to perform every imaginable experiment in order to confirm a law in every possible scenario. Physicists operate under the assumption that all scientific laws and theories are valid until a counterexample is observed. If a good-quality, verifiable experiment contradicts a well-

established law, then the law must be modified or overthrown completely.

Questions

1. Why do scientists find the phrase "it's just a theory" meaningless?
 - a. Because to a scientist a theory is a testable explanation supported by evidence and verified many times
 - b. Because theories are always proven absolutely true
 - c. Because theories never change
 - d. Because a theory is the same as a law
2. Why is the planetary picture of the atom called a model?
 - a. Because it is a small copy built from wire
 - b. Because it has been proven true in every situation
 - c. Because electron orbits cannot be observed directly, yet the image helps explain what we can observe
 - d. Because it is one single equation
3. What happens to a theory if an experiment shows one of its implications to be false?
 - a. Nothing, because theories are not tested
 - b. It becomes a law
 - c. It is kept unchanged because it is elegant
 - d. It is thrown out or modified, for example by limiting its domain

4. Why can laws never be known with absolute certainty?
- a. Because it is impossible to perform every imaginable experiment in every possible scenario
 - b. Because laws are only guesses
 - c. Because scientists disagree about every law
 - d. Because laws change every year

Answers

1. **a)** To a scientist a theory is not a guess but a testable explanation supported by evidence and verified repeatedly by various groups.
2. **c)** A model represents something we cannot display directly; the mental image explains observations such as light from hot gases.
3. **d)** If an experiment shows an implication false, the theory is either thrown out or suitably modified.
4. **a)** It is impossible to perform every experiment that would confirm a law in every scenario, so laws hold until a counterexample appears.

Practice

1. Explain in your own words the difference between a law and a theory, using the text's examples.

Hint: Compare how concise each is and how much each covers.

Answer: A law is a concise, very general statement of a pattern, often a single equation, such as conservation of energy or Newton's second law, $F = ma$. A theory is less concise and more complex; it explains a whole group of related phenomena, like the Theory of Evolution or the Theory of Relativity.

2. Why does Newton's theory of gravity not need a model, while the kinetic theory of gases does?

Hint: Ask whether the objects involved can be seen with our senses.

Answer: The objects in gravity, such as falling bodies and planets, can be observed directly with our senses. The atoms and molecules of a gas are too small to observe, so we picture them mentally to understand what our instruments tell us.

3. The text says a law, however elegant, must be modified or overthrown in a certain case. Which case, and why?

Hint: Think of what science must describe: the universe as it is, or as we imagine it.

Answer: When a good-quality, verifiable experiment contradicts it. Science must describe the universe as it is, so observation and experiment decide, not elegance or convenience.

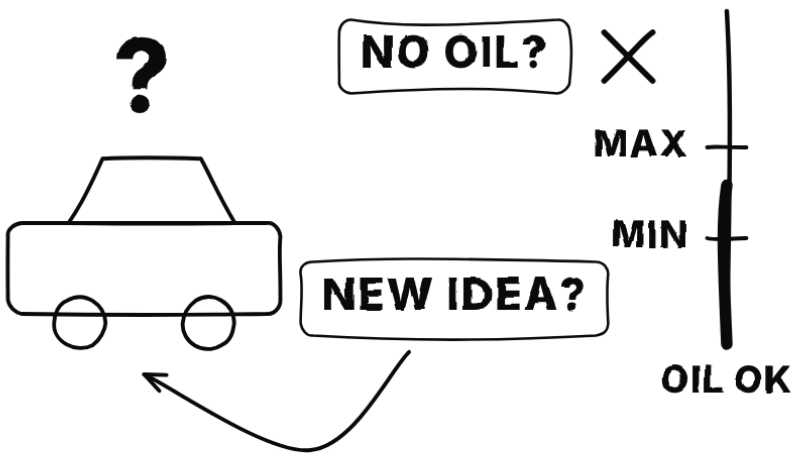
The Scientific Method and the Rise of Modern Physics

The study of science in general and physics in particular is an adventure much like the exploration of uncharted ocean. Discoveries are made; models, theories, and laws are formulated; and the beauty of the physical universe is made more sublime for the insights gained.

Ibn al-Haytham (sometimes referred to as Alhazen), a 10th–11th century scientist working in Cairo, significantly advanced the understanding of optics and vision. But his contributions go much further. In demonstrating that previous approaches were incorrect, he emphasized that scientists must be ready to reject existing knowledge and become “the enemy” of everything they read; he expressed that scientists must trust only objective evidence. Al-Haytham emphasized repeated experimentation and validation, and acknowledged that senses and predisposition could lead to poor conclusions. His work was a precursor to the scientific method that we use today.

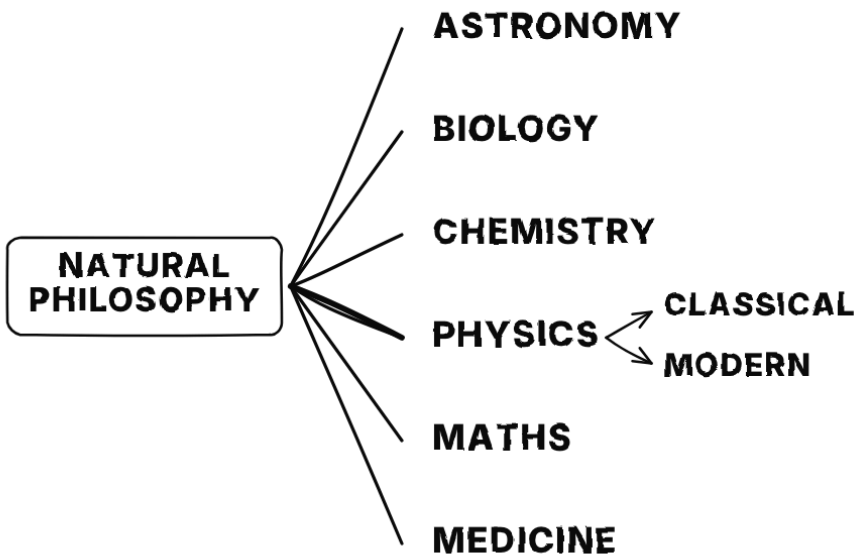
As scientists inquire and gather information about the world, they follow a process called the scientific method. This process typically begins with an observation and question that the scientist will research. Next, the scientist typically performs some research about the topic and then devises a hypothesis. Then, the scientist will test the hypothesis by performing an experiment. Finally, the scientist analyzes the results of the experiment and draws a conclusion. Note that the scientific method can be applied to many situations that are not limited to science, and this method can be modified to suit the situation.

Consider an example. Let us say that you try to turn on your car, but it will not start. You undoubtedly wonder: Why will the car not start? You can follow a scientific method to answer this question. First off, you may perform some research to determine a variety of reasons why the car will not start. Next, you will state a hypothesis. For example, you may believe that the car is not starting because it has no engine oil. To test this, you open the hood of the car and examine the oil level. You observe that the oil is at an acceptable level, and you thus conclude that the oil level is not contributing to your car issue. To troubleshoot the issue further, you may devise a new hypothesis to test and then repeat the process again.



Why won't the car start?

Physics was not always a separate and distinct discipline. It remains connected to other sciences to this day. The word physics comes from Greek, meaning nature. The study of nature came to be called “natural philosophy.” From ancient times through the Renaissance, natural philosophy encompassed many fields, including astronomy, biology, chemistry, physics, mathematics, and medicine. Over the last few centuries, the growth of knowledge has resulted in ever-increasing specialization and branching of natural philosophy into separate fields, with physics retaining the most basic facets. Physics as it developed from the Renaissance to the end of the 19th century is called classical physics. It was transformed into modern physics by revolutionary discoveries made starting at the beginning of the 20th century.



Natural philosophy branches out

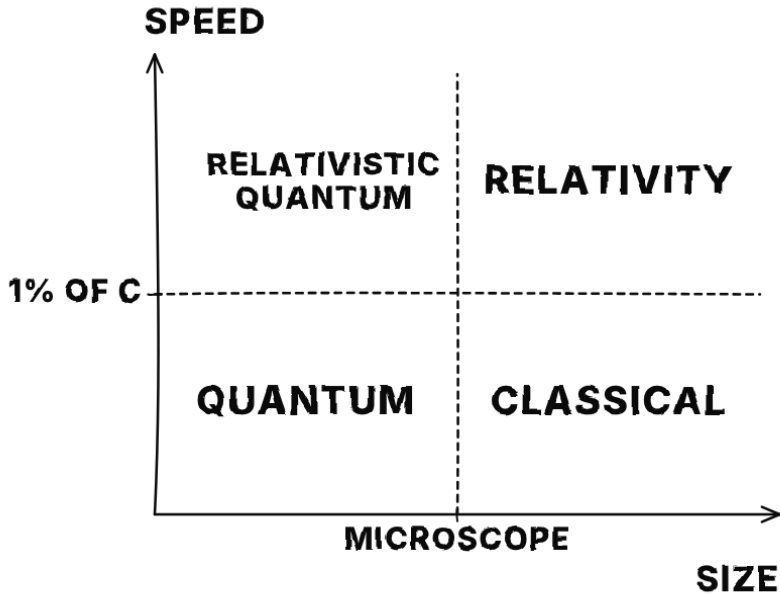
Classical physics is not an exact description of the universe, but it is an excellent approximation under the following conditions: Matter must be moving at speeds less than about 1% of the speed of light, the objects dealt with must be large enough to be seen with a microscope, and only weak gravitational fields, such as the field generated by the Earth, can be involved. Because humans live under such circumstances, classical physics seems intuitively reasonable, while many aspects of modern physics seem bizarre. This is why models are so useful in modern physics: they let us conceptualize phenomena we do not ordinarily experience. We can relate to models in human terms and visualize what happens when objects move at high speeds or imagine what objects too small to observe with our senses might be like. For example, we can understand an atom's properties because we can picture it in our minds, although we have never seen an atom with our eyes. New tools, of course, allow us to better picture phenomena we cannot see. In fact, new instrumentation has allowed us in recent years to actually "picture" the atom.

For the laws of classical physics to apply, the following criteria must be met: Matter must be moving at speeds less than about 1% of the speed of light, the objects dealt with must be large enough to be seen with a microscope, and only weak gravitational fields (such as the field generated by the Earth) can be involved.

Some of the most spectacular advances in science have been made in modern physics. Many of the laws of classical physics have been modified or rejected, and revolutionary changes in technology, society, and our view of the universe have resulted. Like science fiction, modern physics is filled with fascinating objects beyond our normal experiences, but it has the advantage over science fiction of being very real. Why, then, is the majority of this text devoted to

topics of classical physics? There are two main reasons: Classical physics gives an extremely accurate description of the universe under a wide range of everyday circumstances, and knowledge of classical physics is necessary to understand modern physics.

Modern physics itself consists of the two revolutionary theories, relativity and quantum mechanics. These theories deal with the very fast and the very small, respectively. Relativity must be used whenever an object is traveling at greater than about 1% of the speed of light or experiences a strong gravitational field such as that near the Sun. Quantum mechanics must be used for objects smaller than can be seen with a microscope. The combination of these two theories is relativistic quantum mechanics, and it describes the behavior of small objects traveling at high speeds or experiencing a strong gravitational field. Relativistic quantum mechanics is the best universally applicable theory we have. Because of its mathematical complexity, it is used only when necessary, and the other theories are used whenever they will produce sufficiently accurate results. We will find, however, that we can do a great deal of modern physics with the algebra and trigonometry used in this text.



Which theory to use

Questions

1. In the scientific method as the text describes it, what comes right after stating a hypothesis?
 - a. Drawing a conclusion
 - b. Testing it by performing an experiment
 - c. Asking a new question
 - d. Publishing the result

2. Why does classical physics seem intuitively reasonable to us while modern physics seems bizarre?
 - a. Because classical physics is exact and modern physics is not
 - b. Because modern physics has not been tested
 - c. Because we live under the conditions where classical physics works: slow speeds, visible objects, weak gravity
 - d. Because classical physics was discovered first
3. An object is smaller than can be seen with a microscope. Which theory must be used to describe it?
 - a. Quantum mechanics
 - b. Relativity
 - c. Classical physics
 - d. Natural philosophy
4. Why is most of the text devoted to classical physics, even though modern physics is more exact?
 - a. Because modern physics is only science fiction
 - b. Because modern physics cannot be done with algebra
 - c. Because classical physics has never been modified
 - d. Because classical physics is very accurate in everyday circumstances and is needed to understand modern physics

Answers

1. **b)** The scientist devises a hypothesis and then tests it by performing an experiment, before analyzing the results.
2. **c)** Humans live among slow speeds, objects large enough to see, and weak gravity, exactly where classical physics is an excellent approximation.

3. a) Quantum mechanics must be used for objects smaller than can be seen with a microscope.

4. d) The text gives two reasons: classical physics is extremely accurate under everyday circumstances, and it is necessary for understanding modern physics.

Worked examples

Why won't the car start? Your car will not start. Use the scientific method, as the text does, to test the idea that it has no engine oil.

Observation and question: the car will not start; why?

Research: find out the various reasons a car may fail to start.

Hypothesis: the car is not starting because it has no engine oil.

Experiment: open the hood and examine the oil level.

Analysis and conclusion: the oil is at an acceptable level, so oil is not the cause; devise a new hypothesis and repeat.

Answer: The oil hypothesis is rejected; a new hypothesis must be tested.

Practice

1. For each case, say which theory the text says must be used: (a) a spacecraft moving at more than about 1% of the speed of light; (b) an electron inside an atom; (c) a thrown ball on Earth.

Hint: Recall the three conditions under which classical physics is a good approximation.

Answer: (a) Relativity, because it is faster than about 1% of the speed of light. (b) Quantum mechanics, because it is smaller than can be seen with a microscope. (c) Classical physics, because it is slow, visible and in Earth's weak gravity.

2. What did Ibn al-Haytham contribute to the way science is done, beyond his work on optics?

Hint: Think of his attitude to existing knowledge and to evidence.

Answer: He insisted that scientists be ready to reject existing knowledge and trust only objective evidence, stressed repeated experimentation and validation, and warned that our senses and predispositions can mislead us. This made his work a precursor of the scientific method.

Physical Quantities and Units

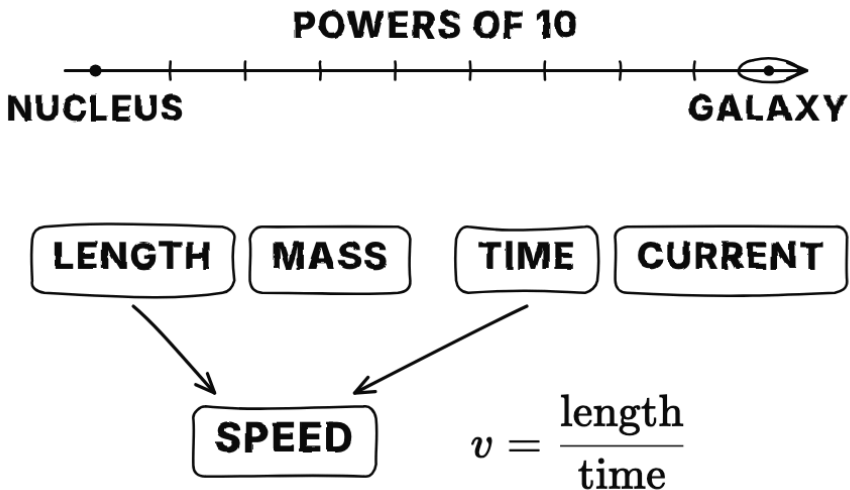
Check your understanding. A friend tells you they have learned about a new law of nature. What can you know about the information even before your friend describes the law? How would the information be different if your friend told you they had learned about a scientific theory rather than a law?

Without knowing the details of the law, you can still infer that the information your friend has learned conforms to the requirements of all laws of nature: it will be a concise description of the universe around us; a statement of the underlying rules that all natural processes follow. If the information had been a theory, you would be able to infer that the information will be a large-scale, broadly applicable generalization.

Equation grapher: learn about graphing polynomials. The shape of the curve changes as the constants are adjusted. View the curves for the individual terms (for example, $y = bx$) to see how they add to generate the polynomial curve.

The range of objects and phenomena studied in physics is immense. From the incredibly short lifetime of a nucleus to the age of the Earth, from the tiny sizes of sub-nuclear particles to the vast distance to the edges of the known universe, from the force exerted by a jumping flea to the force between Earth and the Sun, there are enough factors of 10 to challenge the imagination of even the most experienced scientist. Giving numerical values for physical quantities and equations for physical principles allows us to understand nature much more deeply than does qualitative description alone. To comprehend these vast

ranges, we must also have accepted units in which to express them. And we shall find that (even in the potentially mundane discussion of meters, kilograms, and seconds) a profound simplicity of nature appears: most physical quantities can be expressed as combinations of only four fundamental physical quantities: length, mass, time, and electric current.



Four fundamental quantities

We define a physical quantity either by specifying how it is measured or by stating how it is calculated from other measurements. For example, we define distance and time by specifying methods for measuring them, whereas we define average speed by stating that it is calculated as distance traveled divided by time of travel.

Measurements of physical quantities are expressed in terms of units, which are standardized values. For example, the length of a race, which is a physical quantity, can be expressed in units of meters (for sprinters) or kilometers (for distance runners). Without standardized units, it would be extremely difficult for scientists to express and compare measured values in a meaningful way.

There are two major systems of units used in the world: SI units (also known as the metric system) and English units (also known as the customary or imperial system). English units were historically used in nations once ruled by the British Empire and are still widely used in the United States. Virtually every other country in the world now uses SI units as the standard; the metric system is also the standard system agreed upon by scientists and mathematicians. The acronym “SI” is derived from the French *Système International*.

The table of fundamental SI units gives the units used throughout this textbook: for length, the meter (m); for mass, the kilogram (kg); for time, the second (s); and for electric current, the ampere (A). This text uses non-SI units in a few applications where they are in very common use, such as the measurement of blood pressure in millimeters of mercury (mm Hg). Whenever non-SI units are discussed, they will be tied to SI units through conversions.

It is an intriguing fact that some physical quantities are more fundamental than others and that the most fundamental physical quantities can be defined only in terms of the procedure used to measure them. The units in which they are measured are thus called fundamental units. In this textbook, the fundamental physical quantities are taken to be length, mass, time, and electric current. (Note that electric current will not be introduced until much later in

this text.) All other physical quantities, such as force and electric charge, can be expressed as algebraic combinations of length, mass, time, and current (for example, speed is length divided by time); these units are called derived units.

Questions

1. How is average speed defined, according to the text?
 - a. By a method for measuring it directly, like a ruler
 - b. By calculating it as distance traveled divided by time of travel
 - c. As one of the four fundamental quantities
 - d. By comparing it with the speed of light
2. Why are standardized units necessary?
 - a. Because without them scientists could not express and compare measured values meaningfully
 - b. Because they make numbers smaller
 - c. Because every country must use the same language
 - d. Because physical quantities change over time
3. Which of these is a derived quantity rather than a fundamental one, in this textbook?
 - a. Length
 - b. Mass
 - c. Time
 - d. Speed

4. What makes a physical quantity fundamental, according to the text?
- a. It is the largest quantity in nature
 - b. It can be defined only in terms of the procedure used to measure it
 - c. It was the first to be discovered
 - d. It is measured in English units

Answers

1. **b)** Distance and time are defined by how they are measured, but average speed is defined by how it is calculated from them.
2. **a)** Without standardized units it would be extremely difficult to express and compare measured values in a meaningful way.
3. **d)** Speed is length divided by time, an algebraic combination of fundamental quantities, so its unit is derived.
4. **b)** The most fundamental quantities can be defined only by the procedure used to measure them; their units are fundamental units.

Worked examples

A law or a theory? 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 differ if it were a theory?

Every law of nature is a concise description of the universe, a statement of the underlying rules all natural processes follow.

So, even without details, the friend's law must be such a concise statement of an underlying rule.

A theory, by contrast, is a large-scale, broadly applicable generalization rather than a concise rule.

Answer: A law will be a concise statement of an underlying rule of nature; a theory would be a large-scale, broadly applicable generalization.

Practice

1. Sort these into fundamental and derived quantities as this textbook defines them: mass, speed, electric current, force, time.

Hint: The textbook names exactly four fundamental quantities.

Answer: Fundamental: mass, electric current and time (the fourth is length). Derived: speed (length divided by time) and force, which are algebraic combinations of the fundamental quantities.

2. A runner covers a 400-meter race in 50 seconds. Using the text's definition, what is the runner's average speed?

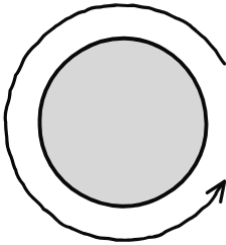
Hint: Average speed is calculated as distance traveled divided by time of travel.

Answer: 8 meters per second: 400 m divided by 50 s. The unit, meters per second, is a derived unit, length divided by time.

The Second, the Meter, and the Kilogram

The SI unit for time, the second (abbreviated s), has a long history. For many years it was defined as $1/86,400$ of a mean solar day. More recently, a new standard was adopted to gain greater accuracy and to define the second in terms of a non-varying, or constant, physical phenomenon (because the solar day is getting longer due to very gradual slowing of the Earth's rotation). Cesium atoms can be made to vibrate in a very steady way, and these vibrations can be readily observed and counted. In 1967 the second was redefined as the time required for 9,192,631,770 of these vibrations. Accuracy in the fundamental units is essential, because all measurements are ultimately expressed in terms of fundamental units and can be no more accurate than are the fundamental units themselves.

1 DAY



$\frac{1}{86\,400}$ day

SLOWING

CAESIUM



9,192,631,770

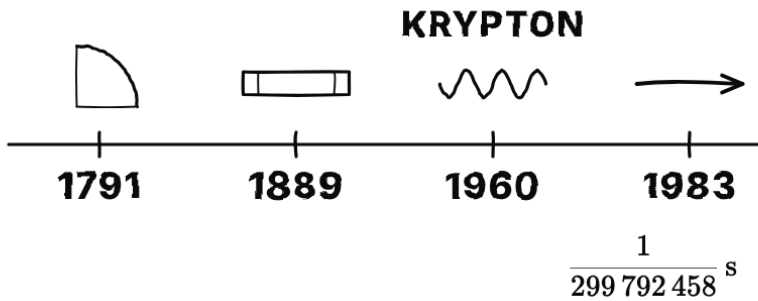
VIBRATIONS = 1 S

Defining the second

The SI unit for length is the meter (abbreviated m); its definition has also changed over time to become more accurate and precise. The meter was first defined in 1791 as $1/10,000,000$ of the distance from the equator to the North Pole. This measurement was improved in 1889 by redefining the meter to be the distance between two engraved lines on a platinum-iridium bar now kept near Paris. By 1960, it had become possible to define the meter even more accurately in terms of the wavelength of light, so it was again redefined as 1,650,763.73 wavelengths of orange light emitted by krypton atoms. In 1983, the meter was given its present definition (partly for greater accuracy) as the distance light travels in a vacuum in $1/299,792,458$ of a second. This change defines the speed of light to be exactly 299,792,458

meters per second. The length of the meter will change if the speed of light is someday measured with greater accuracy.

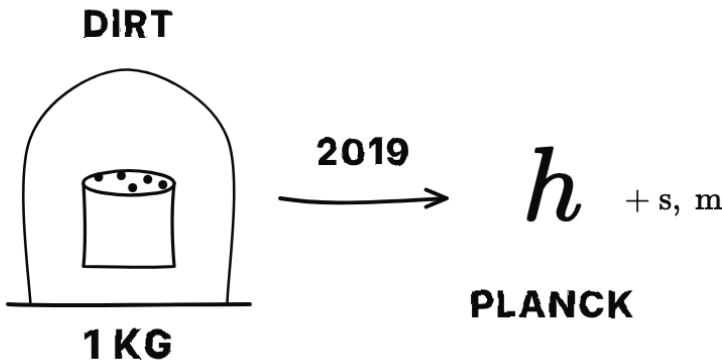
$$c = 299\,792\,458 \text{ m/s}$$



Four definitions of the metre

The SI unit for mass is the kilogram (abbreviated kg); it was previously defined to be the mass of a platinum-iridium cylinder kept with the old meter standard at the International Bureau of Weights and Measures near Paris. Exact replicas of the previously defined kilogram are also kept at the United States' National Institute of Standards and Technology, or NIST, located in Gaithersburg, Maryland outside of Washington, D.C., and at other locations around the world. The determination of all other masses could be ultimately traced to a comparison with the standard mass. Even though the platinum-iridium cylinder was resistant to corrosion, airborne

contaminants were able to adhere to its surface, slightly changing its mass over time. In May 2019, the scientific community adopted a more stable definition of the kilogram. The kilogram is now defined in terms of the second, the meter, and Planck's constant, h (a quantum mechanical value that relates a photon's energy to its frequency).



Defining the kilogram

Electric current and its accompanying unit, the ampere, will be introduced in the chapter on electric current, resistance, and Ohm's law, when electricity and magnetism are covered. The initial modules in this textbook are concerned with mechanics, fluids, heat, and waves. In these subjects all pertinent physical quantities can be expressed in terms of the fundamental units of length, mass, and time.

Questions

1. Why was the second redefined in terms of cesium vibrations instead of the solar day?
 - a. Because the solar day is slowly getting longer, so it is not constant
 - b. Because cesium is cheaper than a clock
 - c. Because the solar day is too short to measure
 - d. Because cesium vibrations are easier to see with the eye
2. Why does accuracy in the fundamental units matter so much?
 - a. Because only scientists use them
 - b. Because they are expensive to keep
 - c. Because every measurement is expressed in them and can be no more accurate than they are
 - d. Because they change every year
3. What follows from defining the meter as the distance light travels in $1/299,792,458$ of a second?
 - a. The speed of light is measured more roughly
 - b. The speed of light is exactly 299,792,458 meters per second by definition
 - c. The meter becomes longer each year
 - d. Light travels one meter each second
4. Why was the old platinum-iridium kilogram replaced in 2019?
 - a. It was lost
 - b. It rusted away completely

- c. It was too heavy to compare
- d. Contaminants from the air stuck to it and slightly changed its mass over time

Answers

- 1. a) The Earth's rotation is gradually slowing, so the solar day gets longer; cesium vibrations give a constant standard.
- 2. c) All measurements are ultimately expressed in fundamental units and can be no more accurate than those units themselves.
- 3. b) Fixing the meter by light's travel time defines the speed of light to be exactly 299,792,458 meters per second.
- 4. d) Though resistant to corrosion, the cylinder gathered airborne contaminants, slightly changing its mass, so a more stable definition was adopted.

Worked examples

Where 1/86,400 comes from The second was once defined as 1/86,400 of a mean solar day. Show that a day has 86,400 seconds.

A day has 24 hours.

Each hour has 60 minutes, so a day has $24 \times 60 = 1,440$ minutes.

Each minute has 60 seconds, so a day has $1,440 \times 60 = 86,400$ seconds.

One second is therefore 1/86,400 of a day.

Answer: 86,400 seconds in a day

Practice

- 1. The meter was first defined in 1791 as 1/10,000,000 of the distance from the equator to the North Pole. By that definition, how far is it

from the equator to the pole, in kilometers?

Hint: If one meter is a ten-millionth of the distance, the distance is ten million meters.

Answer: 10,000 km: 10,000,000 m, and 1,000 m make 1 km.

2. Light travels 299,792,458 meters in one second. Roughly how far does it travel in one thousandth of a second?

Hint: Divide the distance in one second by 1,000.

Answer: About 300,000 meters, or 300 km: $299,792,458 \div 1,000 \approx 299,792$ m.

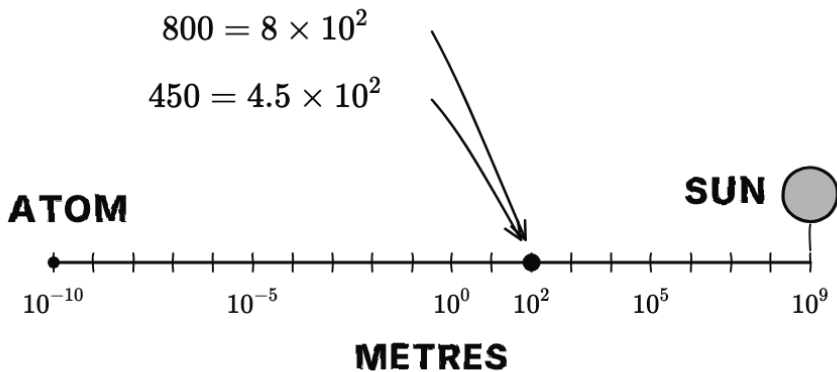
Metric Prefixes

SI units are part of the metric system. The metric system is convenient for scientific and engineering calculations because the units are categorized by factors of 10. The table of metric prefixes gives the prefixes and symbols used to denote various factors of 10.

Metric systems have the advantage that conversions of units involve only powers of 10. There are 100 centimeters in a meter, 1000 meters in a kilometer, and so on. In nonmetric systems, such as the system of U.S. customary units, the relationships are not as simple: there are 12 inches in a foot, 5280 feet in a mile, and so on. Another advantage of the metric system is that the same unit can be used over extremely large ranges of values simply by using an appropriate metric prefix. For example, distances in meters are suitable in construction, while distances in kilometers are appropriate for air travel, and the tiny measure of nanometers are convenient in optical design. With the metric system there is no need to invent new units for particular applications.

The term order of magnitude refers to the scale of a value expressed in the metric system. Each power of 10, such as 10^0 , 10^1 , 10^2 , and so forth, is a different order of magnitude. All quantities that can be expressed as a product of a specific power of 10 are said to be of the same order of magnitude. For example, the number 800 can be written as 8×10^2 , and the number 450 can be written as 4.5×10^2 . Thus, the numbers 800 and 450 are of the same order of magnitude: 10^2 . Order of magnitude can be thought of as a ballpark estimate for

the scale of a value. The diameter of an atom is on the order of 10^{-10} m, while the diameter of the Sun is on the order of 10^9 m.



Orders of magnitude

The fundamental units described in this chapter are those that produce the greatest accuracy and precision in measurement. There is a sense among physicists that, because there is an underlying microscopic substructure to matter, it would be most satisfying to base our standards of measurement on microscopic objects and fundamental physical phenomena such as the speed of light. A microscopic standard has been accomplished for the standard of time, which is based on the oscillations of the cesium atom.

The standard for length was once based on the wavelength of light (a small-scale length) emitted by a certain type of atom, but it has been supplanted by the more precise measurement of the speed of light. If it becomes possible to measure the mass of atoms or a particular arrangement of atoms such as a silicon sphere to greater precision than the kilogram standard, it may become possible to base mass measurements on the small scale. There are also possibilities that electrical phenomena on the small scale may someday allow us to base a unit of charge on the charge of electrons and protons, but at present current and charge are related to large-scale currents and forces between wires.

The table of metric prefixes for powers of 10 lists each prefix with its symbol, its value, and an example. Exa, symbol E, is 10^{18} : an exameter is about the distance light travels in a century. Peta, symbol P, is 10^{15} : a petasecond is about 30 million years. Tera, symbol T, is 10^{12} : a terawatt is the output of a powerful laser. Giga, symbol G, is 10^9 : a gigahertz is a microwave frequency. Mega, symbol M, is 10^6 : a megacurie is high radioactivity. Kilo, symbol k, is 10^3 : a kilometer is about 6/10 of a mile. Hecto, symbol h, is 10^2 : a hectoliter is 26 gallons. Deka, symbol da, is 10^1 : a dekagram is a teaspoon of butter. Without a prefix, the value is 10^0 , which equals 1. Deci, symbol d, is 10^{-1} : a deciliter is less than half a soda. Centi, symbol c, is 10^{-2} : a centimeter is the thickness of a fingertip. Milli, symbol m, is 10^{-3} : a millimeter is the height of a flea at its shoulders. Micro, symbol μ , is 10^{-6} : a micrometer is a detail seen in a microscope. Nano, symbol n, is 10^{-9} : a nanogram is a small speck of dust. Pico, symbol p, is 10^{-12} : a picofarad is a small capacitor in a radio. Femto, symbol f, is 10^{-15} : a femtometer is the size of a proton. Atto, symbol a, is 10^{-18} : an attosecond is the time light takes to cross an atom.

exa	<i>E</i>	10^{18}	deci	<i>d</i>	10^{-1}
peta	<i>P</i>	10^{15}	centi	<i>c</i>	10^{-2}
tera	<i>T</i>	10^{12}	milli	<i>m</i>	10^{-3}
giga	<i>G</i>	10^9	micro	μ	10^{-6}
mega	<i>M</i>	10^6	nano	<i>n</i>	10^{-9}
kilo	<i>k</i>	10^3	pico	<i>p</i>	10^{-12}
			femto	<i>f</i>	10^{-15}
			atto	<i>a</i>	10^{-18}

Metric prefixes

Questions

- Why are unit conversions easier in the metric system than in U.S. customary units?
 - Because metric units are smaller
 - Because metric conversions involve only powers of 10
 - Because the metric system has fewer quantities
 - Because metric units are older
- Why are 800 and 450 of the same order of magnitude?

- a. Because both are even numbers
 - b. Because both are less than 1000 and more than 400
 - c. Because both can be written as a number times 10^2
 - d. Because their difference is less than 400
3. For which basic unit has a microscopic standard already been achieved, according to the text?
- a. Time, based on the oscillations of the cesium atom
 - b. Mass, based on a silicon sphere
 - c. Electric charge, based on electrons
 - d. Length, based on krypton light
4. What is one advantage of metric prefixes, according to the text?
- a. They make every quantity a whole number
 - b. They remove the need for measurement
 - c. They are the same as English units
 - d. The same unit can be used over extremely large ranges, without inventing new units

Answers

1. **b)** Metric conversions involve only powers of 10, like 100 centimeters in a meter, while customary units use 12 inches in a foot and 5280 feet in a mile.
2. **c)** 800 is 8×10^2 and 450 is 4.5×10^2 , so both share the power 10^2 .
3. **a)** A microscopic standard has been accomplished for time, based on cesium oscillations.
4. **d)** With prefixes the same unit serves from nanometers in optics to kilometers in air travel, so no new units are needed.

Worked examples

From the atom to the Sun The diameter of an atom is on the order of 10^{-10} m and that of the Sun on the order of 10^9 m. By how many orders of magnitude do they differ?

Each order of magnitude is one power of 10.

Going from 10^{-10} up to 10^0 takes 10 powers of 10.

Going from 10^0 up to 10^9 takes 9 more.

In all, $10 + 9 = 19$ powers of 10.

Answer: 19 orders of magnitude

Practice

1. Write 3,000 meters and 5 millimeters using metric prefixes, and say what order of magnitude each is in meters.

Hint: Kilo is 10^3 and milli is 10^{-3} .

Answer: 3,000 m = 3 km, which is 3×10^3 m, of order 10^3 m. 5 mm = 5×10^{-3} m, of order 10^{-3} m.

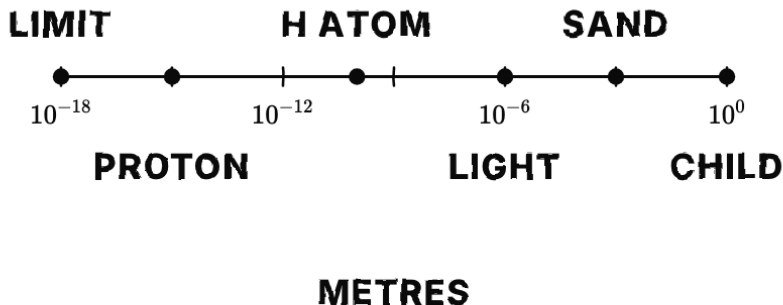
2. How many centimeters are in a kilometer?

Hint: There are 100 centimeters in a meter and 1000 meters in a kilometer.

Answer: 100,000 centimeters: $1000 \times 100 = 100,000$, which is 10^5 .

Known Ranges and Unit Conversion

The vastness of the universe and the breadth over which physics applies are illustrated by the wide range of examples of known lengths, masses, and times in the table of approximate values. Examination of this table will give you some feeling for the range of possible topics and numerical values.

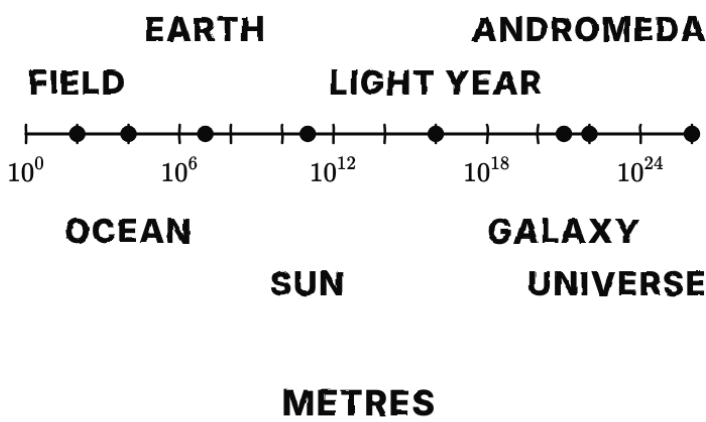


Small lengths, powers of ten

The table lists lengths in meters, masses in kilograms, and times in seconds, each as a power of 10, with more precise values in parentheses. At 10^{-18} m lies the present experimental limit to the

smallest observable detail; a mass of 10^{-30} kg is that of an electron (9.11×10^{-31} kg); and 10^{-23} s is the time for light to cross a proton. 10^{-15} m is the diameter of a proton; 10^{-27} kg is the mass of a hydrogen atom (1.67×10^{-27} kg); 10^{-22} s is the mean life of an extremely unstable nucleus. 10^{-14} m is the diameter of a uranium nucleus; 10^{-15} kg is the mass of a bacterium; 10^{-15} s is the time for one oscillation of visible light. 10^{-10} m is the diameter of a hydrogen atom; 10^{-5} kg is the mass of a mosquito; 10^{-13} s is the time for one vibration of an atom in a solid. 10^{-8} m is the thickness of membranes in cells of living organisms; 10^{-2} kg is the mass of a hummingbird; 10^{-8} s is the time for one oscillation of an FM radio wave. 10^{-6} m is the wavelength of visible light; 1 kilogram is the mass of a liter of water (about a quart); 10^{-3} s is the duration of a nerve impulse. 10^{-3} m is the size of a grain of sand; 10^2 kg is the mass of a person; 1 second is the time for one heartbeat. 1 meter is the height of a 4-year-old child; 10^3 kg is the mass of a car; 10^5 s is one day (8.64×10^4 s). 10^2 m is the length of a football field; 10^8 kg is the mass of a large ship; 10^7 s is one year (3.16×10^7 s). 10^4 m is the greatest ocean depth; 10^{12} kg is the mass of a large iceberg; 10^9 s is about half the life expectancy of a human. 10^7 m is the diameter of the Earth; 10^{15} kg is the mass of the nucleus of a comet; 10^{11} s is recorded history. 10^{11} m is the distance from the Earth to the Sun; 10^{23} kg is the mass of the Moon (7.35×10^{22} kg); 10^{17} s is the age of the Earth. 10^{16} m is the distance traveled by light in 1 year, a light year; 10^{25} kg is the mass of the Earth (5.97×10^{24} kg); 10^{18} s is the age of the universe. 10^{21} m is the diameter of the Milky Way galaxy, and 10^{30} kg is the mass of the Sun (1.99×10^{30} kg). 10^{22} m is the distance from the Earth to the nearest large galaxy, Andromeda, and 10^{42} kg is the mass of the Milky Way galaxy (current upper limit). 10^{26} m is the distance

from the Earth to the edges of the known universe, and 10^{53} kg is the mass of the known universe (current upper limit).



Large lengths, powers of ten

It is often necessary to convert from one type of unit to another. For example, if you are reading a European cookbook, some quantities may be expressed in units of liters and you need to convert them to cups. Or, perhaps you are reading walking directions from one location to another and you are interested in how many miles you will be walking. In this case, you will need to convert units of feet to miles.

$$80 \text{ m} \rightarrow \text{km}$$

CONVERSION FACTOR

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

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

METRES CANCEL

Converting 80 m to km

Let us consider a simple example of how to convert units. Let us say that we want to convert 80 meters (m) to kilometers (km).

The first thing to do is to list the units that you have and the units that you want to convert to. In this case, we have units in meters and we want to convert to kilometers.

Next, we need to determine a conversion factor relating meters to kilometers. A conversion factor is a ratio expressing how many of one unit are equal to another unit. For example, there are 12 inches in 1 foot, 100 centimeters in 1 meter, 60 seconds in 1 minute, and so on. In this case, we know that there are 1,000 meters in 1 kilometer.

Now we can set up our unit conversion. We will write the units that we have and then multiply them by the conversion factor so that the units cancel out, as shown: $80 \text{ m} \times (1 \text{ km} / 1000 \text{ m}) = 0.080 \text{ km}$.

Note that the unwanted m unit cancels, leaving only the desired km unit. You can use this method to convert between any types of unit. Appendix C gives a more complete list of conversion factors.

Example: unit conversions, a short drive home. Suppose that you drive the 10.0 km from your school to home in 20.0 min. Calculate your average speed (a) in kilometers per hour (km/h) and (b) in meters per second (m/s). (Note: Average speed is distance traveled divided by time of travel.)

$$\frac{10.0 \text{ KM}}{20.0 \text{ MIN}}$$


$$\frac{10.0 \text{ km}}{20.0 \text{ min}} = 0.500 \frac{\text{km}}{\text{min}}$$

$$0.500 \frac{\text{km}}{\text{min}} \times \frac{60 \text{ min}}{1 \text{ h}} = 30.0 \frac{\text{km}}{\text{h}}$$

A drive home: 30.0 km/h

Strategy. First we calculate the average speed using the given units. Then we can get the average speed into the desired units by picking the correct conversion factor and multiplying by it. The correct conversion factor is the one that cancels the unwanted unit and leaves the desired unit in its place.

Solution for (a). (1) Calculate average speed. Average speed is distance traveled divided by time of travel. (Take this definition as a given for now; average speed and other motion concepts will be covered in a later module.) In equation form, average speed = distance / time. (2) Substitute the given values for distance and time: average speed = $10.0 \text{ km} / 20.0 \text{ min} = 0.500 \text{ km/min}$. (3) Convert km/min to km/h: multiply by the conversion factor that will cancel minutes and leave hours. That conversion factor is 60 min/hr: $0.500 \text{ km/min} \times 60 \text{ min/1 hr} = 30.0 \text{ km/h}$.

Discussion for (a). To check your answer, consider the following. (1) Be sure that you have properly cancelled the units in the unit conversion. If you have written the unit conversion factor upside down, the units will not cancel properly in the equation. If you accidentally get the ratio upside down, then the units will not cancel; rather, they will give you the wrong units as follows: $\text{km/min} \times 1 \text{ hr/60 min} = (1/60) \text{ km}\cdot\text{hr/min}^2$, which are obviously not the desired units of km/h. (2) Check that the units of the final answer are the desired units. The problem asked us to solve for average speed in units of km/h and we have indeed obtained these units. (3) Check the significant figures. Because each of the values given in the problem has three significant figures, the answer should also have three significant figures. The answer 30.0 km/hr does indeed have three significant figures, so this is appropriate. Note that the significant figures in the conversion factor are not relevant because an hour is

defined to be 60 minutes, so the precision of the conversion factor is perfect.

Questions

1. What is a conversion factor?
 - a. A ratio expressing how many of one unit equal another unit
 - b. A number that makes every answer smaller
 - c. The precision of a measuring tool
 - d. A power of 10 attached to a unit
2. How can you tell that a conversion factor was written upside down?
 - a. The answer comes out negative
 - b. The units do not cancel and the result has the wrong units
 - c. The answer has too many significant figures
 - d. The number becomes larger
3. Why do the significant figures of the factor 60 min/hr not limit the answer 30.0 km/h?
 - a. Because 60 is a round number
 - b. Because the factor is used only once
 - c. Because an hour is defined to be 60 minutes, so the factor is perfectly precise
 - d. Because minutes cancel out
4. Roughly how many orders of magnitude separate the diameter of a hydrogen atom (10^{-10} m) from the diameter of the Earth

$(10^7 \text{ m})?$

- a. 3
- b. 7
- c. 10
- d. 17

Answers

1. **a)** A conversion factor is a ratio such as 1000 meters in 1 kilometer or 60 seconds in 1 minute.
2. **b)** Upside down, the units do not cancel; you get $\text{km}\cdot\text{hr}/\text{min}^2$, obviously not km/h .
3. **c)** An hour is defined to be exactly 60 minutes, so the conversion factor's precision is perfect.
4. **d)** From 10^{-10} to 10^7 is 17 powers of 10, which shows the vast range of lengths in the table.

Worked examples

A short drive home You drive the 10.0 km from your school to home in 20.0 min. What is your average speed in km/h ?

Average speed is distance traveled divided by time of travel.

Substitute: $10.0 \text{ km} \div 20.0 \text{ min} = 0.500 \text{ km}/\text{min}$.

To change minutes into hours, multiply by the conversion factor $60 \text{ min}/1 \text{ hr}$, which cancels minutes and leaves hours.

$0.500 \text{ km}/\text{min} \times 60 \text{ min}/\text{hr} = 30.0 \text{ km}/\text{h}$, with three significant figures like the data.

Answer: $30.0 \text{ km}/\text{h}$

Practice

1. Part (b) of the same example: express the average speed of 30.0 km/h in meters per second.

Hint: Use 1000 m in 1 km and 3600 s in 1 hr, so that km and hr cancel.

Answer: 8.33 m/s: $30.0 \text{ km/h} \times 1000 \text{ m/km} \times 1 \text{ hr}/3600 \text{ s} = 30,000/3600 \text{ m/s} \approx 8.33 \text{ m/s}$.

2. Convert 2,500 meters to kilometers using a conversion factor.

Hint: Multiply by 1 km/1000 m so that the meters cancel.

Answer: 2.5 km: $2,500 \text{ m} \times 1 \text{ km}/1000 \text{ m} = 2.5 \text{ km}$.

3. A walk is 15,840 feet long. How many miles is it?

Hint: There are 5280 feet in a mile; multiply by 1 mile/5280 feet.

Answer: 3 miles: $15,840 \div 5280 = 3$.

Finishing the Drive Home

(4) Next, check whether the answer is reasonable. Let us consider some information from the problem: if you travel 10 km in a third of an hour (20 min), you would travel three times that far in an hour. The answer does seem reasonable.

$$30.0 \text{ km/h}$$

$$10 \text{ km in } \frac{1}{3} \text{ h} \Rightarrow 30 \text{ km in } 1 \text{ h}$$

$$30.0 \frac{\cancel{\text{km}}}{\cancel{\text{h}}} \times \frac{1\cancel{\text{h}}}{3600 \text{ s}} \times \frac{1000 \text{ m}}{1\cancel{\text{km}}} = 8.33 \frac{\text{m}}{\text{s}}$$

$$0.500 \text{ km/min} \Rightarrow 8.33 \text{ m/s}$$

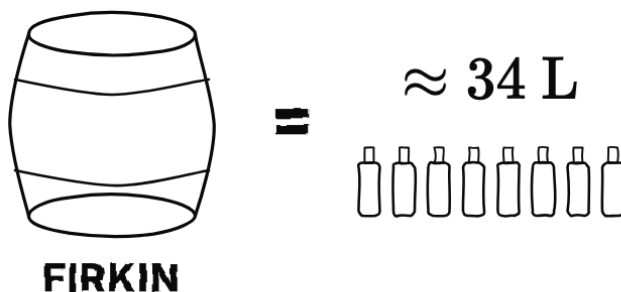
From km/h to m/s

Solution for (b). There are several ways to convert the average speed into meters per second. (1) Start with the answer to (a) and convert km/h to m/s. Two conversion factors are needed: one to convert hours to seconds, and another to convert kilometers to meters. (2)

Multiplying by these yields average speed = $30.0 \text{ km/h} \times 1 \text{ h}/3,600 \text{ s} \times 1,000 \text{ m}/1 \text{ km}$, so average speed = 8.33 m/s .

Discussion for (b). If we had started with 0.500 km/min , we would have needed different conversion factors, but the answer would have been the same: 8.33 m/s .

You may have noted that the answers in the worked example just covered were given to three digits. Why? When do you need to be concerned about the number of digits in something you calculate? Why not write down all the digits your calculator produces? The module Accuracy, Precision, and Significant Figures will help you answer these questions.

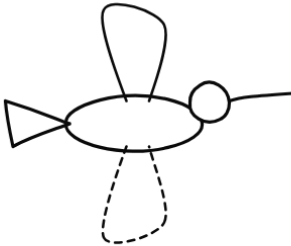


BARLEYCORN?

A firkin of beer

Nonstandard units. While there are numerous types of units that we are all familiar with, there are others that are much more obscure. For example, a firkin is a unit of volume that was once used to measure beer. One firkin equals about 34 liters. To learn more about nonstandard units, use a dictionary or encyclopedia to research different “weights and measures.” Take note of any unusual units, such as a barleycorn, that are not listed in the text. Think about how the unit is defined and state its relationship to SI units.

Check your understanding. Some hummingbirds beat their wings more than 50 times per second. A scientist is measuring the time it takes for a hummingbird to beat its wings once. Which fundamental unit should the scientist use to describe the measurement? Which factor of 10 is the scientist likely to use to describe the motion precisely? Identify the metric prefix that corresponds to this factor of 10.



50 BEATS/S

$$\frac{1}{50} \text{ s} = 0.020 \text{ s}$$

$$= 20 \text{ ms}$$

$$1 \text{ ms} = 10^{-3} \text{ s}$$

$$1 \text{ cm}^3 = 1 \text{ mL}$$

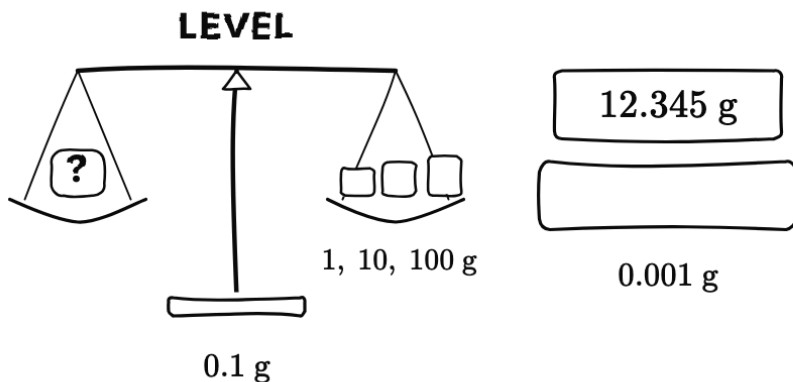
A hummingbird's wingbeat

The scientist will measure the time between each movement using the fundamental unit of seconds. Because the wings beat so fast, the scientist will probably need to measure in milliseconds, or 10^{-3} seconds. (50 beats per second corresponds to 20 milliseconds per beat.)

Check your understanding. One cubic centimeter is equal to one milliliter. What does this tell you about the different units in the SI metric system?

The fundamental unit of length (meter) is probably used to create the derived unit of volume (liter). The measure of a milliliter is dependent on the measure of a centimeter.

A double-pan mechanical balance is used to compare different masses. Usually an object with unknown mass is placed in one pan and objects of known mass are placed in the other pan. When the bar that connects the two pans is horizontal, then the masses in both pans are equal. The “known masses” are typically metal cylinders of standard mass such as 1 gram, 10 grams, and 100 grams. Many mechanical balances, such as double-pan balances, have been replaced by digital scales, which can typically measure the mass of an object more precisely. Whereas a mechanical balance may only read the mass of an object to the nearest tenth of a gram, many digital scales can measure the mass of an object up to the nearest thousandth of a gram.



Balance and digital scale

Questions

1. Why does 30.0 km/h seem a reasonable answer for 10 km driven in 20 min?
 - a. Because 20 minutes is a third of an hour, so in an hour you would go three times as far
 - b. Because all car speeds are near 30 km/h
 - c. Because 10 plus 20 is 30
 - d. Because the conversion factor is 60
2. Why are two conversion factors needed to change km/h into m/s?
 - a. Because speed has two significant figures
 - b. Because both the distance unit and the time unit must change
 - c. Because meters and seconds are derived units
 - d. Because one factor is always upside down
3. Why would a scientist describe one hummingbird wingbeat in milliseconds?
 - a. Because milliseconds are the fundamental unit of time
 - b. Because wingbeats last several seconds
 - c. Because the wings beat so fast that each beat lasts only thousandths of a second
 - d. Because milliseconds are more precise than any other unit
4. What does it mean that one cubic centimeter equals one milliliter?

- a. That volume is a fundamental quantity
- b. That liters and meters are unrelated
- c. That cubic centimeters are larger
- d. That the unit of volume is derived from the unit of length

Answers

- 1. **a)** In a third of an hour you go 10 km, so in a full hour you go three times that, 30 km.
- 2. **b)** One factor converts hours to seconds and the other converts kilometers to meters.
- 3. **c)** At 50 beats per second, each beat lasts 20 milliseconds, so the prefix milli, 10^{-3} , fits.
- 4. **d)** The liter is a derived unit built from the meter, so a milliliter depends on the centimeter.

Worked examples

Converting the drive home to m/s Convert the average speed of 30.0 km/h into meters per second.

Two conversion factors are needed: one for hours to seconds and one for kilometers to meters.

Multiply: $30.0 \text{ km/h} \times 1 \text{ h}/3,600 \text{ s} \times 1,000 \text{ m}/1 \text{ km}$.

Hours and kilometers cancel, leaving m/s.

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

Answer: 8.33 m/s

Practice

1. Some hummingbirds beat their wings more than 50 times per second. How long does one beat take, in milliseconds?

Hint: One second shared among 50 beats; then 1 second is 1000 milliseconds.

Answer: 20 milliseconds: $1 \text{ s} \div 50 = 0.02 \text{ s}$, which is 20 ms.

2. One firkin equals about 34 liters. About how many liters are in 3 firkins?

Hint: Multiply by the conversion factor 34 liters per firkin.

Answer: About 102 liters: $3 \text{ firkins} \times 34 \text{ L/firkin} = 102 \text{ L}$.

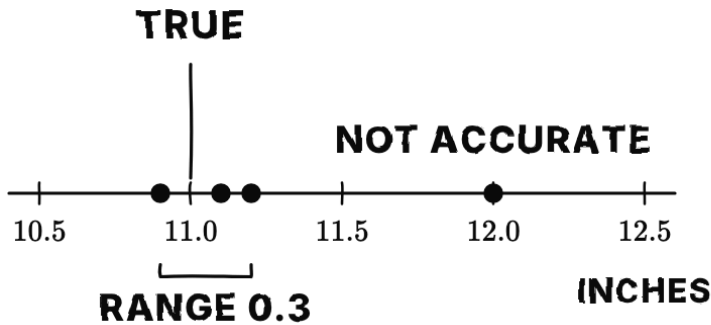
3. Convert 72 km/h into meters per second.

Hint: Multiply by 1 h/3,600 s and 1,000 m/1 km.

Answer: 20 m/s: $72 \times 1,000 \div 3,600 = 20$.

Accuracy, Precision, and Uncertainty

Science is based on observation and experiment, that is, on measurements. Accuracy is how close a measurement is to the correct value for that measurement. For example, let us say that you are measuring the length of standard computer paper. The packaging in which you purchased the paper states that it is 11.0 inches long. You measure the length of the paper three times and obtain the following measurements: 11.1 in., 11.2 in., and 10.9 in. These measurements are quite accurate because they are very close to the correct value of 11.0 inches. In contrast, if you had obtained a measurement of 12 inches, your measurement would not be very accurate.



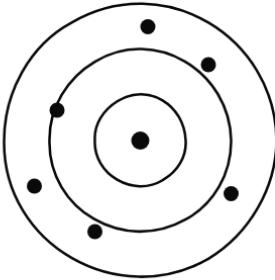
Accurate and precise

The precision of a measurement system refers to how close the agreement is between repeated measurements (which are repeated under the same conditions). Consider the example of the paper measurements. The precision of the measurements refers to the spread of the measured values. One way to analyze the precision of the measurements would be to determine the range, or difference, between the lowest and the highest measured values. In that case, the lowest value was 10.9 in. and the highest value was 11.2 in. Thus, the measured values deviated from each other by at most 0.3 in. These measurements were relatively precise because they did not vary too much in value. However, if the measured values had been 10.9, 11.1, and 11.9, then the measurements would not be very precise because

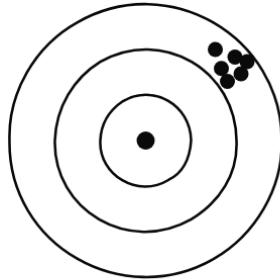
there would be significant variation from one measurement to another.

The measurements in the paper example are both accurate and precise, but in some cases, measurements are accurate but not precise, or they are precise but not accurate. Let us consider an example of a GPS system that is attempting to locate the position of a restaurant in a city. Think of the restaurant location as existing at the center of a bull's-eye target, and think of each GPS attempt to locate the restaurant as a black dot. In the first figure, you can see that the GPS measurements are spread out far apart from each other, but they are centered close to the actual location of the restaurant at the center of the target. This indicates a low precision, high accuracy measuring system. However, in the second figure, the GPS measurements are concentrated quite closely to one another, but they are far away from the target location. This indicates a high precision, low accuracy measuring system.

● = RESTAURANT



**ACCURATE,
NOT PRECISE**

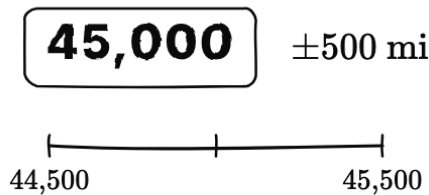


**PRECISE,
NOT ACCURATE**

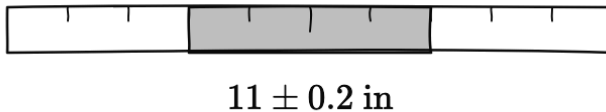
Two GPS targets

The degree of accuracy and precision of a measuring system are related to the uncertainty in the measurements. Uncertainty is a quantitative measure of how much your measured values deviate from a standard or expected value. If your measurements are not very accurate or precise, then the uncertainty of your values will be very high. In more general terms, uncertainty can be thought of as a disclaimer for your measured values. For example, if someone asked you to provide the mileage on your car, you might say that it is 45,000 miles, plus or minus 500 miles. The plus or minus amount is the uncertainty in your value. That is, you are indicating that the actual mileage of your car might be as low as 44,500 miles or as high as 45,500 miles, or anywhere in between. All measurements contain some amount of uncertainty. In our example of measuring the length

of the paper, we might say that the length of the paper is 11 in., plus or minus 0.2 in. The uncertainty in a measurement, A , is often denoted as δA , so the measurement result would be recorded as $A \pm \delta A$. In our paper example, the length of the paper could be expressed as 11 in. $\pm$ 0.2.



$$A \pm \delta A$$

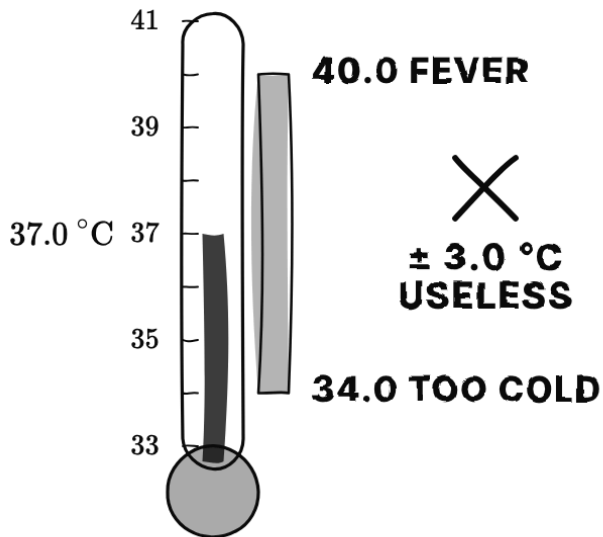


$$A \pm \delta A$$

The factors contributing to uncertainty in a measurement include: first, limitations of the measuring device; second, the skill of the person making the measurement; third, irregularities in the object being measured; and fourth, any other factors that affect the outcome (highly dependent on the situation). In our example, such factors contributing to the uncertainty could be the following: the smallest division on the ruler is 0.1 in., the person using the ruler has bad

eyesight, or one side of the paper is slightly longer than the other. At any rate, the uncertainty in a measurement must be based on a careful consideration of all the factors that might contribute and their possible effects.

Making connections: fevers or chills? Uncertainty is a critical piece of information, both in physics and in many other real-world applications. Imagine you are caring for a sick child. You suspect the child has a fever, so you check their temperature with a thermometer. What if the uncertainty of the thermometer were $3.0\text{ }^{\circ}\text{C}$? If the child's temperature reading was $37.0\text{ }^{\circ}\text{C}$ (which is normal body temperature), the "true" temperature could be anywhere from a hypothermic $34.0\text{ }^{\circ}\text{C}$ to a dangerously high $40.0\text{ }^{\circ}\text{C}$. A thermometer with an uncertainty of $3.0\text{ }^{\circ}\text{C}$ would be useless.



A thermometer that is useless

Questions

1. GPS fixes for a restaurant are spread far apart but centered on the restaurant. How would you describe this system?
 - a. High precision, low accuracy
 - b. Low precision, high accuracy
 - c. High precision, high accuracy
 - d. Low precision, low accuracy

2. Three measurements of a paper sheet are 10.9, 11.1 and 11.9 in. Why are they not very precise?
- Because they vary significantly from one measurement to another
 - Because none equals 11.0 in.
 - Because they were made with a ruler
 - Because there are only three of them
3. What does writing a car's mileage as 45,000 miles plus or minus 500 miles tell you?
- The car has driven exactly 45,500 miles
 - The odometer is broken
 - The true mileage lies anywhere from 44,500 to 45,500 miles
 - The car drives 500 miles a year
4. Why would a thermometer with an uncertainty of 3.0°C be useless for checking a fever?
- Because it reads in Celsius
 - Because it would always read 37.0°C
 - Because body temperature never changes
 - Because a reading of 37.0°C could mean anything from 34.0°C to 40.0°C

Answers

- b)** Spread-out dots mean low precision; their being centered on the target means high accuracy.
- a)** Precision is the spread of repeated values; a range of 1.0 in. is significant variation.

- 3. c)** The plus or minus amount is the uncertainty, so the true value can be anywhere in that range.
- 4. d)** The true temperature could be anywhere from hypothermic to dangerously high, so the reading tells you nothing useful.

Worked examples

Range of the paper measurements The paper's three measured lengths are 11.1 in., 11.2 in. and 10.9 in. What is the range, and what does it say about precision?

Precision can be judged by the range: the difference between the highest and lowest values.

The highest value is 11.2 in. and the lowest is 10.9 in.

$$11.2 - 10.9 = 0.3 \text{ in.}$$

The values deviate from each other by at most 0.3 in., so they are relatively precise.

Answer: 0.3 in.; the measurements are relatively precise

Practice

1. A length is recorded as 11 in. $\pm$ 0.2 in. What are the smallest and largest values the true length could have?

Hint: Subtract and add the uncertainty.

Answer: From 10.8 in. to 11.2 in.: $11 - 0.2$ and $11 + 0.2$.

2. Name the four factors the text lists that contribute to uncertainty, and give one example of each for measuring the paper.

Hint: Think of the ruler, the person, the paper and anything else.

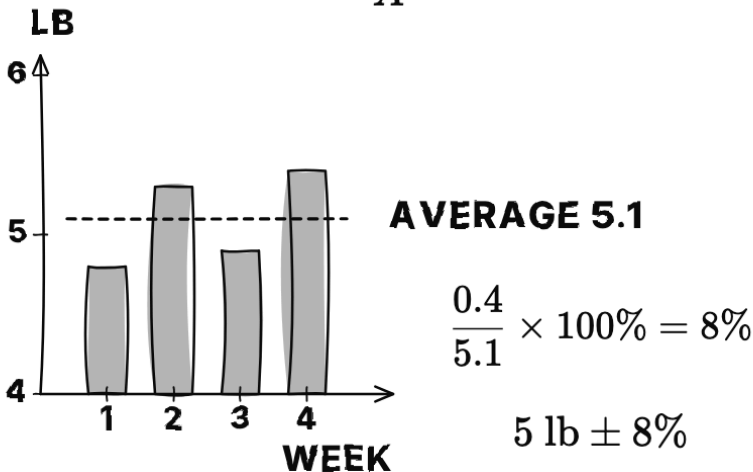
Answer: Limitations of the device (the ruler's smallest division is 0.1 in.), the skill of the person (bad eyesight), irregularities in the object (one

side of the paper slightly longer), and other factors that depend on the situation.

Percent Uncertainty and Significant Figures

One method of expressing uncertainty is as a percent of the measured value. If a measurement A is expressed with uncertainty, δA , the percent uncertainty (%unc) is defined to be $\% \text{unc} = \delta A / A \times 100\%$.

$$\% \text{unc} = \frac{\delta A}{A} \times 100\%$$



Percent uncertainty of a bag of apples

Example: calculating percent uncertainty, a bag of apples. A grocery store sells 5-lb bags of apples. You purchase four bags over the course of a month and weigh the apples each time. You obtain the following measurements: week 1 weight, 4.8 lb; week 2 weight, 5.3 lb; week 3

weight, 4.9 lb; week 4 weight, 5.4 lb. You have previously determined, using additional measurements, that the uncertainty in the average weight of the 5-lb bag is ± 0.4 lb. What is the average weight and percent uncertainty of the bag's weight, given these 4 measurements?

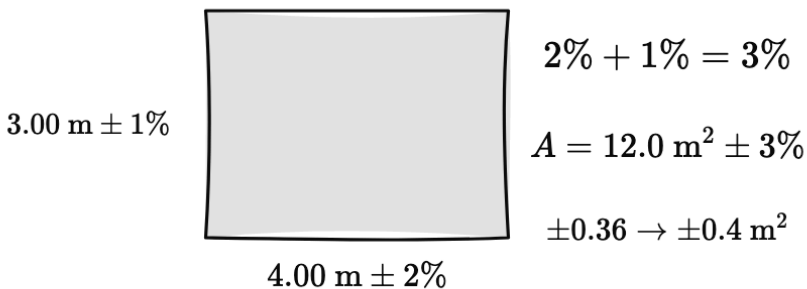
Strategy. The average of the four measured weights is 5.1 lb. Observe that the measured average agrees with the nominal weight of 5 lb within the uncertainty of 0.4 lb. The uncertainty in this value, δA , is 0.4 lb. We can use the following equation to determine the percent uncertainty of the weight: $\%unc = \delta A/A \times 100\%$.

Solution. Plug the known values into the equation: $\%unc = 0.4 \text{ lb}/5.1 \text{ lb} \times 100\% = 8\%$.

Discussion. We can conclude that the weight of the apple bag is $5 \text{ lb} \pm 8\%$. Consider how this percent uncertainty would change if the bag of apples were half as heavy, but the uncertainty in the weight remained the same. Hint for future calculations: when calculating percent uncertainty, always remember that you must multiply the fraction by 100%. If you do not do this, you will have a decimal quantity, not a percent value.

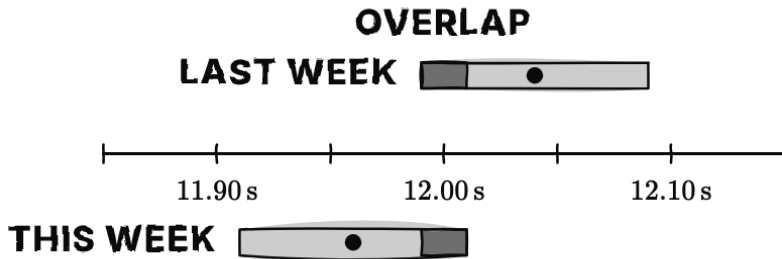
There is an uncertainty in anything calculated from measured quantities. For example, the area of a floor calculated from measurements of its length and width has an uncertainty because the length and width have uncertainties. How big is the uncertainty in something you calculate by multiplication or division? If the measurements going into the calculation have small uncertainties (a few percent or less), then the method of adding percents can be used for multiplication or division. This method says that the percent uncertainty in a quantity calculated by multiplication or division is the sum of the percent uncertainties in the items used to make the

calculation. For example, if a floor has a length of 4.00 m and a width of 3.00 m, with uncertainties of 2% and 1%, respectively, then the area of the floor is 12.0 m² and has an uncertainty of 3%. (Expressed as an area this is 0.36 m², which we round to 0.4 m² since the area of the floor is given to a tenth of a square meter.)



Adding percents for a floor

Check your understanding. A high school track coach has just purchased a new stopwatch. The stopwatch manual states that the stopwatch has an uncertainty of $\pm 0.05 \text{ s}$. The team's top sprinter clocked a 100 meter sprint at 12.04 seconds last week and at 11.96 seconds this week. Can we conclude that this week's time was faster?



ruler: 1 mm caliper: 0.01 mm

Faster or not?

No, the uncertainty in the stopwatch is too great to effectively differentiate between the sprint times.

An important factor in the accuracy and precision of measurements involves the precision of the measuring tool. In general, a precise measuring tool is one that can measure values in very small increments. For example, a standard ruler can measure length to the nearest millimeter, while a caliper can measure length to the nearest 0.01 millimeter. The caliper is a more precise measuring tool because it can measure extremely small differences in length. The more precise the measuring tool, the more precise and accurate the measurements can be.

When we express measured values, we can only list as many digits as we initially measured with our measuring tool. For example, if you use a standard ruler to measure the length of a stick, you may measure it to be 36.7 cm. You could not express this value as 36.71 cm because your measuring tool was not precise enough to measure a hundredth of a centimeter. It should be noted that the last digit in a measured value has been estimated in some way by the person performing the measurement. For example, the person measuring the length of a stick with a ruler notices that the stick length seems to be somewhere in between 36.6 cm and 36.7 cm, and they must estimate the value of the last digit. Using the method of significant figures, the rule is that the last digit written down in a measurement is the first digit with some uncertainty. In order to determine the number of significant digits in a value, start with the first measured value at the left and count the number of digits through the last digit written on the right. For example, the measured value 36.7 cm has three digits, or significant figures. Significant figures indicate the precision of a measuring tool that was used to measure a value.

Questions

1. If a bag of apples were half as heavy but its uncertainty stayed 0.4 lb, what would happen to the percent uncertainty?
 - a. It would stay the same
 - b. It would be halved
 - c. It would roughly double
 - d. It would become zero

2. A floor's length has 2% uncertainty and its width 1%. What is the percent uncertainty of its area?
- a. 3%
 - b. 2%
 - c. 1%
 - d. 1.5%
3. Why can't the coach conclude that 11.96 s was faster than 12.04 s?
- a. Because the sprinter ran a different distance
 - b. Because the times were recorded in different weeks
 - c. Because the stopwatch rounds to whole seconds
 - d. Because the stopwatch's uncertainty is too great to tell the times apart
4. Why could a stick measured with a standard ruler not be reported as 36.71 cm?
- a. Because the ruler cannot measure to a hundredth of a centimeter
 - b. Because sticks are never that long
 - c. Because 36.71 has too few digits
 - d. Because the last digit must be zero

Answers

1. c) Percent uncertainty is $\delta A/A \times 100\%$; halving A with the same δA doubles the fraction.

2. a) For multiplication with small uncertainties, the percent uncertainties add: $2\% + 1\% = 3\%$.

3. d) With ± 0.05 s on each reading, the two times overlap, so the stopwatch cannot distinguish them.

4. a) You can list only as many digits as the tool measured; a ruler is not precise enough for hundredths of a centimeter.

Worked examples

A bag of apples Four 5-lb bags of apples weigh 4.8 lb, 5.3 lb, 4.9 lb and 5.4 lb. The uncertainty in the 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 4: the average is 5.1 lb, which agrees with the nominal 5 lb within 0.4 lb.

Use $\%unc = \delta A/A \times 100\%$ with $\delta A = 0.4$ lb and $A = 5.1$ lb.

$0.4 \div 5.1 \times 100\% \approx 8\%$.

Answer: 5.1 lb, with a percent uncertainty of about 8%

Practice

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

Hint: Multiply length by width, then add the percent uncertainties.

Answer: $12.0 \text{ m}^2 \pm 0.4 \text{ m}^2$: the area is 12.0 m^2 , the uncertainty is 3%, and 3% of 12.0 m^2 is 0.36 m^2 , rounded to 0.4 m^2 .

2. A bag of apples weighs 2.55 lb with an uncertainty of 0.4 lb. What is its percent uncertainty?

Hint: Divide the uncertainty by the value and multiply by 100%.

Answer: About 16%: $0.4 \div 2.55 \times 100\% \approx 15.7\%$, about twice the 8% of the 5.1-lb bag.

3. How many significant figures does each value have: 36.7 cm, 11.96 s, 4.00 m?

Hint: Count from the first measured digit on the left through the last digit written.

Answer: Three, four and three: 36.7 has three, 11.96 has four, and 4.00 has three because the written zeros were measured.

Zeros and Significant Figures in Calculations

Special consideration is given to zeros when counting significant figures. The zeros in 0.053 are not significant, because they are only placekeepers that locate the decimal point. There are two significant figures in 0.053. The zeros in 10.053 are not placekeepers but are significant: this number has five significant figures. The zeros in 1300 may or may not be significant depending on the style of writing numbers. They could mean the number is known to the last digit, or they could be placekeepers. So 1300 could have two, three, or four significant figures. (To avoid this ambiguity, write 1300 in scientific notation.) Zeros are significant except when they serve only as placekeepers.

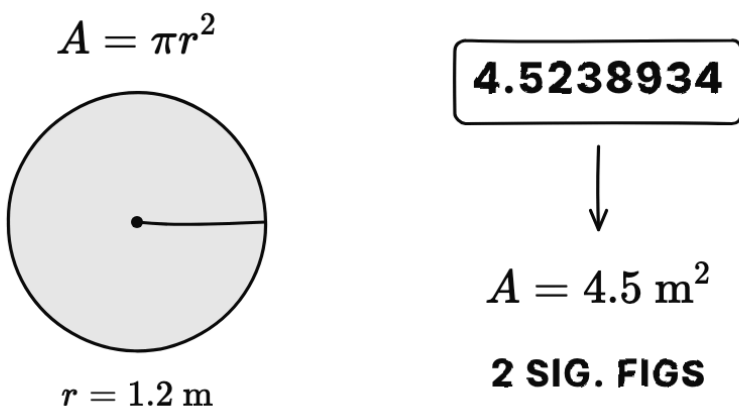
	SIG. FIGS
0.0009	1
15,450.0	6
6×10^3	1
87.990	5
30.42	4

Which zeros count

Check your understanding. Determine the number of significant figures in the following measurements: (1) 0.0009; (2) 15,450.0; (3) 6×10^3 ; (4) 87.990; (5) 30.42.

(a) 1; the zeros in this number are placekeepers that indicate the decimal point. (b) 6; here, the zeros indicate that a measurement was made to the 0.1 decimal point, so the zeros are significant. (c) 1; the value 10^3 signifies the decimal place, not the number of measured values. (d) 5; the final zero indicates that a measurement was made to the 0.001 decimal point, so it is significant. (e) 4; any zeros located in between significant figures in a number are also significant.

When combining measurements with different degrees of accuracy and precision, the number of significant digits in the final answer can be no greater than the number of significant digits in the least precise measured value. There are two different rules, one for multiplication and division and the other for addition and subtraction, as discussed below.



Rounding the area of a circle

1. For multiplication and division: The result should have the same number of significant figures as the quantity having the least significant figures entering into the calculation. For example, the area of a circle can be calculated from its radius using $A = \pi r^2$. Let us see how many significant figures the area has if the radius has only two, say, $r = 1.2 \text{ m}$. Then, $A = \pi r^2 = (3.1415927...) \times (1.2 \text{ m})^2 = 4.5238934$

m^2 is what you would get using a calculator that has an eight-digit output. But because the radius has only two significant figures, it limits the calculated quantity to two significant figures, or $A = 4.5 \text{ m}^2$, even though π is good to at least eight digits.

2. For addition and subtraction: The answer can contain no more decimal places than the least precise measurement. Suppose that you buy 7.56 kg of potatoes in a grocery store as measured with a scale with precision 0.01 kg. Then you drop off 6.052 kg of potatoes at your laboratory as measured by a scale with precision 0.001 kg. Finally, you go home and add 13.7 kg of potatoes as measured by a bathroom scale with precision 0.1 kg. How many kilograms of potatoes do you now have, and how many significant figures are appropriate in the answer? The mass is found by simple addition and subtraction: $7.56 \text{ kg} - 6.052 \text{ kg} + 13.7 \text{ kg} = 15.208 \text{ kg}$, which rounds to 15.2 kg. Next, we identify the least precise measurement: 13.7 kg. This measurement is expressed to the 0.1 decimal place, so our final answer must also be expressed to the 0.1 decimal place. Thus, the answer is rounded to the tenths place, giving us 15.2 kg.

POTATOES, KG

$$\begin{array}{r} 7.56 \\ - 6.052 \\ \hline + 13.7 \\ \hline 15.208 \end{array} \begin{array}{l} 0.01 \text{ kg} \\ 0.001 \text{ kg} \\ 0.1 \text{ kg} \\ \rightarrow 15.2 \text{ kg} \end{array}$$

Adding potatoes

In this text, most numbers are assumed to have three significant figures. Furthermore, consistent numbers of significant figures are used in all worked examples. You will note that an answer given to three digits is based on input good to at least three digits, for example. If the input has fewer significant figures, the answer will also have fewer significant figures. Care is also taken that the number of significant figures is reasonable for the situation posed. In some topics, particularly in optics, more accurate numbers are needed and more than three significant figures will be used. Finally, if a number is exact, such as the two in the formula for the circumference of a circle, $c = 2\pi r$, it does not affect the number of significant figures in a calculation.

Check your understanding. Perform the following calculations and express your answer using the correct number of significant digits. (a) A woman has three bags: two of the bags weigh 13.5 pounds each, and one bag weighs 10.2 pounds. What is the total weight of the bags? (b) The force F on an object is equal to its mass m multiplied by its acceleration a . If a wagon with mass 55 kg accelerates at a rate of 0.0255 m/s^2 , what is the force on the wagon? (The unit of force is called the newton, and it is expressed with the symbol N.)

(a) 37.2 pounds; because the number of bags is an exact value, it is not considered in the significant figures. (b) 1.4 N; because the value 55 kg has only two significant figures, the final value must also contain two significant figures.

Questions

1. Why are the zeros in 0.053 not significant?
 - a. Because they are only placekeepers that locate the decimal point
 - b. Because zeros are never significant
 - c. Because the number is less than one
 - d. Because they come after the decimal point
2. A circle's radius is 1.2 m. Why is its area given as 4.5 m^2 and not 4.5238934 m^2 ?
 - a. Because π is only known to two digits
 - b. Because calculators round automatically

- c. Because the radius has only two significant figures, which limits the result
 - d. Because areas are always rounded to one decimal
3. When adding 7.56 kg, subtracting 6.052 kg and adding 13.7 kg, why is the answer 15.2 kg?
- a. Because 6.052 kg has the most decimal places
 - b. Because the answer can have no more decimal places than the least precise measurement, 13.7 kg
 - c. Because all scales round to a tenth
 - d. Because the potatoes were weighed three times
4. Why does the two in $c = 2\pi r$ not affect the number of significant figures?
- a. Because it is a small number
 - b. Because it is even
 - c. Because it multiplies π
 - d. Because it is an exact number

Answers

1. **a)** In 0.053 the zeros only locate the decimal point, so the number has two significant figures.
2. **c)** In multiplication the result has as many significant figures as the least precise quantity; the radius has two.
3. **b)** For addition and subtraction, the answer keeps only as many decimal places as the least precise value.
4. **d)** Exact numbers, such as the two in the circumference formula, do not limit significant figures.

Worked examples

Area of a circle A circle has radius $r = 1.2$ m. Find its area $A = \pi r^2$ with the correct number of significant figures.

A calculator gives $(3.1415927...) \times (1.2 \text{ m})^2 = 4.5238934 \text{ m}^2$.

For multiplication, the result has as many significant figures as the least precise input.

The radius, 1.2 m, has two significant figures; π is good to many more.

So the area is rounded to two significant figures.

Answer: 4.5 m^2

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 correct significant figures?

Hint: The number of bags is exact; add the weights and keep the decimal places of the measured values.

Answer: 37.2 pounds: $2 \times 13.5 + 10.2 = 37.2$; the count of two bags is exact and does not limit the answer.

2. A wagon of mass 55 kg accelerates at 0.0255 m/s^2 . Using $F = ma$, what is the force, with the correct significant figures?

Hint: Multiply, then keep as many significant figures as the least precise input.

Answer: 1.4 N: $55 \times 0.0255 = 1.4025$, and 55 kg has only two significant figures.

3. How many significant figures are in 0.0009, 15,450.0 and 30.42?

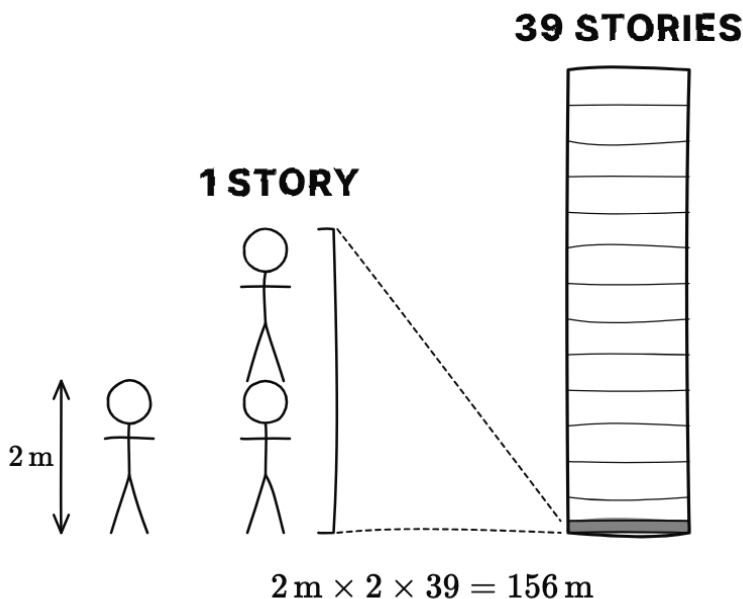
Hint: Zeros that only place the decimal point do not count; zeros between digits or measured at the end do.

Answer: 1, 6 and 4: the zeros in 0.0009 are placekeepers, the zeros in 15,450.0 show measurement to 0.1, and the zero in 30.42 sits between significant figures.

Approximation

On many occasions, physicists, other scientists, and engineers need to make approximations or “guesstimates” for a particular quantity. What is the distance to a certain destination? What is the approximate density of a given item? About how large a current will there be in a circuit? Many approximate numbers are based on formulae in which the input quantities are known only to a limited accuracy. As you develop problem-solving skills (that can be applied to a variety of fields through a study of physics), you will also develop skills at approximating. You will develop these skills through thinking more quantitatively, and by being willing to take risks. As with any endeavor, experience helps, as well as familiarity with units. These approximations allow us to rule out certain scenarios or unrealistic numbers. Approximations also allow us to challenge others and guide us in our approaches to our scientific world. Let us do two examples to illustrate this concept.

Example: approximate the height of a building. Can you approximate the height of one of the buildings on your campus, or in your neighborhood? Let us make an approximation based upon the height of a person. In this example, we will calculate the height of a 39-story building.



A 39-story building in people

Strategy. Think about the average height of an adult male. We can approximate the height of the building by scaling up from the height of a person.

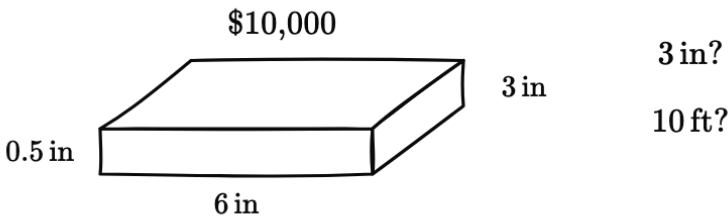
Solution. Based on information in the example, we know there are 39 stories in the building. If we use the fact that the height of one story is approximately equal to about the length of two adult humans (each human is about 2 m tall), then we can estimate the total height of the building to be $2\text{ m}/1\text{ person} \times 2\text{ persons}/1\text{ story} \times 39\text{ stories} = 156\text{ m}$.

Discussion. You can use known quantities to determine an approximate measurement of unknown quantities. If your hand measures 10 cm across, how many hand lengths equal the width of

your desk? What other measurements can you approximate besides length?

Example: approximating vast numbers, a trillion dollars. A bank stack contains one hundred \$100 bills, and is worth \$10,000. The U.S. federal debt in 2021 was a little more than \$28 trillion. Most of us do not have any concept of how much even one trillion actually is.

Suppose that you were given a trillion dollars in \$100 bills. If you made 100-bill stacks and used them to evenly cover a football field (between the end zones), make an approximation of how high the money pile would become. (We will use feet and inches rather than meters here because football fields are measured in yards.) One of your friends says 3 in., while another says 10 ft. What do you think?



$$6 \times 3 \times 0.5 = 9 \text{ in}^3$$

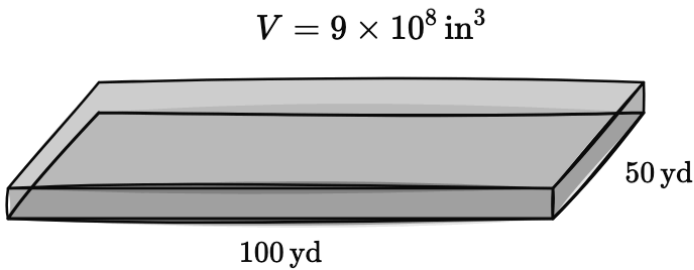
$$\frac{10^{12}}{10^4} = 10^8 \text{ stacks}$$

A trillion dollars in stacks

Strategy. When you imagine the situation, you probably envision thousands of small stacks of 100 wrapped \$100 bills, such as you might see in movies or at a bank. Since this is an easy-to-approximate quantity, let us start there. We can find the volume of a stack of 100 bills, find out how many stacks make up one trillion dollars, and then set this volume equal to the area of the football field multiplied by the unknown height.

Solution. (1) Calculate the volume of a stack of 100 bills. The dimensions of a single bill are approximately 3 in. by 6 in. A stack of 100 of these is about 0.5 in. thick. So the total volume of a stack of 100 bills is: volume of stack equals length times width times height, $6 \text{ in.} \times 3 \text{ in.} \times 0.5 \text{ in.} = 9 \text{ in.}^3$. (2) Calculate the number of stacks. Note that a trillion dollars is equal to $\$1 \times 10^{12}$, and a stack of one hundred \$100 bills is equal to \$10,000, or $\$1 \times 10^4$. The number of stacks you will have is $\$1 \times 10^{12} / \$1 \times 10^4 \text{ per stack} = 1 \times 10^8 \text{ stacks}$. (3) Calculate the area of a football field in square inches. The area of a football field is 100 yd by 50 yd, which gives $5,000 \text{ yd}^2$. Because we are working in inches, we need to convert square yards to square inches: $\text{Area} = 5,000 \text{ yd}^2 \times 3 \text{ ft/1 yd} \times 3 \text{ ft/1 yd} \times 12 \text{ in./1 ft} \times 12 \text{ in./1 ft} = 6,480,000 \text{ in.}^2$, so the area is approximately $6 \times 10^6 \text{ in.}^2$. This conversion gives us $6 \times 10^6 \text{ in.}^2$ for the area of the field. (Note that we are using only one significant figure in these calculations.) (4) Calculate the total volume of the bills. The volume of all the \$100-bill stacks is $9 \text{ in.}^3/\text{stack} \times 10^8 \text{ stacks} = 9 \times 10^8 \text{ in.}^3$. (5) Calculate the height. To determine the height of the bills, use the equation: volume of bills equals area of field times height of money, so height of money equals volume of bills divided by area of field. $\text{Height of money} = 9 \times 10^8 \text{ in.}^3 / 6 \times 10^6 \text{ in.}^2 = 1.33 \times 10^2 \text{ in.} \approx 1 \times 10^2 \text{ in.} = 100 \text{ in.}$ The height of the

money will be about 100 in. high. Converting this value to feet gives
 $100 \text{ in.} \times 1 \text{ ft}/12 \text{ in.} = 8.33 \text{ ft} \approx 8 \text{ ft}.$

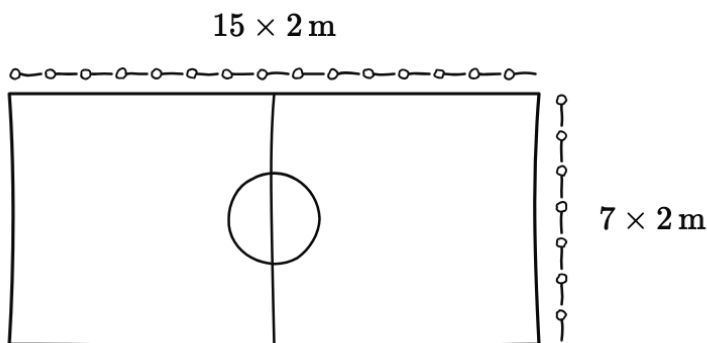


$$A \approx 6 \times 10^6 \text{ in}^2$$

$$h = \frac{9 \times 10^8}{6 \times 10^6} \approx 100 \text{ in} \qquad \approx 8 \text{ ft}$$

How high the money piles

Discussion. The final approximate value is much higher than the early estimate of 3 in., but the other early estimate of 10 ft (120 in.) was roughly correct. How did the approximation measure up to your first guess? What can this exercise tell you in terms of rough “guesstimates” versus carefully calculated approximations?



$$30 \text{ m} \times 14 \text{ m} \approx 420 \text{ m}^2$$

A basketball court in people

Check your understanding. Using mental math and your understanding of fundamental units, approximate the area of a regulation basketball court. Describe the process you used to arrive at your final approximation.

An average male is about two meters tall. It would take approximately 15 males laid out end to end to cover the length, and about 7 to cover the width. That gives an approximate area of 420 m^2 .

Questions

1. What is one use of approximations named in the text?
 - a. They give exact values without measuring
 - b. They allow us to rule out certain scenarios or unrealistic numbers
 - c. They replace units
 - d. They are only for money problems
2. In the building example, why is one story taken as about 4 m?
 - a. Because one story is about the length of two adults, each about 2 m tall
 - b. Because building codes require 4 m
 - c. Because 39 divided by 10 is about 4
 - d. Because a story equals one adult's height
3. How is the height of the money pile found once its volume and the field's area are known?
 - a. By multiplying volume and area
 - b. By adding them
 - c. By dividing the volume of the bills by the area of the field
 - d. By dividing the area by the volume
4. Which friend's guess was roughly right, and why does the exercise matter?
 - a. The 3 in. guess, showing that guesses are usually right
 - b. Neither, showing approximation is useless
 - c. Both equally
 - d. The 10 ft guess, showing that a careful approximation can test rough guesses

Answers

1. **b)** Approximations let us rule out unrealistic numbers and challenge others' claims.
2. **a)** One story is about two adult humans, each about 2 m, so $2 \text{ m/person} \times 2 \text{ persons/story}$.
3. **c)** Volume equals area times height, so height equals volume divided by area.
4. **d)** The pile is about 8 ft, far above 3 in.; 10 ft was roughly correct, and the calculation tells which guess holds.

Worked examples

Height of a 39-story building Estimate the height of a 39-story building, taking one story as about two adults, each about 2 m tall.

One person is about 2 m tall.

One story is about 2 persons, so about $2 \text{ m} \times 2 = 4 \text{ m}$.

$39 \text{ stories} \times 4 \text{ m per story} = 156 \text{ m}$.

Answer: about 156 m

A trillion dollars on a football field A trillion dollars in stacks of one hundred \$100 bills (each stack 6 in. $\times$ 3 in. $\times$ 0.5 in.) evenly covers a football field of 100 yd $\times$ 50 yd. About how high is the pile?

Each stack has volume $6 \times 3 \times 0.5 = 9 \text{ in.}^3$.

Number of stacks: $\$10^{12} \div \$10^4 \text{ per stack} = 10^8 \text{ stacks}$, so total volume $9 \times 10^8 \text{ in.}^3$.

Field area: $5,000 \text{ yd}^2 \times 9 \text{ ft}^2/\text{yd}^2 \times 144 \text{ in.}^2/\text{ft}^2 = 6,480,000 \text{ in.}^2$, about $6 \times 10^6 \text{ in.}^2$.

Height = volume $\div$ area = $9 \times 10^8 \div 6 \times 10^6 \approx 1 \times 10^2 \text{ in.}$, about 100 in., or about 8 ft.

Answer: about 100 in., roughly 8 ft

Practice

1. Using the same reasoning as the book, estimate the height of a 20-story building.

Hint: Take one story as about two adults, each about 2 m tall.

Answer: About 80 m: 20 stories $\times$ 4 m per story.

2. Approximate the area of a regulation basketball court using the height of an average man, about 2 m.

Hint: Count about how many men laid end to end cover the length and the width.

Answer: About 420 m²: about 15 men (30 m) along the length and 7 men (14 m) along the width, and $30 \text{ m} \times 14 \text{ m} = 420 \text{ m}^2$.