# PHYSICS FOR THE IMPATIENT
## 4th Edition

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# Introduction

You wish you knew something about physics, but you don't have time to take a course or read a book, and you find the Wikipedia article on physics to be inaccessible. You don't need to calculate the strength of a load-bearing wall, and you don't really care how Planck's constant was derived. You'd just like to have some minimal grasp of the concepts of physics that appear in the news; or you want to sound knowledgeable at social gatherings. This discussion is for you.

Here you'll find very brief discussions of many of the most important concepts of physics. But there are numerous glaring omissions; if you want completeness, look elsewhere. Likewise, you won't find here any overall understanding of how the different areas of physics relate to one another. Nevertheless, you should leave with a certain feel for many of the most important ideas of physics.

In serious books and articles on physics, an effort is made to give credit to every individual and institution who contributed to each advance. "In 1991, Fritz Dingelhopper of the University of Dusseldorf, Xavier Kipple of UCLA, and Aloysius Anderson of MIT reformulated the Goldberg-Greenblatt-Brown derivations, resulting in ..." You won't see any of that here. This isn't about people, or about giving credit. Only the most famous of physicists are mentioned by name.

One aspect of physics that's ignored in popular treatments (including this one) is the math. For the theoretical physicist, it's almost all math - horrendous math! Newton's laws may look reasonably clear to you (once you've read the description below); but to develop them, Newton had to invent calculus. Calculus is bad enough as a high school or college course; how hard must it have been to invent it!?! And that was just to get started with the *fundamentals* of physics. As time went by, physicists found themselves relying on such mathematical mumbo-jumbo as tensors, perturbation theory, gauge symmetries, eigenvalues, Hamiltonians, and Calabi-Yau manifolds. To make it worse, they use Greek letters! If you doubt that the math of physics could be that difficult, consider the glacially slow progress of string theory over the past few decades; it's because the best minds in the world have spent that much time trying to work out the math.

Not to worry - you'll find very little math (and *no* Greek letters) here. Even the number of equations presented is kept to a minimum. Of course, there can be no discussion of Einstein's Special Theory of Relativity without mention of the equation $\mathbf{E = m\, c^2}$. You might not see the need of using it to calculate the amount of energy in an ounce of peanut butter; but at least you'll have some idea of what it means.

Now, let's jump right in.

## Newton's Laws of Motion

Isaac Newton (1642-1727) stated three laws of motion.

**First Law of Motion**: Every object either stays motionless or continues moving in a straight line, unless some outside force makes it move differently.

**Second Law of Motion**: A force **F** acting on an object causes the object to accelerate. This acceleration **a** is proportional to the force **F**, and is in the same direction as the force. Also, the acceleration **a** is inversely proportional to the mass **m** of the body (the larger the mass, the smaller the acceleration):

$$\mathbf{a} = \frac{\mathbf{F}}{\mathbf{m}} \qquad \text{or} \qquad \mathbf{F} = \mathbf{m\,a}$$

**Third Law of Motion**: When two objects interact by exerting force on each other, these action and reaction forces are equal in magnitude, but opposite in direction.

**Velocity** gives us both the speed and the direction of motion. **Acceleration** is the rate of change of velocity. So acceleration could be a change in speed, a change in direction, or a combination of the two.

Newton's First Law can be seen as a special case of the Second Law. If no force is being exerted on the object then **F** = 0, and **a** (acceleration) is also zero. This means that the velocity of the object doesn't change, so it keeps going at the same speed (which may be zero), and in the same direction (if any).

The Third Law, incidentally, is the basis for rockets. When mass (the rocket exhaust) is accelerated downward, that same amount of force (**F = m a**) acts in the opposite direction, thereby accelerating the rocket's mass upward. If the rocket is starting on the earth, the upward acceleration required is large (and the mass expelled in the exhaust is huge), because the upward force must be more than the large downward force exerted by gravity. Out in interplanetary space, far from earth, where the earth's gravitational pull is almost zero, much less force is needed to accelerate (change the speed or direction of) the rocket.

## Newton's Law of Universal Gravitation

Newton found that **gravity** is a force that causes any two objects to attract each other.

$$\mathbf{F} = \mathbf{G}\left(\frac{\mathbf{m_1\,m_2}}{\mathbf{r^2}}\right)$$

where
**F** is the force of attraction,
**G** is a constant ($6.674\times10^{-11}$ N $m^2$ $kg^{-2}$ - but don't worry about it)

$\mathbf{m_1}$ and $\mathbf{m_2}$ are the masses of the two objects, and
$\mathbf{r}$ is the distance between the two objects.

Based on observation of the planets, he found that gravitation had to be a force transmitted *instantaneously*, e.g., not at the speed of light.

Since gravitation is a force, any object on the earth's surface is always being acted on by a force. In ordinary life, it would be difficult to find an example of "uniform motion" as described in the First Law of Motion. However, out in interplanetary space, far from any planet, uniform motion would be commonplace, e.g. the spacewalking astronaut in science fiction stories who becomes untethered and is doomed to drift away from the spaceship at a constant speed and direction.

## Maxwell's Electromagnetic Theory

James Clerk Maxwell (1831-1879) described **electric fields**, **magnetic fields**, and **electromagnetic radiation**. Visible light is a form of electromagnetic radiation; so are ultraviolet light, infrared light, radio waves, X-rays, and gamma rays. The speed of all electromagnetic radiation (in a vacuum), including the speed of light, is a physical constant (an unchanging number, a characteristic of nature), calculated as

$$\mathbf{c} = \frac{\mathbf{1}}{\sqrt{\mathbf{m_0 e_0}}}$$

or 299,792,458 meters per second,
where
$\mathbf{c}$ is the speed of light,
$\mathbf{m_0}$ is the *permeability of free space*, also called the magnetic constant (a physical constant); and
$\mathbf{e_0}$ is the *permittivity of free space*, also called the electric constant (a physical constant).

You don't need to worry about what $\mathbf{m_0}$ and $\mathbf{e_0}$ really mean. What's important is that they are two unchanging characteristics of the universe. Since the speed of light can be calculated from them, **the speed of light is a constant**. Note that this is the speed of light *in a vacuum*. Light travels a little slower through air, and significantly slower through glass; nevertheless, the speed of light in a vacuum is a constant.

## Thermodynamic Theory

The **First Law of Thermodynamic**s states that the energy of an *isolated* system is constant. This is a statement of the **conservation of energy**. An isolated system is one that has no exchange of matter or energy with anything outside the system.

The **Second Law of Thermodynamics** states (loosely) that the entropy, or degree of disorder, of an *isolated* system will tend to increase. The earth is *not* an isolated system, if only because it has a large input of energy from the sun. Therefore, entropy *can decrease* on earth, which means that things can (and do) become more highly ordered. Evolution proceeds, industry creates integrated circuits, and philatelists organize their stamp collections.

## Einstein's Special Theory of Relativity

In 1905, Albert Einstein (1879-1955) proposed a **Special Theory of Relativity**. The word "special" here means that it isn't a general theory. It applies only to the specific case where gravity and acceleration can be ignored.

In the discussion below, the term "**frame of reference**" means everything moving in the same direction at the same speed. For example, if you're walking across the deck of a ferry boat as it passes a lighthouse, then you're one frame of reference, the ferry boat is another, and the lighthouse (and the land it's connected to) is a third frame of reference.

Elements of the theory include these:

- Three-dimensional space and one-dimensional time aren't separate; they're parts of a **four-dimensional spacetime**.
- Any frame of reference moving at a constant velocity is *relative* to all others. No one frame of reference can be shown to be motionless. In other words, **there is no absolute motion, only relative motion**. (Using the example, you're moving in one way relative to the ferry boat and in another way relative to the lighthouse. None of them can be said to be completely motionless - even the earth is moving through space.)
- In addition to being treated as a wave, light can be treated as a particle, the **photon**.
- **The speed of light is the same for all observers**, no matter how fast they're moving toward or away from the source of the light. (This comes from Maxwell's conclusion that the speed of light [in a vacuum] is a constant, no matter what.)
- **No object or signal can move faster than the speed of light.**
- An object that's moving at speed $\mathbf{v}$ relative to an observer has more energy, so it has more mass, *relative to that observer*:

  $$\mathbf{m} = \mathbf{m_0\,g}$$

  where
  $\mathbf{m}$ is the mass of the object relative to the observer,
  $\mathbf{m_0}$ is the mass if the object *weren't* moving relative to the observer, and
  $\mathbf{g}$ is the **Lorentz factor** defined as

$$\mathbf{g} = \frac{\mathbf{1}}{\sqrt{\mathbf{1} - \left(\frac{\mathbf{v}^2}{\mathbf{c}^2}\right)}}$$

where
**v** is the speed of the object relative to the observer, and
**c** is the speed of light.

If **v** = 0 (the object isn't moving relative to the observer), then **g = 1**, so the mass is unchanged (**m** = $\mathbf{m_0}$). But if **v** is (for example) 99.5% of **c** (the speed of light), then **g = 10** (approximately) and the mass **m = 10** $\mathbf{m_0}$. (Do the math if you like - it isn't hard, if you have a calculator that will do square roots.) As **v** approaches **c** (as the speed of the object gets closer to the speed of light), **g** and therefore the mass **m** approach infinity.

- Therefore, **no object can be accelerated to the speed of light**. It would take infinite energy to do so.

- But the *length* of the object *contracts* by the Lorentz factor:

$$\mathbf{x} = \frac{\mathbf{x_0}}{\mathbf{g}}$$

where
**x** is the length as seen by the observer,
$\mathbf{x_0}$ is the length if the object weren't moving with respect to the observer, and
**g** is the Lorentz factor.

If you watch a 19-foot-long Rolls Royce going by at 99.5% of the speed of light, it would appear to be 1.9 feet long. (But its height would be unchanged.)

- *Time* is *slowed down* by the Lorentz factor:

$$\mathbf{t} = \frac{\mathbf{t_0}}{\mathbf{g}}$$

where
**t** is the passage of time on a moving clock as seen by the observer,
$\mathbf{t_0}$ is the passage of time on a clock that's motionless with respect to the observer, and
**g** is the Lorentz factor.

If you could observe a clock going by you at 99.5% of the speed of light, it would appear to be running slow by a factor of 10. This phenomenon is called "**time dilation**".

- Energy and mass are equivalent:

$$\mathbf{E = m\ c^2}$$

  where
  **E** is energy,
  **m** is mass, and
  **c** is the speed of light (a constant).

  Because **c** is a large number, a small amount of mass is equivalent to a large amount of energy. (Later this would be used to calculate the energy resulting from atomic fission or nuclear fusion.) Likewise, an object that gives off energy, such as an operating flashlight, loses tiny amounts of mass.

To get the general idea, you can use the equation $\mathbf{E = m\ c^2}$ to calculate the amount of energy that could be obtained by converting a one-ounce serving of peanut butter (or any other substance) entirely into energy: 708,000,000 kilowatt-hours, or enough to power the average American home for 64,000 years. Keep in mind, though, that even nuclear fusion would convert only a tiny fraction of its fuel to energy.

## Einstein's General Theory of Relativity

In 1915, Einstein proposed a **General Theory of Relativity**, this time encompassing gravity and acceleration.

- **Gravity and acceleration are equivalent**, in the sense that a person in an elevator that's in free fall (falling down the elevator shaft with nothing to slow it down) won't be able (at that instant) to distinguish that situation from being in a location where there is no gravity.

- Likewise, a person in a closed elevator-like room that's *not* falling won't be able to distinguish the effects of gravity from the identical effects that would occur if the room were being accelerated (at a certain constant rate) in the absence of gravity.

- Gravitation, or acceleration that's equivalent to gravity, can cause a red shift in light, deflection of light, and time dilation.

- **An object with mass causes spacetime to be curved**, or warped, in a way that accounts for gravity. Spacetime tells matter how to move, and matter tells spacetime how to curve.

- This accounts for gravitational force being "transmitted" instantaneously.

You can get a rough idea of how the curvature of space explains gravity by imagining a flat rubber sheet stretched tight horizontally. This two-dimensional surface is an analogy for three-dimensional space. Now place a bowling ball (representing a planet) carefully near the middle of the sheet. The presence of this large mass curves the space (the rubber sheet). If you roll a marble (representing a spaceship) across the sheet, it'll be affected by the curvature of space in one of three ways. If the marble doesn't come too close to the bowling ball, it'll curve a bit toward the ball and then proceed off into the distance. If the marble does come too close, it'll follow the curved sheet downward until it runs into the ball. But if the marble is rolled just right, it'll circle around and around the ball, like a satellite in orbit around a planet.

Time dilation caused by gravity or acceleration, in the General Theory of Relativity, is separate from time dilation caused by relative motion, as explained in the Special Theory of Relativity. In other words, gravity and motion both cause time to slow down.

Time dilation leads to the "**twin paradox**". If an astronaut makes a round trip to Mars while her identical twin sister stays on earth, the astronaut will have aged less than the earth-bound sister. This would really happen (although with current rocket speeds the effect would be small); the explanation has to do with relative motion as well as with the fact that the astronaut twin has undergone acceleration (when taking off from the earth and again when taking off from Mars).

## Quantum Theory

In general, **quantum theory says that things work differently at the scale of atoms or smaller**.

- The electrons around an atom can exist only in a limited number of orbits. Since a higher orbit represents a higher energy level, **each electron can only have certain specific energy values**. If an electron falls from a higher energy state to a lower one, it makes the transition instantly without ever having an in-between energy value. As the electron goes from the higher energy value to the lower energy value, it emits a photon of light with a specific amount of energy equal to the difference between the two energy values; the frequency or wavelength of this light is determined by the energy of the photon.

- Atoms of different elements have different discrete energy levels for their electrons. If energy is added to the atoms of an element, e.g. by heating a gas of that element, the electrons will move into higher orbits and eventually drop back down to lower orbits, thereby giving off light at specific frequencies that can be used to identify the element. This is useful for determining the makeup of faraway stars.

- **Just as light has both wave-like and matter-like properties, matter can be seen to have wave-like properties**. If either photons (light) or electrons (matter) are beamed through a board with two parallel slits in it onto a screen, the screen will show a diffraction pattern either way.

- Much of quantum theory is expressed in terms of **Planck's Constant**:

$$\mathbf{h} = \frac{\mathbf{E}}{\mathbf{f}}$$

  where
  **h** is Planck's Constant,
  **E** is the energy of a photon of light, and
  **f** is the frequency of the light.

  Planck's Constant is a very, very small number. For light, the frequency **f** is a very big number - for green light it's 540 x $10^{12}$ hertz (cycles per second). And the energy **E** of the photon is a very small number - for green light it's 3.58 x $10^{-19}$ joule (a unit of energy). When you divide a very small number by a very big number, you get a very, very small number. In fact,

$$\mathbf{h} = 6.63 \times 10^{-34} \text{ joule seconds}$$

- It isn't possible to know all of the properties of an object (e.g., the speed and location of an electron) at the same time. Those properties that aren't completely known can be described only in terms of probabilities. This is expressed in the **Heisenberg Uncertainty Principle**:

$$\mathbf{s_x}\, \mathbf{s_p} \geq \frac{\mathbf{h}}{\mathbf{4\pi}}$$

  where
  $\mathbf{s_x}$ is the standard deviation of position,
  $\mathbf{s_p}$ is the standard deviation of momentum, and
  **h** is Planck's constant.

  (Loosely, "standard deviation" means "the amount of uncertainty" or "margin of error".) Since Planck's constant is very, very small, we can measure both the position and the momentum of a large object very precisely; but when we get down near the size of an atom or smaller, the amount of uncertainty becomes significant.

(The Heisenberg Uncertainty Principle is sometimes seen as a metaphor useful in everyday life, but it really only applies to very tiny sizes. A more general principle, not part of physics, that applies to macroscopic [normal-sized] situations is the Observer Effect. For example, measuring the air pressure in a tire changes the air pressure, because a little bit of air always escapes. Studying primitive cultures or animals in the wild is made more difficult by the fact that detection of the observer may alter the behavior being observed. Again, these are examples of the Observer Effect, not the Heisenberg Uncertainty Principle.)

"**Shrödinger's Cat**" is the name of a thought experiment designed to illustrate the indeterminacy (uncertainty) in some versions of quantum theory. Imagine a cat closed into a sealed metal box for one hour, along with a tiny amount of a radioactive substance that has a 50% chance of having at least one atom decay during the hour. Also included is a mechanism that, if it detects the decay of a radioactive atom, will release a poison gas that would kill the cat. Just before the box is reopened at the end of the hour, is the cat alive or dead? Of course, we don't know until we look, but we assume that the cat is either alive or dead, one or the other. However, the **Copenhagen Interpretation** of quantum theory (one of several competing interpretations) says that the cat is *both alive and dead* until the box is opened; it is only the act of observation that causes the cat to become either definitely alive or definitely dead. The uncertainty comes from the fact that the decay of a single atom is a quantum event.

## Standard Model of Particle Physics

Early ideas of physics proposed that the smallest particles of matter were atoms. This was followed by the idea that the smallest particles were protons, neutrons, and electrons, with protons and neutrons making up the nucleus of the atom, and electrons surrounding the nucleus to complete the atom.

But according to the **Standard Model of Particle Physics**, the elementary (indivisible) particles are **quarks** (various types), **leptons** (various types), and **bosons** (various types). A proton isn't an elementary particle, but is composed of three quarks; the same is true of the neutron. The electron is one type of lepton. The photon (particle of light) is one type of boson.

To be more specific, there appear to be six kinds of quarks (arbitrarily named "up", "down", "charm", "strange", "top", and "bottom") and six kinds of leptons (including the electron and three types of neutrino). Each of these twelve particles has a corresponding **antiparticle**; when a particle and its antiparticle meet, they annihilate each other, and their matter becomes energy according to $\mathbf{E = m\ c^2}$. (As we'll see later, the antiparticle of the electron is called a "**positron**".) There also seem to be five or six kinds of bosons, including the **Higgs boson** (whose existence, at this writing, has been tentatively confirmed at the Large Hadron Collider in Europe); the other bosons are related to the four fundamental forces of nature (see below).

A proton is made up of two up-quarks and one down-quark. A neutron is one up-quark and two down-quarks. Since all ordinary matter consists of protons, neutrons, and electrons, it appears that the elementary particles that make up all ordinary matter are electrons, up-quarks, and down-quarks.

There are **four fundamental forces of nature**. They are **gravity**, the **electromagnetic force**, the **strong force**, and the **weak force**. The electromagnetic force is the basis of electricity. The strong and weak forces are evident only at subatomic distances. The strong force keeps protons and neutrons together inside the atomic nucleus (overcoming the electromagnetic force that would like to drive the positive protons away from each other);

it also keeps quarks together inside protons and neutrons. The weak force is harder to explain, but it's responsible for one type of radioactivity.

One type of boson that's expected to exist is the **graviton**, responsible for the force of gravity; but the graviton isn't part of the Standard Model. The Standard Model doesn't explain gravitation, and doesn't account for dark matter (see "Astrophysics and Cosmology").

## Astrophysics and Cosmology

Our universe was created fourteen billion years ago by the **big bang**, an unimaginable explosion which started with all matter (or energy) compressed into an extremely small volume. After about 379,000 years, things quieted down enough for atoms to form, mostly of hydrogen. Eventually gravity caused matter to clump together, forming the first stars. The thermonuclear reactions at the centers of the stars, as well as the explosions of dying stars (novas and supernovas), caused heavier atoms to be created; this is how all of the elements heavier than hydrogen, helium, and lithium were created. When stars exploded, they spread their matter into space. Later generations of stars had planets made up of these star-bred elements.

If a star is massive enough, when it dies it might collapse to such an extreme density that its gravitational pull captures everything that comes close enough, including light. This is known as a "**black hole**". What happens inside a black hole is a subject of great speculation for physicists.

Today there are about 100 billion galaxies in the universe, with from ten million to a hundred trillion stars in each galaxy. The universe continues to expand, as evidenced by the "**red shift**" (light from stars far away is shifted toward the red end of the color spectrum). However, it isn't expanding as fast as expected, and it's thought that the universe might be permeated by "**dark matter**", unlike any known form of matter, whose gravitational pull is holding back the expansion.

Space-time, i.e. the universe, might be curved (not in the sense of local warping around objects with mass, but curved overall). For example, if it has "spherical curvature", then theoretically if you had a powerful enough telescope you could look off into space in any direction and see the back of your head (very, very far away). (This is analogous to the idea that the surface of the earth is a spherical two-dimensional space; if you walk in a "straight" line long enough, you come back to where you started.) And ours might not be the *only* universe. If there are other universes, they might have different physical laws and different numbers of dimensions. This hypothetical collection of universes is called the "**multiverse**".

## String Theory

Physicists who deal with astronomy rely on the ideas of general relativity. Those who study the subatomic world depend on the ideas of quantum mechanics. But the two theories don't mesh; each is inconsistent with the other. This matters because there are important areas of study in which both relativistic and quantum phenomena must be described, for example, black holes and the big bang. It matters so much that Einstein spent most of his adult life searching (fruitlessly) for a "**Unified Field Theory**".

**String Theory**, a.k.a. "**Superstring Theory**", starts by supposing that each of the elementary particles isn't a point but a tiny vibrating loop called a "**string**". In this context, "string" means a one-dimensional line, with zero width and a tiny but non-zero length. (Drive from your mind any temptation to think of cotton or nylon string. These strings are [probably] not "made" of *anything*.) Imagine that this line has been joined to itself end-to-end to form a loop. Now imagine further that this loop vibrates with certain patterns, like a guitar string. At this point the analogy becomes strained; a guitar string is straight and stretched tight, whereas the string loop is curved and apparently floating in space. Take comfort in knowing that quantum-level phenomena often defy common sense.

One of the problems with the Standard Model is that elementary particles were considered to be points. That is, they had zero size - no width, no area, no volume. Consequently, the math sometimes resulted in division by zero, which, mathematically, is a catastrophe. Since strings have non-zero size, some of the previous math problems became solvable by eliminating division by zero.

Strings are about the size of a constant called the **Planck length**:

$$\mathbf{L_p = 1.616x10^{-33}cm}$$

This is a length so ridiculously small that it would take about ten million billion billion Planck lengths to add up to the size of an atom.

All of these strings are identical, except that they vibrate at various resonant frequencies. Each of the elementary particle types is represented by a particular frequency pattern that somehow determines that particle's properties, such as mass and charge. For example, a string that has a frenzied vibration pattern will have more energy than a calmer string. Since energy and mass are interchangeable (**$E = m\,c^2$**), the frenzied string represents (*is*) a particle with a larger mass.

One area of current research is the application of string theory to the big bang. Specifically, what was the universe like when it was compressed to the size of the Planck length?

At this ultramicroscopic level, quantum uncertainty rules. Even in what should be the total vacuum of empty space, far from any galaxy, space and time fluctuate violently at the level of the Planck length, and particles of matter appear and disappear. For example, an electron and its anti-particle, a positron, might appear from nowhere, and then annihilate each other. This tumultuous state of affairs is sometimes referred to as "**quantum foam**".

In addition to Einstein's four-dimensional spacetime (three spatial dimensions and the fourth dimension of time), **string theory requires that there be six or seven additional spatial dimensions** that are "curled up" in such a way that we can't detect them.

How can a dimension be curled up? Consider a universe with two spatial dimensions. If these are simple "flat" dimensions, this universe might be a flat sheet, or it might be in the shape of a cylinder (just the outer surface) or a sphere so huge that it looks flat to its inhabitants (who would also have to be two-dimensional, by the way). But suppose that this universe is a cylinder that's *not* huge. As the diameter of the cylinder gets smaller, the universe gets more restrictive. If the diameter gets so small that the inhabitants can't detect it, then as far as they're concerned, they're living in a one-dimensional universe. They can go as far as they want in either direction on what looks to them like an infinite line, but that's the only way they can move. The second dimension is still there, because the diameter of the cylinder is larger than zero; but it plays no part in the everyday life of the inhabitants.

According to string theory, the six or seven additional dimensions are curled up to about the size of the Planck length, not into simple cylinders, but into incredibly complex shapes, one category of which is called the **Calabi-Yau manifold**.

String theory may be the physics theory that eventually consolidates general relativity, quantum mechanics, gravity, and so on. But total acceptance is a long way off. The traditional approach in which theoretical physicists and experimental physicists work hand in hand, the former with their math and the latter with their equipment, is less applicable in string theory. For example, building an accelerator that can probe down to the level of strings seems literally impossible. But to many, string theory is the only existing candidate for a **Theory of Everything**.