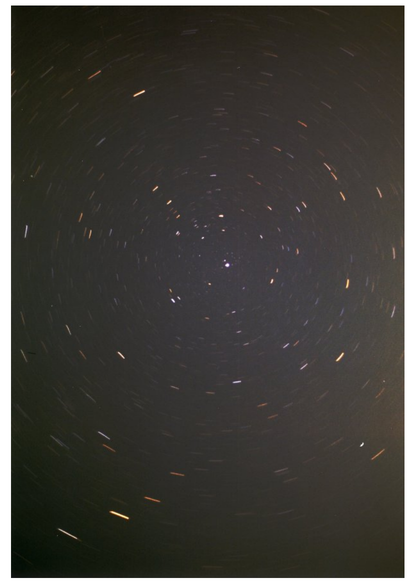
Chapter 1
Conservation of Mass and Energy

1.1 Symmetry and Conservation Laws

Even before history began, people must already have noticed certain facts about the sky. The sun and moon both rise in the east and set in the west. Another fact that can be settled to a fair degree of accuracy using the naked eye is that the apparent sizes of the sun and moon don't change noticeably. (There is an optical illusion that makes the moon appear bigger when it's near the horizon, but you can easily verify that it's nothing more than an illusion by checking its angular size against some standard, such as your pinkie held at arm's length.) If the sun and moon were varying their distances from us, they would appear to get bigger and smaller, and since they don't appear to change in size, it appears, at least approximately, that they always stay at the same distance from us.



a / Due to the rotation of the earth, everything in the sky appears to spin in circles. In this time-exposure photograph, each star appears as a streak.

From observations like these, the ancients constructed a scientific *model*, in which the sun and moon traveled around the earth in perfect circles. Of course, we now know that the earth isn't the center of the universe, but that doesn't mean the model wasn't useful. That's the way science always works. Science never aims to reveal the ultimate reality. Science only tries to make models of reality that have predictive power.

Our modern approach to understanding physics revolves around the concepts of *symmetry* and *conservation laws*, both of which are demonstrated by this example.

The sun and moon were believed to move in circles, and a circle is a very symmetric shape. If you rotate a circle about its center, like a spinning wheel, it doesn't change. Therefore, we say that the circle is *symmetric* with respect to rotation about its center. The ancients thought it was beautiful that the universe seemed to have this type of symmetry built in, and they became very attached to the idea.

A *conservation law* is a statement that some number stays the same with the passage of time. In our example, the distance between the sun and the earth is conserved, and so is the distance between the moon and the earth. (The ancient Greeks were even able to determine that earth-moon distance.)

b / Emmy Noether (1882-1935). The daughter of a prominent German mathematician, she did not show any early precocity at mathematics — as a teenager she was more interested in music and dancing. She received her doctorate in 1907 and rapidly built a world-wide reputation, but the University of Göttingen refused to let her teach, and her colleague Hilbert had to advertise her courses in the university's catalog under his own name. A long controversy ensued, with her opponents asking what the country's soldiers would think when they returned home and were expected to learn at the feet of a woman. Allowing her on the faculty would also mean letting her vote in the academic senate. Said Hilbert, "I do not see that the sex of the candidate is against her admission as a privatdozent [instructor]. After all, the university senate is not a bathhouse." She was finally admitted to the faculty in 1919. A Jew, Noether fled Germany in 1933 and joined the faculty at Bryn Mawr in the U.S.

In our example, the symmetry and the conservation law both give the same information. Either statement can be satisfied only by a circular orbit. That isn't a coincidence. Physicist Emmy Noether showed on very general mathematical grounds that for physical theories of a certain type, every symmetry leads to a corresponding conservation law. Although the precise formulation of Noether's theorem, and its proof, are too mathematical for this book, we'll see many examples like this one, in which the physical content of the theorem is fairly straightforward.

c / In this scene from Swan Lake, the choreography has a symmetry with respect to left and right.

The idea of perfect circular orbits seems very beautiful and intuitively appealing. It came as a great disappointment, therefore, when the astronomer Johannes Kepler discovered, by the painstaking analysis of precise observations, that orbits such as the moon's were actually ellipses, not circles. This is the sort of thing that led the biologist Huxley to say, "The great tragedy of science is the slaying of a beautiful theory by an ugly fact." The lesson of the story, then, is that symmetries are important and beautiful, but we can't decide which symmetries are right based only on common sense or aesthetics; their validity has to be determined based on observations and experiments.

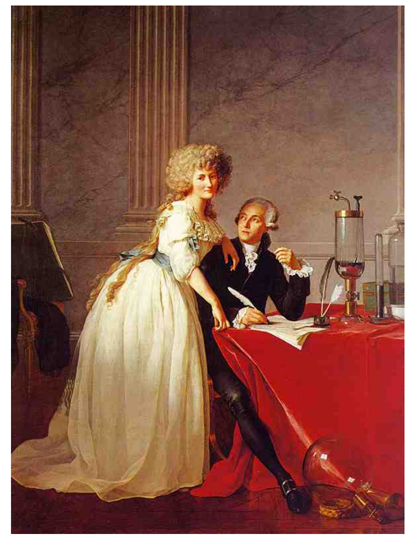
d / C.S. Wu at Columbia University in 1963.

As a more modern example, consider the symmetry between right and left. For example, we observe that a top spinning clockwise has exactly the same behavior as a top spinning counterclockwise. This kind of observation led physicists to believe, for hundreds of years, that the laws of physics were perfectly symmetric with respect to right and left. This mirror symmetry appealed to physicists' common sense. However, experiments by Chien-Shiung Wu et al. in 1957 showed that right-left symmetry was violated in certain types of nuclear reactions. Physicists were thus forced to change their opinions about what constituted common sense.

1.2 Conservation of Mass

We intuitively feel that matter shouldn't appear or disappear out of nowhere: that the amount of matter should be a conserved quantity. If that was to happen, then it seems as though atoms would have to be created or destroyed, which doesn't happen in any physical processes that are familiar from everyday life, such as chemical reactions. On the other hand, I've already cautioned you against believing that a law of physics must be true just because it seems appealing. The laws of physics have to be found by experiment, and there seem to be experiments that are exceptions to the conservation of matter. A log weighs more than its ashes. Did some matter simply disappear when the log was burned?

The French chemist Antoine-Laurent Lavoisier was the first scientist to realize that there were no such exceptions. Lavoisier hypothesized that when wood burns, for example, the supposed loss of weight is actually accounted for by the escaping hot gases that the flames are made of. Before Lavoisier, chemists had almost never weighed their chemicals to quantify the amount of each substance that was undergoing reactions. They also didn't completely understand that gases were just another state of matter, and hadn't tried performing reactions in sealed chambers to determine whether gases were being consumed from or released into the air. For this they had at least one practical excuse, which is that if you perform a gas-releasing reaction in a sealed chamber with no room for expansion, you get an explosion! Lavoisier invented a balance that was capable of measuring milligram masses, and figured out how to do reactions in an upside-down bowl in a basin of water, so that the gases could expand by pushing out some of the water. In one crucial experiment, Lavoisier heated a red mercury compound, which we would now describe as mercury oxide (HgO), in such a sealed chamber. A gas was produced (Lavoisier later named it "oxygen"), driving out some of the water, and the red compound was transformed into silvery liquid mercury metal. The crucial point was that the total mass of the entire apparatus was exactly the same before and after the reaction. Based on many observations of this type, Lavoisier proposed a general law of nature, that matter is always conserved.



e / Portrait of Monsieur Lavoisier and His Wife, by Jacques-Louis David, 1788. Lavoisier invented the concept of conservation of mass. The husband is depicted with his scientific apparatus, while in the background on the left is the portfolio belonging to Madame Lavoisier, who is thought to have been a student of David's.

self-check A

In ordinary speech, we say that you should "conserve" something, because if you don't, pretty soon it will all be gone. How is this different from the meaning of the term "conservation" in physics? ▷ Answer, p. 179

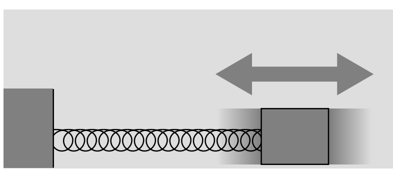
Although Lavoisier was an honest and energetic public official, he was caught up in the Terror and sentenced to death in 1794. He requested a fifteen-day delay of his execution so that he could complete some experiments that he thought might be of value to the Republic. The judge, Coffinhal, infamously replied that "the state has no need of scientists." As a scientific experiment, Lavoisier decided to try to determine how long his consciousness would continue after he was guillotined, by blinking his eyes for as long as possible. He blinked twelve times after his head was chopped off. Ironically, Judge Coffinhal was himself executed only three months later, falling victim to the same chaos.

f / Example 1.

A stream of water *example 1*

The stream of water is fatter near the mouth of the faucet, and skinnier lower down. This can be understood using conservation of mass. Since water is being neither created nor destroyed, the mass of the water that leaves the faucet in one second must be the same as the amount that flows past a lower point in the same time interval. The water speeds up as it falls, so the two quantities of water can only be equal if the stream is narrower at the bottom.

Physicists are no different than plumbers or ballerinas in that they have a technical vocabulary that allows them to make precise distinctions. A pipe isn't just a pipe, it's a PVC pipe. A jump isn't just a jump, it's a grand jeté. We need to be more precise now about what we really mean by "the amount of matter," which is what we're saying is conserved. Since physics is a mathematical science, definitions in physics are usually definitions of numbers, and we define these numbers *operationally*. An operational definition is one that spells out the steps required in order to *measure* that quantity. For example, one way that an electrician knows that current and voltage are two different things is that she knows she has to do completely different things in order to measure them with a meter.



g / The time for one cycle of vibration is related to the object's mass.

h / Astronaut Tamara Jernigan measures her mass aboard the Space Shuttle. She is strapped into a chair attached to a spring, like the mass in figure g. (*NASA*)

If you ask a room full of ordinary people to define what is meant by mass, they'll probably propose a bunch of different, fuzzy ideas, and speak as if they all pretty much meant the same thing: "how much space it takes up," "how much it weighs," "how much matter is in it." Of these, the first two can be disposed of easily. If we were to define mass as a measure of how much space an object occupied, then mass wouldn't be conserved when we squished a piece of foam rubber. Although Lavoisier did use weight in his experiments, weight also won't quite work as the ultimate, rigorous definition, because weight is a measure of how hard gravity pulls on an object, and gravity varies in strength from place to place. Gravity is measurably weaker on the top of a mountain that at sea level, and much weaker on the moon. The reason this didn't matter to Lavoisier was that he was doing all his experiments in one location. The third proposal is better, but how exactly should we define "how much matter?" To make it into an operational definition, we could do something like figure g. A larger mass is harder to whip back and forth — it's harder to set into motion, and harder to stop once it's started. For this reason, the vibration of the mass on the spring will take a longer time if the mass is greater. If we put two different masses on the spring, and they both take the same time to complete one oscillation, we can define them as having the same mass.

Since I started this chapter by highlighting the relationship between conservation laws and symmetries, you're probably wondering what symmetry is related to conservation of mass. I'll come back to that at the end of the chapter.

When you learn about a new physical quantity, such as mass, you need to know what units are used to measure it. This will lead us to a brief digression on the metric system, after which we'll come back to physics.

1.3 Review of the Metric System and Conversions

The metric system

Every country in the world besides the U.S. has adopted a system of units known colloquially as the "metric system." Even in the U.S., the system is used universally by scientists, and also by many engineers. This system is entirely decimal, thanks to the same eminently logical people who brought about the French Revolution. In deference to France, the system's official name is the Système International, or SI, meaning International System. (The phrase "SI system" is therefore redundant.)

The metric system works with a single, consistent set of prefixes (derived from Greek) that modify the basic units. Each prefix stands for a power of ten, and has an abbreviation that can be combined with the symbol for the unit. For instance, the meter is a unit of distance. The prefix kilo- stands for 1000, so a kilometer, 1 km, is a thousand meters.

In this book, we'll be using a flavor of the metric system, the SI, in which there are three basic units, measuring distance, time, and mass. The basic unit of distance is the meter (m), the one for time is the second (s), and for mass the kilogram (kg). Based on these units, we can define others, e.g., m/s (meters per second) for the speed of a car, or kg/s for the rate at which water flows through a pipe. It might seem odd that we consider the basic unit of mass to be the kilogram, rather than the gram. The reason for doing this is that when we start defining other units starting from the basic three, some of them come out to be a more convenient size for use in everyday life. For example, there is a metric unit of force, the newton (N), which is defined as the push or pull that would be able to change a 1-kg object's velocity by 1 m/s, if it acted on it for 1 s. A newton turns out to be about the amount of force you'd use to pick up your keys. If the system had been based on the gram instead of the kilogram, then the newton would have been a thousand times smaller, something like the amount of force required in order to pick up a breadcrumb.

The following are the most common metric prefixes. You should memorize them.

prefix		meaning	example	
kilo-	k	1000	60 kg	= a person's mass
centi-	c	1/100	28 cm	= height of a piece of paper
milli-	m	1/1000	1 ms	= time for one vibration of a guitar string playing the note D

The prefix centi-, meaning 1/100, is only used in the centimeter; a hundredth of a gram would not be written as 1 cg but as 10 mg. The centi- prefix can be easily remembered because a cent is 1/100 of a dollar. The official SI abbreviation for seconds is "s" (not "sec") and grams are "g" (not "gm").

You may also encounter the prefixes mega- (a million) and micro- (one millionth).

Scientific notation

Most of the interesting phenomena in our universe are not on the human scale. It would take about 1,000,000,000,000,000,000,000 bacteria to equal the mass of a human body. When the physicist Thomas Young discovered that light was a wave, scientific notation hadn't been invented, and he was obliged to write that the time required for one vibration of the wave was 1/500 of a millionth of a millionth of a second. Scientific notation is a less awkward way to write very large and very small numbers such as these. Here's a quick review.

Scientific notation means writing a number in terms of a product of something from 1 to 10 and something else that is a power of ten. For instance,

$$32 = 3.2 \times 10^1$$
$$320 = 3.2 \times 10^2$$
$$3200 = 3.2 \times 10^3 \quad \ldots$$

Each number is ten times bigger than the last.

Since 10^1 is ten times smaller than 10^2, it makes sense to use the notation 10^0 to stand for one, the number that is in turn ten times smaller than 10^1. Continuing on, we can write 10^{-1} to stand for 0.1, the number ten times smaller than 10^0. Negative exponents are used for small numbers:

$$3.2 = 3.2 \times 10^0$$
$$0.32 = 3.2 \times 10^{-1}$$
$$0.032 = 3.2 \times 10^{-2} \quad \ldots$$

A common source of confusion is the notation used on the displays of many calculators. Examples:

3.2×10^6	(written notation)
3.2E+6	(notation on some calculators)
3.2^6	(notation on some other calculators)

The last example is particularly unfortunate, because 3.2^6 really stands for the number $3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 \times 3.2 = 1074$, a totally different number from $3.2 \times 10^6 = 3200000$. The calculator notation should never be used in writing. It's just a way for the manufacturer to save money by making a simpler display.

self-check B

A student learns that 10^4 bacteria, standing in line to register for classes at Paramecium Community College, would form a queue of this size:

The student concludes that 10^2 bacteria would form a line of this length:

Why is the student incorrect? ▷ Answer, p. 179

Conversions

I suggest you avoid memorizing lots of conversion factors between SI units and U.S. units. Suppose the United Nations sends its black helicopters to invade California (after all who wouldn't rather live here than in New York City?), and institutes water fluoridation and the SI, making the use of inches and pounds into a crime punishable by death. I think you could get by with only two mental conversion factors:

> 1 inch = 2.54 cm
>
> An object with a weight on Earth of 2.2 pounds-force has a mass of 1 kg.

The first one is the present definition of the inch, so it's exact. The second one is not exact, but is good enough for most purposes. (U.S. units of force and mass are confusing, so it's a good thing they're not used in science. In U.S. units, the unit of force is the pound-force, and the best unit to use for mass is the slug, which is about 14.6 kg.)

More important than memorizing conversion factors is understanding the right method for doing conversions. Even within the SI, you may need to convert, say, from grams to kilograms. Different people have different ways of thinking about conversions, but the method I'll describe here is systematic and easy to understand. The idea is that if 1 kg and 1000 g represent the same mass, then we can consider a fraction like

$$\frac{10^3\text{ g}}{1\text{ kg}}$$

to be a way of expressing the number one. This may bother you. For instance, if you type 1000/1 into your calculator, you will get 1000, not one. Again, different people have different ways of thinking about it, but the justification is that it helps us to do conversions, and it works! Now if we want to convert 0.7 kg to units of grams, we can multiply kg by the number one:

$$0.7\text{ kg} \times \frac{10^3\text{ g}}{1\text{ kg}}$$

If you're willing to treat symbols such as "kg" as if they were variables as used in algebra (which they're really not), you can then cancel the kg on top with the kg on the bottom, resulting in

$$0.7\ \cancel{\text{kg}} \times \frac{10^3\text{ g}}{1\ \cancel{\text{kg}}} = 700\text{ g}.$$

To convert grams to kilograms, you would simply flip the fraction upside down.

One advantage of this method is that it can easily be applied to a series of conversions. For instance, to convert one year to units of seconds,

$$1\ \cancel{\text{year}} \times \frac{365\ \cancel{\text{days}}}{1\ \cancel{\text{year}}} \times \frac{24\ \cancel{\text{hours}}}{1\ \cancel{\text{day}}} \times \frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hour}}} \times \frac{60\text{ s}}{1\ \cancel{\text{min}}} = \\ = 3.15 \times 10^7\text{ s}.$$

Should that exponent be positive or negative?

A common mistake is to write the conversion fraction incorrectly. For instance the fraction

$$\frac{10^3\text{ kg}}{1\text{ g}} \qquad \text{(incorrect)}$$

does not equal one, because 10^3 kg is the mass of a car, and 1 g is the mass of a raisin. One correct way of setting up the conversion factor would be

$$\frac{10^{-3}\text{ kg}}{1\text{ g}} \qquad \text{(correct)}.$$

You can usually detect such a mistake if you take the time to check your answer and see if it is reasonable.

If common sense doesn't rule out either a positive or a negative exponent, here's another way to make sure you get it right. There are big prefixes, like kilo-, and small ones, like milli-. In the example above, we want the top of the fraction to be the same as the bottom. Since k is a big prefix, we need to *compensate* by putting a small number like 10^{-3} in front of it, not a big number like 10^3.

Discussion question

A Each of the following conversions contains an error. In each case, explain what the error is.

(a) 1000 kg $\times \frac{1 \text{ kg}}{1000 \text{ g}}$ = 1 g

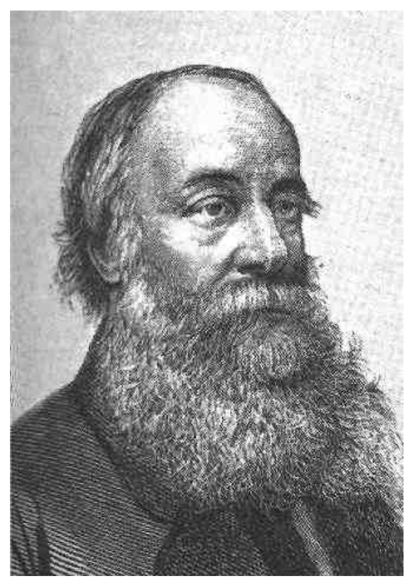
(b) 50 m $\times \frac{1 \text{ cm}}{100 \text{ m}}$ = 0.5 cm

1.4 Conservation of Energy

Energy

i / A hockey puck is released at rest. If it spontaneously scooted off in some direction, that would violate the symmetry of all directions in space.

Consider the hockey puck in figure i. If we release it at rest, we expect it to remain at rest. If it did start moving all by itself, that would be strange: it would have to pick some direction in which to move, and why would it pick that direction rather than some other one? If we observed such a phenomenon, we would have to conclude that that direction in space was somehow special. It would be the favored direction in which hockey pucks (and presumably other objects as well) preferred to move. That would violate our intuition about the symmetry of space, and this is a case where our intuition is right: a vast number of experiments have all shown that that symmetry is a correct one. In other words, if you secretly pick up the physics laboratory with a crane, and spin it around gently with all the physicists inside, all their experiments will still come out the same, regardless of the lab's new orientation. If they don't have windows they can look out of, or any other external cues (like the Earth's magnetic field), then they won't notice anything until they hang up their lab coats for the evening and walk out into the parking lot.



j / James Joule (1818-1889) discovered the law of conservation of energy.

Another way of thinking about it is that a moving hockey puck would have some *energy*, whereas a stationary one has none. I haven't given you an operational definition of energy yet, but we'll gradually start to build one up, and it will end up fitting in pretty well with your general idea of what energy means from everyday life. Regardless of the mathematical details of how you would actually calculate the energy of a moving hockey puck, it makes sense that a puck at rest has zero energy. It starts to look like energy is conserved. A puck that initially has zero energy must continue to have zero energy, so it can't start moving all by itself.

You might conclude from this discussion that we have a new example of Noether's theorem: that the symmetry of space with respect to different directions must be equivalent, in some mysterious way, to conservation of energy. Actually that's not quite right, and the possible confusion is related to the fact that we're not going to deal with the full, precise mathematical statement of Noether's theorem. In fact, we'll see soon that conservation of energy is really more closely related to a different symmetry, which is symmetry with respect to the passage of time.

The principle of inertia

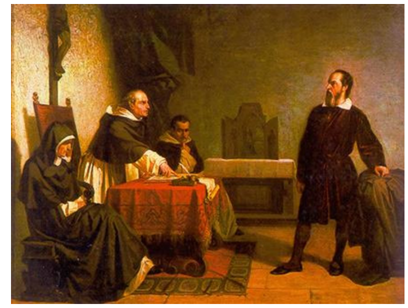
Now there's one very subtle thing about the example of the hockey puck, which wouldn't occur to most people. If we stand on the ice and watch the puck, and we don't see it moving, does that mean that it really is at rest in some absolute sense? Remember, the planet earth spins once on its axis every 24 hours. At the latitude where I live, this results in a speed of about 800 miles per hour, or something like 400 meters per second. We could say, then that the puck wasn't really staying at rest. We could say that it was really in motion at a speed of 400 m/s, and remained in motion at that same speed. This may be inconsistent with our earlier description, but it is still consistent with the same description of the laws of physics. Again, we don't need to know the relevant formula for energy in order to believe that if the puck keeps the same speed (and its mass also stays the same), it's maintaining the same energy.

k / Why does Aristotle look so sad? Is it because he's realized that his entire system of physics is wrong?

In other words, we have two different *frames of reference*, both equally valid. The person standing on the ice measures all velocities relative to the ice, finds that the puck maintained a velocity of zero, and says that energy was conserved. The astronaut watching the scene from deep space might measure the velocities relative to her own space station; in her frame of reference, the puck is moving at 400 m/s, but energy is still conserved.

This probably seems like common sense, but it wasn't common sense to one of the smartest people ever to live, the ancient Greek philosopher Aristotle. He came up with an entire system of physics based on the premise that there is one frame of reference that is special: the frame of reference defined by the dirt under our feet. He believed that all motion had a tendency to slow down unless a force was present to maintain it. Today, we know that Aristotle was wrong. One thing he was missing was that he didn't understand the concept of friction as a force. If you kick a soccer ball, the reason it eventually comes to rest on the grass isn't that it "naturally" wants to stop moving. The reason is that there's a frictional force from the grass that is slowing it down. (The energy of the ball's motion is transformed into other forms, such as heat and sound.) Modern people may also have an easier time seeing his mistake, because we have experience with smooth motion at high speeds. For instance, consider a passenger on a jet plane who stands up in the aisle and inadvertently drops his bag of peanuts. According to Aristotle, the bag would naturally slow to a stop, so it would become a life-threatening projectile in the cabin! From the modern point of view, the cabin can just as well be considered to be at rest.

l / The jets are at rest. The Empire State Building is moving.



m / Galileo Galilei was the first physicist to state the principle of inertia (in a somewhat different formulation than the one given here). His contradiction of Aristotle had serious consequences. He was interrogated by the Church authorities and convicted of teaching that the earth went around the sun as a matter of fact and not, as he had promised previously, as a mere mathematical hypothesis. He was placed under permanent house arrest, and forbidden to write about or teach his theories. Immediately after being forced to recant his claim that the earth revolved around the sun, the old man is said to have muttered defiantly "and yet it does move."

The *principle of inertia* says, roughly, that all frames of reference are equally valid:

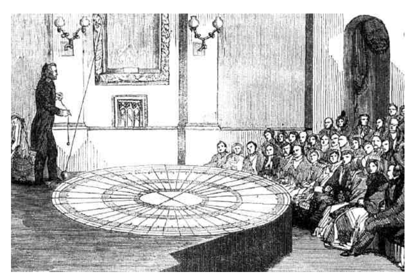
The principle of inertia
The results of experiments don't depend on the straight-line, constant-speed motion of the apparatus.

Speaking slightly more precisely, the principle of inertia says that if frame B moves at constant speed, in a straight line, relative to frame A, then frame B is just as valid as frame A, and in fact an observer in frame B will consider B to be at rest, and A to be moving. The laws of physics will be valid in both frames. The necessity for the more precise formulation becomes evident if you think about examples in which the motion changes its speed or direction. For instance, if you're in a car that's accelerating from rest, you feel yourself being pressed back into your seat. That's very different from the experience of being in a car cruising at constant speed, which produces no physical sensation at all. A more extreme example of this is shown in figure n on page 18.

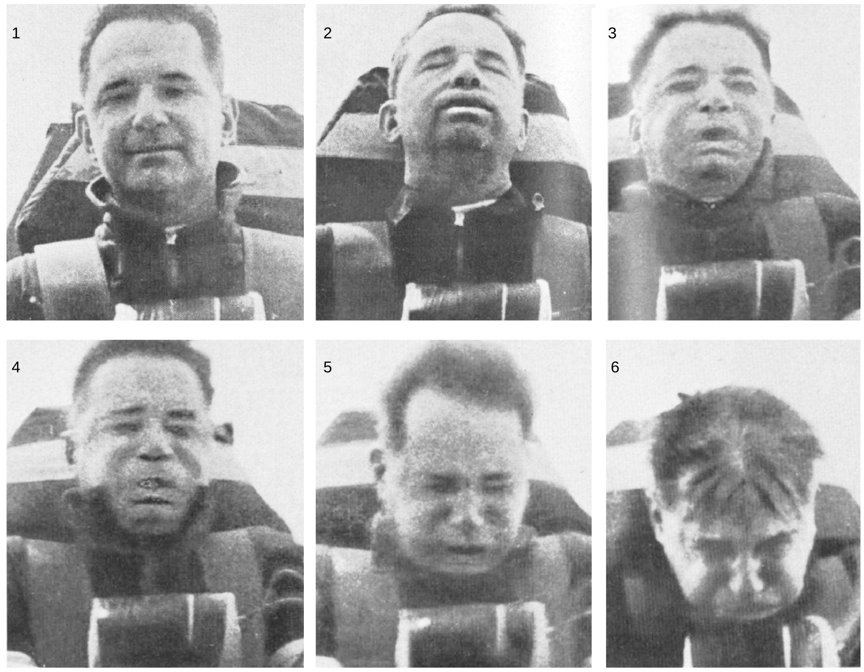
A frame of reference moving at constant speed in a straight line is known as an inertial frame of reference. A frame that changes its speed or direction of motion is called noninertial. The principle of inertia applies only to inertial frames. The frame of reference defined by an accelerating car is noninertial, but the one defined by a car cruising at constant speed in a straight line is inertial.

Foucault's pendulum — *example 2*

Earlier, I spoke as if a frame of reference attached to the surface of the rotating earth was just as good as any other frame of reference. Now, with the more exact formulation of the principle of inertia, we can see that that isn't quite true. A point on the earth's surface moves in a circle, whereas the principle of inertia refers only to motion in a straight line. However, the curve of the motion is so gentle that under ordinary conditions we don't notice that the local dirt's frame of reference isn't quite inertial. The first demonstration of the noninertial nature of the earth-fixed frame of reference was by Léon Foucault using a very massive pendulum



o / Foucault demonstrates his pendulum to an audience at a lecture in 1851.



n / This Air Force doctor volunteered to ride a rocket sled as a medical experiment. The obvious effects on his head and face are not because of the sled's speed but because of its rapid changes in speed: increasing in 2 and 3, and decreasing in 5 and 6. In 4 his speed is greatest, but because his speed is not increasing or decreasing very much at this moment, there is little effect on him.

(figure o) whose oscillations would persist for many hours without becoming imperceptible. Although Foucault did his demonstration in Paris, it's easier to imagine what would happen at the north pole: the pendulum would keep swinging in the same plane, but the earth would spin underneath it once every 24 hours. To someone standing in the snow, it would appear that the pendulum's plane of motion was twisting. The effect at latitudes less than 90 degrees turns out to be slower, but otherwise similar. The Foucault pendulum was the first definitive experimental proof that the earth really did spin on its axis, although scientists had been convinced of its rotation for a century based on more indirect evidence about the structure of the solar system.

People have a strong intuitive belief that there is a state of absolute rest, and that the earth's surface defines it. But Copernicus proposed as a mathematical assumption, and Galileo argued as a matter of physical reality, that the earth spins on its axis, and also circles the sun. Galileo's opponents objected that this was impossible, because we would observe the effects of the motion. They said, for example, that if the earth was moving, then you would never be able to jump up in the air and land in the same place again — the earth would have moved out from under you. Galileo realized that this wasn't really an argument about the earth's motion but about physics. In one of his books, which were written in the form of dialogues, he has the three characters debate what would happen if a ship was cruising smoothly across a calm harbor and a sailor climbed up to the top of its mast and dropped a rock. Would it hit the deck at the base of the mast, or behind it because the ship had moved out from under it? This is the kind of experiment referred to in the principle of inertia, and Galileo knew that it would come out the same regardless of the ship's motion. His opponents' reasoning, as represented by the dialog's stupid character Simplicio, was based on the assumption that once the rock lost contact with the sailor's hand, it would naturally start to lose its forward motion. In other words, they didn't even believe in the idea that motion naturally continues unless a force acts to stop it.

But the principle of inertia says more than that. It says that motion isn't even real: to a sailor standing on the deck of the ship, the deck and the masts and the rigging are not even moving. People on the shore can tell him that the ship and his own body are moving in a straight line at constant speed. He can reply, "No, that's an illusion. I'm at rest. The only reason you think I'm moving is because you and the sand and the water are moving in the opposite direction." The principle of inertia says that straight-line, constant-speed motion is a matter of opinion. Thus things can't "naturally" slow down and stop moving, because we can't even agree on which things are moving and which are at rest.

If observers in different frames of reference disagree on velocities, it's natural to want to be able to convert back and forth. For motion in one dimension, this can be done by simple addition.

A sailor running on the deck *example 3*

▷ A sailor is running toward the front of a ship, and the other sailors say that in their frame of reference, fixed to the deck, his velocity is 7.0 m/s. The ship is moving at 1.3 m/s relative to the shore. How fast does an observer on the beach say the sailor is moving?

▷ They see the ship moving at 7.0 m/s, and the sailor moving even faster than that because he's running from the stern to the bow. In one second, the ship moves 1.3 meters, but he moves $1.3+7.0$ m, so his velocity relative to the beach is 8.3 m/s.

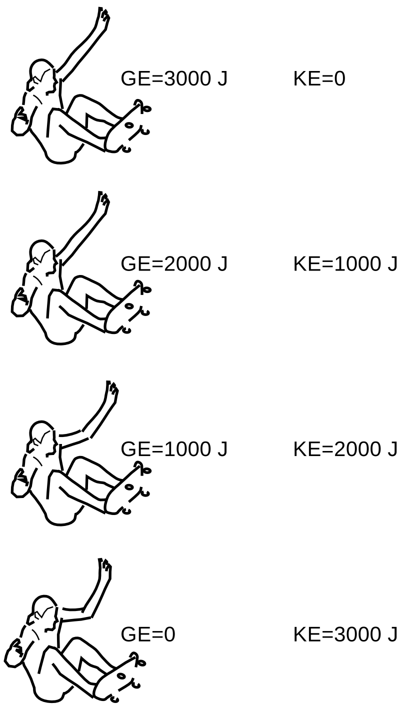
The only way to make this rule give consistent results is if we define velocities in one direction as positive, and velocities in the opposite direction as negative.

Running back toward the stern *example 4*

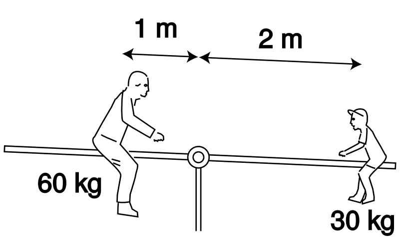
▷ The sailor of example 3 turns around and runs back toward the stern at the same speed relative to the deck. How do the other sailors describe this velocity mathematically, and what do observers on the beach say?

▷ Since the other sailors described his original velocity as positive, they have to call this negative. They say his velocity is now -7.0 m/s. A person on the shore says his velocity is $1.3+(-7.0) = -5.7$ m/s.

p / The skater has converted all his kinetic energy into gravitational energy on the way up the side of the pool. Photo by J.D. Rogge, www.sonic.net/∼shawn.



q / As the skater free-falls, his gravitational energy is converted into kinetic energy.



r / Example 5.

Kinetic and gravitational energy

Now suppose we drop a rock. The rock is initially at rest, but then begins moving. This seems to be a violation of conservation of energy, because a moving rock would have more energy. But actually this is a little like the example of the burning log that seems to violate conservation of mass. Lavoisier realized that there was a second form of mass, the mass of the smoke, that wasn't being accounted for, and proved by experiments that mass *was*, after all, conserved once the second form had been taken into account. In the case of the falling rock, we have two forms of energy. The first is the energy it has because it's moving, known as *kinetic energy*. The second form is a kind of energy that it has because it's interacting with the planet earth via gravity. This is known as *gravitational energy*.[1] The earth and the rock attract each other gravitationally, and the greater the distance between them, the greater the gravitational energy — it's a little like stretching a spring.

The SI unit of energy is the joule (J), and in those units, we find that lifting a 1-kg mass through a height of 1 m requires 9.8 J of energy. This number, 9.8 joules per meter per kilogram, is a measure of the strength of the earth's gravity near its surface. We notate this number, known as the gravitational field, as g, and often round it off to 10 for convenience in rough calculations. If you lift a 1-kg rock to a height of 1 m above the ground, you're giving up 9.8 J of the energy you got from eating food, and changing it into gravitational energy stored in the rock. If you then release the rock, it starts transforming the energy into kinetic energy, until finally when the rock is just about to hit the ground, all of that energy is in the form of kinetic energy. That kinetic energy is then transformed into heat and sound when the rock hits the ground.

Stated in the language of algebra, the formula for gravitational energy is

$$GE = mgh,$$

where m is the mass of an object, g is the gravitational field, and h is the object's height.

A lever *example 5*

Figure r shows two sisters on a seesaw. The one on the left has twice as much mass, but she's at half the distance from the center. No energy input is needed in order to tip the seesaw. If

[1] You may also see this referred to in some books as gravitational potential energy.

the girl on the left goes up a certain distance, her gravitational energy will increase. At the same time, her sister on the right will drop twice the distance, which results in an equal decrease in energy, since her mass is half as much. In symbols, we have

$$(2m)gh$$

for the gravitational energy gained by the girl on the left, and

$$mg(2h)$$

for the energy lost by the one on the right. Both of these equal $2mgh$, so the amounts gained and lost are the same, and energy is conserved.

Looking at it another way, this can be thought of as an example of the kind of experiment that you'd have to do in order to arrive at the equation $GE = mgh$ in the first place. If we didn't already know the equation, this experiment would make us suspect that it involved the product mh, since that's what's the same for both girls.

Once we have an equation for one form of energy, we can establish equations for other forms of energy. For example, if we drop a rock and measure its final velocity, v, when it hits the ground, we know how much GE it lost, so we know that's how much KE it must have had when it was at that final speed. Here are some imaginary results from such an experiment.

m (kg)	**v** (m/s)	**energy** (J)
1.00	1.00	0.50
1.00	2.00	2.00
2.00	1.00	1.00

Comparing the first line with the second, we see that doubling the object's velocity doesn't just double its energy, it quadruples it. If we compare the first and third lines, however, we find that doubling the mass only doubles the energy. This suggests that kinetic energy is proportional to mass times the square of velocity, mv^2, and further experiments of this type would indeed establish such a general rule. The proportionality factor equals 0.5 because of the design of the metric system, so the kinetic energy of a moving object is given by

$$KE = \frac{1}{2}mv^2.$$

t / The spinning coin slows down. It looks like conservation of energy is violated, but it isn't.

Energy in general

By this point, I've casually mentioned several forms of energy: kinetic, gravitational, heat, and sound. This might be disconcerting, since we can get thoroughly messed up if we don't realize that a

s / A vivid demonstration that heat is a form of motion. A small amount of boiling water is poured into the empty can, which rapidly fills up with hot steam. The can is then sealed tightly, and soon crumples. This can be explained as follows. The high temperature of the steam is interpreted as a high average speed of random motions of its molecules. Before the lid was put on the can, the rapidly moving steam molecules pushed their way out of the can, forcing the slower air molecules out of the way. As the steam inside the can thinned out, a stable situation was soon achieved, in which the force from the less dense steam molecules moving at high speed balanced against the force from the more dense but slower air molecules outside. The cap was put on, and after a while the steam inside the can reached the same temperature as the air outside. The force from the cool, thin steam no longer matched the force from the cool, dense air outside, and the imbalance of forces crushed the can.

certain form of energy is important in a particular situation. For instance, the spinning coin in figure t gradually loses its kinetic energy, and we might think that conservation of energy was therefore being violated. However, whenever two surfaces rub together, friction acts to create heat. The correct analysis is that the coin's kinetic energy is gradually converted into heat.

One way of making the proliferation of forms of energy seem less scary is to realize that many forms of energy that seem different on the surface are in fact the same. One important example is that heat is actually the kinetic energy of molecules in random motion, so where we thought we had two forms of energy, in fact there is only one. Sound is also a form of kinetic energy: it's the vibration of air molecules.

This kind of unification of different types of energy has been a process that has been going on in physics for a long time, and at this point we've gotten it down the point where there really only appear to be four forms of energy:

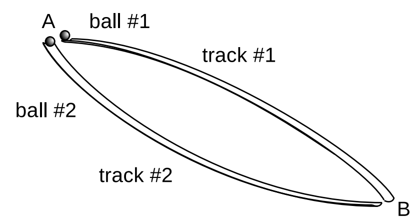
1. kinetic energy
2. gravitational energy
3. electrical energy
4. nuclear energy

We don't even encounter nuclear energy in everyday life (except in the sense that sunlight originates as nuclear energy), so really for most purposes the list only has three items on it. Of these three, electrical energy is the only form that we haven't talked about yet. The interactions between atoms are all electrical, so this form of energy is what's responsible for all of chemistry. The energy in the food you eat, or in a tank of gasoline, are forms of electrical energy.

You take the high road and I'll take the low road. *example 6*

▷ Figure u shows two ramps which two balls will roll down. Compare their final speeds, when they reach point B. Assume friction is negligible.

▷ Each ball loses some gravitational energy because of its decreasing height above the earth, and conservation of energy says that it must gain an equal amount of kinetic energy (minus a little heat created by friction). The balls lose the same amount of height, so their final speeds must be equal.



u / Example 6.

The birth of stars *example 7*

Orion is the easiest constellation to find. You can see it in the winter, even if you live under the light-polluted skies of a big city. Figure v shows an interesting feature of this part of the sky that you can easily pick out with an ordinary camera (that's how I took the picture) or a pair of binoculars. The three stars at the top are Orion's belt, and the stuff near the lower left corner of the picture is known as his sword — to the naked eye, it just looks like three more stars that aren't as bright as the stars in the belt. The middle "star" of the sword, however, isn't a star at all. It's a cloud of gas, known as the Orion Nebula, that's in the process of collapsing due to gravity. Like the pool skater on his way down, the gas is losing gravitational energy. The results are very different, however. The skateboard is designed to be a low-friction device, so nearly all of the lost gravitational energy is converted to kinetic energy, and very little to heat. The gases in the nebula flow and rub against each other, however, so most of the gravitational energy is converted to heat. This is the process by which stars are born: eventually the core of the gas cloud gets hot enough to ignite nuclear reactions.

v / Example 7.

Lifting a weight *example 8*

▷ At the gym, you lift a mass of 40 kg through a height of 0.5 m. How much gravitational energy is required? Where does this energy come from?

▷ The strength of the gravitational field is 10 joules per kilogram per meter, so after you lift the weight, its gravitational energy will be greater by $10 \times 40 \times 0.5 = 200$ joules.

Energy is conserved, so if the weight gains gravitational energy, something else somewhere in the universe must have lost some. The energy that was used up was the energy in your body, which came from the food you'd eaten. This is what we refer to as "burning calories," since calories are the units normally used to describe the energy in food, rather than metric units of joules.

In fact, your body uses up even more than 200 J of food energy, because it's not very efficient. The rest of the energy goes into heat, which is why you'll need a shower after you work out. We can summarize this as

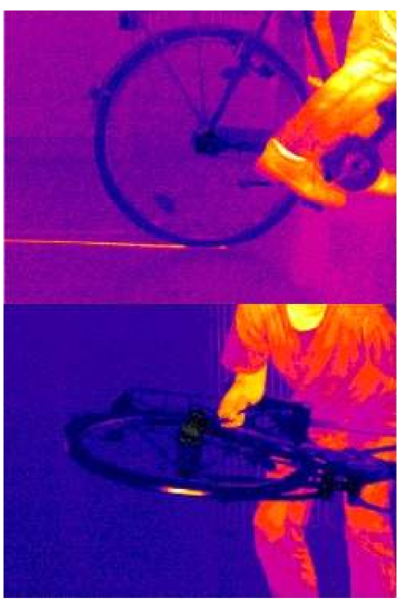
$$\text{food energy} \rightarrow \text{gravitational energy} + \text{heat}.$$

w / Example 10.

Lowering a weight *example 9*

▷ After lifting the weight, you need to lower it again. What's happening in terms of energy?

▷ Your body isn't capable of accepting the energy and putting it back into storage. The gravitational energy all goes into heat. (There's nothing fundamental in the laws of physics that forbids this. Electric cars can do it — when you stop at a stop sign, the car's kinetic energy is absorbed back into the battery, through a generator.)



x / Example 10.

Absorption and emission of light *example 10*

Light has energy. Light can be absorbed by matter and transformed into heat, but the reverse is also possible: an object can glow, transforming some of its heat energy into light. Very hot objects, like a candle flame or a welding torch, will glow in the visible part of the spectrum, as in figure w.

Objects at lower temperatures will also emit light, but in the infrared part of the spectrum, i.e., the part of the rainbow lying beyond the red end, which humans can't see. The photos in figure x were taken using a camera that is sensitive to infrared light. The cyclist locked his rear brakes suddenly, and skidded to a stop. The kinetic energy of the bike and his body are rapidly transformed into heat by the friction between the tire and the floor. In the first panel, you can see the glow of the heated strip on the floor, and in the second panel, the heated part of the tire.

Heavy objects don't fall faster *example 11*

Stand up now, take off your shoe, and drop it alongside a much less massive object such as a coin or the cap from your pen.

Did that surprise you? You found that they both hit the ground at the same time. Aristotle wrote that heavier objects fall faster than lighter ones. He was wrong, but Europeans believed him for thousands of years, partly because experiments weren't an accepted way of learning the truth, and partly because the Catholic Church gave him its posthumous seal of approval as its official philosopher.

Heavy objects and light objects have to fall the same way, because conservation laws are additive — we find the total energy of an object by adding up the energies of all its atoms. If a single atom falls through a height of one meter, it loses a certain amount of gravitational energy and gains a corresponding amount of kinetic energy. Kinetic energy relates to speed, so that determines how fast it's moving at the end of its one-meter drop. (The same reasoning could be applied to any point along the way between zero meters and one.)

Now what if we stick two atoms together? The pair has double the mass, so the amount of gravitational energy transformed into kinetic energy is twice as much. But twice as much kinetic energy is exactly what we need if the pair of atoms is to have the same speed as the single atom did. Continuing this train of thought, it doesn't matter how many atoms an object contains; it will have the same speed as any other object after dropping through the same height.

1.5 Newton's Law of Gravity

Why does the gravitational field on our planet have the particular value it does? For insight, let's compare with the strength of gravity elsewhere in the universe:

location	g (joules per kg per m)
asteroid Vesta (surface)	0.3
earth's moon (surface)	1.6
Mars (surface)	3.7
earth (surface)	9.8
Jupiter (cloud-tops)	26
sun (visible surface)	270
typical neutron star (surface)	10^{12}
black hole (center)	infinite according to some theories, on the order of 10^{52} according to others

A good comparison is Vesta versus a neutron star. They're roughly the same size, but they have vastly different masses — a teaspoonful of neutron star matter would weigh a million tons! The different mass must be the reason for the vastly different gravitational fields. (The notation 10^{12} means 1 followed by 12 zeroes.) This makes sense, because gravity is an attraction between things that have mass.

The mass of an object, however, isn't the only thing that determines the strength of its gravitational field, as demonstrated by the difference between the fields of the sun and a neutron star, despite their similar masses. The other variable that matters is distance. Because a neutron star's mass is compressed into such a small space (comparable to the size of a city), a point on its surface is within a fairly short distance from every part of the star. If you visited the surface of the sun, however, you'd be millions of miles away from most of its atoms.

As a less exotic example, if you travel from the seaport of Guayaquil, Ecuador, to the top of nearby Mt. Cotopaxi, you'll experience a slight reduction in gravity, from 9.7806 to 9.7624 J/kg/m. This is because you've gotten a little farther from the planet's mass. Such differences in the strength of gravity between one location and another on the earth's surface were first discovered because pendulum clocks that were correctly calibrated in one country were found to run too fast or too slow when they were shipped to another location.

The general equation for an object's gravitational field was discovered by Isaac Newton, by working backwards from the observed motion of the planets:[2]

$$g = \frac{GM}{d^2},$$

where M is the mass of the object, d is the distance from the object, and G is a constant that is the same everywhere in the universe. This is known as Newton's law of gravity.[3] This type of relationship, in which an effect is inversely proportional to the square of the distance from the object creating the effect, is known as an inverse square law. For example, the intensity of the light from a candle obeys an inverse square law, as discussed in subsection 7.2.1 on page 140.

y / Isaac Newton (1642-1727)

self-check C

Mars is about twice as far from the sun as Venus. Compare the strength of the sun's gravitational field as experienced by Mars with the strength of the field felt by Venus. ▷ Answer, p. 179

Newton's law of gravity really gives the field of an individual atom, and the field of a many-atom object is the sum of the fields of the atoms. Newton was able to prove mathematically that this scary sum has an unexpectedly simple result in the case of a spherical object such as a planet: the result is the same as if all the object's

[2]Example 12 on page 50 shows the type of reasoning that Newton had to go through.

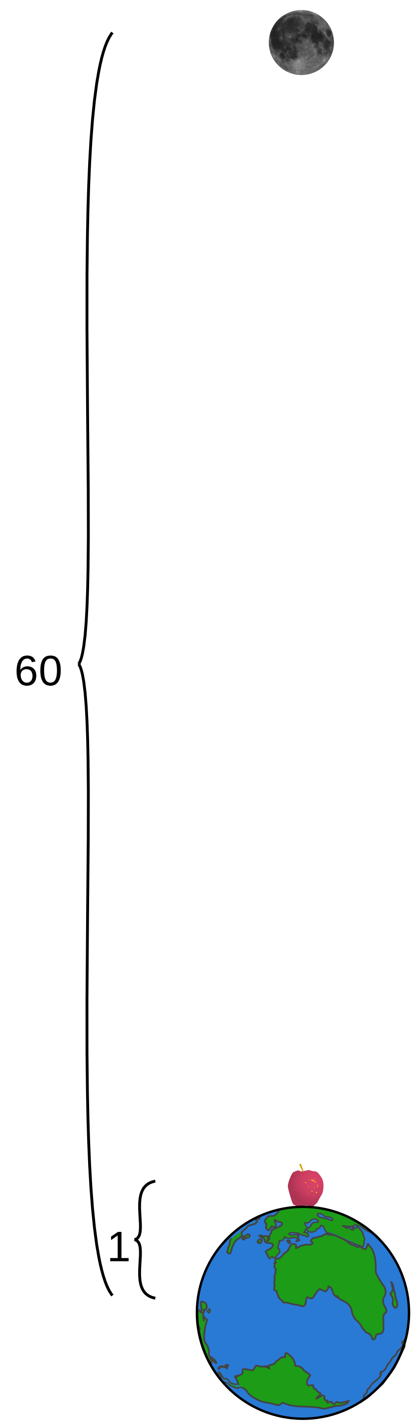
[3]This is not the form in which Newton originally wrote the equation.

mass had been concentrated at its center.

Newton showed that his theory of gravity could explain the orbits of the planets, and also finished the project begun by Galileo of driving a stake through the heart of Aristotelian physics. His book on the motion of material objects, the *Mathematical Principles of Natural Philosophy*, was uncontradicted by experiment for 200 years, but his other main work, *Optics*, was on the wrong track due to his conviction that light was composed of particles rather than waves. He was an avid alchemist, an embarrassing fact that modern scientists would like to forget. Newton was on the winning side of the revolution that replaced King James II with William and Mary of Orange, which led to a lucrative post running the English royal mint; he worked hard at what could have been a sinecure, and took great satisfaction from catching and executing counterfeiters. Newton's personal life was less happy, as we'll see in chapter 5.

Newton's apple — *example 12*

A charming legend attested to by Newton's niece is that he first conceived of gravity as a universal attraction after seeing an apple fall from a tree. He wondered whether the force that made the apple fall was the same one that made the moon circle the earth rather than flying off straight. Newton had astronomical data that allowed him to calculate that the gravitational field the moon experienced from the earth was 1/3600 as strong as the field on the surface of the earth.[4] (The moon has its own gravitational field, but that's not what we're talking about.) The moon's distance from the earth is 60 times greater than the earth's radius, so this fit perfectly with an inverse-square law: $60 \times 60 = 3600$.



z / Example 12.

1.6 Noether's Theorem for Energy

Now we're ready for our first full-fledged example of Noether's theorem. Conservation of energy is a law of physics, and Noether's theorem says that the laws of physics come from symmetry. Specifically, Noether's theorem says that every symmetry implies a conservation law. Conservation of energy comes from a symmetry that we haven't even discussed yet, but one that is simple and intuitively appealing: as time goes by, the universe doesn't change the way it works. We'll call this time symmetry.

We have strong evidence for time symmetry, because when we see a distant galaxy through a telescope, we're seeing light that has taken billions of years to get here. A telescope, then, is like a time machine. For all we know, alien astronomers with advanced technology may be observing our planet right now,[5] but if so, they're

[4] See example 12 on page 50.

[5] Our present technology isn't good enough to let us pick the planets of other solar systems out from the glare of their suns, except in a few exceptional cases.

seeing it not as it is now but as it was in the distant past, perhaps in the age of the dinosaurs, or before life even evolved here. As we observe a particularly distant, and therefore ancient, supernova, we see that its explosion plays out in exactly the same way as those that are closer, and therefore more recent.

Now suppose physics really does change from year to year, like politics, pop music, and hemlines. Imagine, for example, that the "constant" G in Newton's law of gravity isn't quite so constant. One day you might wake up and find that you've lost a lot of weight without dieting or exercise, simply because gravity has gotten weaker since the day before.

If you know about such changes in G over time, it's the ultimate insider information. You can use it to get as rich as Croesus, or even Bill Gates. On a day when G is low, you pay for the energy needed to lift a large mass up high. Then, on a day when gravity is stronger, you lower the mass back down, extracting its gravitational energy. The key is that the energy you get back out is greater than what you originally had to put in. You can run the cycle over and over again, always raising the weight when gravity is weak, and lowering it when gravity is strong. Each time, you make a profit in energy. Everyone else thinks energy is conserved, but your secret technique allows you to keep on increasing and increasing the amount of energy in the universe (and the amount of money in your bank account).

The scheme can be made to work if anything about physics changes over time, not just gravity. For instance, suppose that the mass of an electron had one value today, and a slightly different value tomorrow. Electrons are one of the basic particles from which atoms are built, so on a day when the mass of electrons is low, every physical object has a slightly lower mass. In problem 14 on page 35, you'll work out a way that this could be used to manufacture energy out of nowhere.

Sorry, but it won't work. Experiments show that G doesn't change measurably over time, nor does there seem to be any time variation in any of the other rules by which the universe works.[6] If archaeologists find a copy of this book thousands of years from now, they'll be able to reproduce all the experiments you're doing in this course.

I've probably convinced you that if time symmetry was violated, then conservation of energy wouldn't hold. But does it work the

[6] In 2002, there have been some reports that the properties of atoms as observed in distant galaxies are slightly different than those of atoms here and now. If so, then time symmetry is weakly violated, and so is conservation of energy. However, this is a revolutionary claim, and it needs to be examined carefully. The change being claimed is large enough that, if it's real, it should be detectable from one year to the next in ultra-high-precision laboratory experiments here on earth.

other way around? If time symmetry is valid, must there be a law of conservation of energy? Logically, that's a different question. We may be able to prove that if A is false, then B must be false, but that doesn't mean that if A is true, B must be true as well. For instance, if you're not a criminal, then you're presumably not in jail, but just because someone is a criminal, that doesn't mean he is in jail — some criminals never get caught.

Noether's theorem does work the other way around as well: if physics has a certain symmetry, then there must be a certain corresponding conservation law. This is a stronger statement. The full-strength version of Noether's theorem can't be proved without a model of light and matter more detailed than the one currently at our disposal.

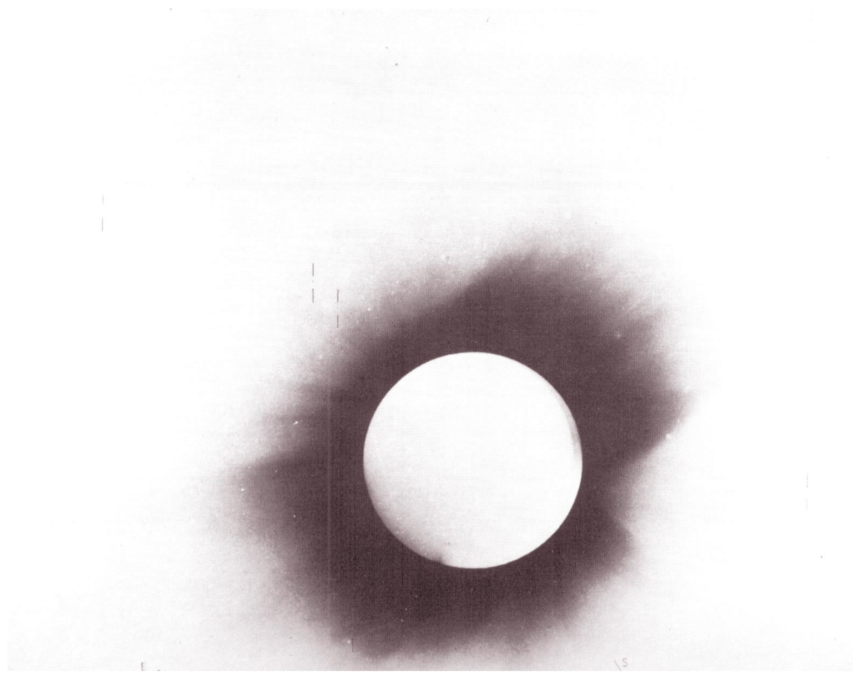
1.7 Equivalence of Mass and Energy

Mass-energy

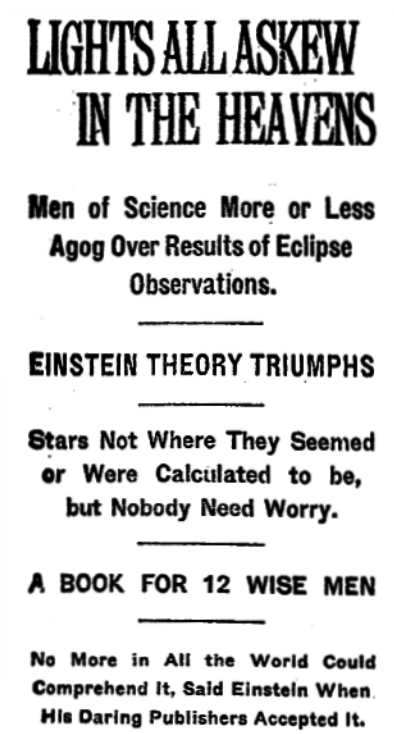
You've encountered two conservation laws so far: conservation of mass and conservation of energy. If conservation of energy is a consequence of symmetry, is there a deeper reason for conservation of mass?

Actually they're not even separate conservation laws. Albert Einstein found, as a consequence of his theory of relativity, that mass and energy are equivalent, and are not separately conserved — one can be converted into the other. Imagine that a magician waves his wand, and changes a bowl of dirt into a bowl of lettuce. You'd be impressed, because you were expecting that both dirt and lettuce would be conserved quantities. Neither one can be made to vanish, or to appear out of thin air. However, there are processes that can change one into the other. A farmer changes dirt into lettuce, and a compost heap changes lettuce into dirt. At the most fundamental level, lettuce and dirt aren't really different things at all; they're just collections of the same kinds of atoms — carbon, hydrogen, and so on.

We won't examine relativity in detail in this book, but mass-energy equivalence is an inevitable implication of the theory, and it's the only part of the theory that most people have heard of, via the famous equation $E = mc^2$. This equation tells us how much energy is equivalent to how much mass: the conversion factor is the square of the speed of light, c. Since c is a big number, you get a really really big number when you multiply it by itself to get c^2. This means that even a small amount of mass is equivalent to a very large amount of energy.



aa / Example 13.



LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

ab / A New York Times headline from November 10, 1919, describing the observations discussed in example 13.

Gravity bending light *example 13*

Gravity is a universal attraction between things that have mass, and since the energy in a beam of light is equivalent to some very small amount of mass, we expect that light will be affected by gravity, although the effect should be very small. The first experimental confirmation of relativity came in 1919 when stars next to the sun during a solar eclipse were observed to have shifted a little from their ordinary position. (If there was no eclipse, the glare of the sun would prevent the stars from being observed.) Starlight had been deflected by the sun's gravity. Figure aa is a photographic negative, so the circle that appears bright is actually the dark face of the moon, and the dark area is really the bright corona of the sun. The stars, marked by lines above and below them, appeared at positions slightly different than their normal ones.

Black holes *example 14*

A star with sufficiently strong gravity can prevent light from leaving. Quite a few black holes have been detected via their gravitational forces on neighboring stars or clouds of gas and dust.

Because mass and energy are like two different sides of the same coin, we may speak of mass-energy, a single conserved quantity, found by adding up all the mass and energy, with the appropriate conversion factor: $E + mc^2$.

A rusting nail *example 15*

▷ An iron nail is left in a cup of water until it turns entirely to rust. The energy released is about 500,000 joules. In theory, would a sufficiently precise scale register a change in mass? If so, how much?

▷ The energy will appear as heat, which will be lost to the environment. The total mass-energy of the cup, water, and iron will indeed be lessened by 500,000 joules. (If it had been perfectly insulated, there would have been no change, since the heat energy would have been trapped in the cup.) The speed of light in metric units is $c = 3 \times 10^8$ meters per second (scientific notation for 3 followed by 8 zeroes), so converting to mass units, we have

$$\begin{aligned} m &= \frac{E}{c^2} \\ &= \frac{500,000}{\left(3 \times 10^8\right)^2} \\ &= 0.000000000006 \text{ kilograms.} \end{aligned}$$

(The design of the metric system is based on the meter, the kilogram, and the second. The joule is designed to fit into this system, so the result comes out in units of kilograms.) The change in mass is too small to measure with any practical technique. This is because the square of the speed of light is such a large number in metric units.

The correspondence principle

The realization that mass and energy are not separately conserved is our first example of a general idea called the correspondence principle. When Einstein came up with relativity, conservation of energy had been accepted by physicists for decades, and conservation of mass for over a hundred years.

Does an example like this mean that physicists don't know what they're talking about? There is a recent tendency among social scientists to deny that the scientific method even exists, claiming that science is no more than a social system that determines what ideas to accept based on an in-group's criteria. If science is an arbitrary social ritual, it would seem difficult to explain its effectiveness in building such useful items as airplanes, CD players and sewers. If voodoo and astrology were no less scientific in their methods than chemistry and physics, what was it that kept them from producing anything useful? This silly attitude was effectively skewered in a famous hoax carried out in 1996 by New York University physicist Alan Sokal. Sokal wrote an article titled "Transgressing the Boundaries: Toward a Transformative Hermeneutics of Quantum Gravity," and got it accepted by a cultural studies journal called *Social Text*.[7]

[7] The paper appeared in *Social Text* #46/47 (1996) pp. 217-

The scientific content of the paper is a carefully constructed soup of mumbo jumbo, using technical terms to create maximum confusion; I can't make heads or tails of it, and I assume the editors and peer reviewers at *Social Text* understood even less. The physics, however, is mixed in with cultural relativist statements designed to appeal to them — "...the truth claims of science are inherently theory-laden and self-referential" — and footnoted references to academic articles such as "Irigaray's and Hayles' exegeses of gender encoding in fluid mechanics ... and ... Harding's comprehensive critique of the gender ideology underlying the natural sciences in general and physics in particular..." On the day the article came out, Sokal published a letter explaining that the whole thing had been a parody — one that apparently went over the heads of the editors of *Social Text*.

What keeps physics from being merely a matter of fashion is that it has to agree with experiments and observations. If a theory such as conservation of mass or conservation of energy became accepted in physics, it was because it was supported by a vast number of experiments. It's just that experiments never have perfect accuracy, so a discrepancy such as the tiny change in the mass of the rusting nail in example 15 was undetectable. The old experiments weren't all wrong. They were right, within their limitations. If someone comes along with a new theory he claims is better, it must still be consistent with all the same experiments. In computer jargon, it must be backward-compatible. This is called the correspondence principle: new theories must be compatible with old ones in situations where they are both applicable. The correspondence principle tells us that we can still use an old theory within the realm where it works, so for instance I'll typically refer to conservation of mass and conservation of energy in this book rather than conservation of mass-energy, except in cases where the new theory is actually necessary.

Ironically, the extreme cultural relativists want to attack what they see as physical scientists' arrogant claims to absolute truth, but what they fail to understand is that science only claims to be able to find partial, provisional truth. The correspondence principle tells us that each of today's scientific truths can be superseded tomorrow by another truth that is more accurate and more broadly applicable. It also tells us that today's truth will not lose any value when that happens.

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