2. Atoms and Heat

Atoms and Molecules – and the Meaning of Heat

Press your hands together hard, and rub them vigorously, for about 15 seconds. (It is actually a good idea to do this right now, before you read further, if nobody is watching.) Your hands feel warmer. The temperature of the skin has risen. You turned kinetic energy into heat.

In fact, heat is kinetic energy, the kinetic energy of molecules. Your hands feel warmer because after rubbing, the molecules are shaking back and forth faster than they were prior to your rubbing.

This is a good time to discuss the makeup of matter. Most of you learned in school that “All substances are made of atoms.” Actually, we know today that this is not right. Most of the stuff in the universe is in the form of dark matter or dark energy, neither of which are composed of atoms. In fact, atomic matter only comprises about 5% of energy in the universe. Of course, we and the matter we interact with in our everyday lives is 100% composed of atoms. This is often called “ordinary matter.” Chemistry, biology and the first 300 years of physics have been focused on the properties of ordinary matter since it impacts our existence and we will do the same for most of this course. However, be aware that some of the biggest open mysteries in science are the (relatively) recently discovered dark matter and dark energy.

Ordinary matter can be classified according to its atomic and molecular structure. There are only about 92 different kinds of atoms: hydrogen, oxygen, carbon, iron, etc. A complete list appears in a chart known as a periodic table.

Molecules are combinations of atoms that stay clumped together. The molecule of water is H₂O, meaning it is made of two atoms of hydrogen (that’s the H₂) and one of oxygen (that’s the O). Helium molecules contain only one atom (He), and hydrogen gas molecules contain only two attached atoms of hydrogen (H₂). But molecules can be very large. The molecule known as DNA (which carries our genetic information) can contain billions of atoms. When molecules break apart or come together, that’s called a chemical reaction.

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1 Molecules are collections of atoms stuck to each other; an example is H₂O = water, with two hydrogen atoms (H₂) and one oxygen (O). We’ll talk more about atoms in Chapter 4.

2 And these atoms can be combined in different ways. That’s how DNA encodes your genetic information.
In all materials, the molecules are shaking. The more vigorously they shake, the hotter the material is. When you rubbed your hands, you made the molecules in your hand shake faster. How fast do they shake? The answer is startling: the typical velocity of shaking is about the same as the speed of sound: 700 miles per hour (1000 feet per second; 330 meters per second). That’s fast. Yet the particles (at least in a solid) can’t travel very far. They bump into their neighbors, and bounce back. They move fast, but like a runner in an indoor track, their average position doesn’t change.

Atoms are too small to be observed with an ordinary microscope. If you move across the diameter of a human hair (typically 25 microns\(^3\)), you will encounter 10,000 atoms from one side to the other. A red blood cell (8 microns across) has about 3,000 atoms spanning its diameter. Some molecules are so large (such as DNA) that they can be seen under a microscope, although the individual atoms in the molecules can’t be resolved.

Even though you can’t see atoms, you can see the effect that their shaking has on small particles. Tiny bits of dust (1 micron in diameter) floating in air, can be seen to be shaking, a phenomenon known as Brownian motion.\(^4\) The shaking comes from the dust being hit on all sides by air molecules, and if the dust is sufficiently small, this bombardment does not average out.

3 A micron is another name for a micro-meter. It is \(10^{-6}\) meters = \(10^{-4}\) cm.

4 This shaking of small particles was first observed on pollen grains in water by the English Botanist, Robert Brown. Since he didn’t know about atoms hitting the dust, the most reasonable interpretation at that time was that the movement indicated that the small particles were alive! A detailed explanation, including predictions of the amount of shaking vs. particle size, was deduced by Albert Einstein in 1905. Based on his work, most scientists were finally won over to the “atomic theory.”
The Speed of Sound and the Speed of Light

Is it a coincidence that the speed of molecules is approximately the speed of sound? No - because sound travels through air by molecules bumping into each other. So the speed of sound is determined by the speed of molecular motion. Sound in a gas cannot travel faster than the velocity of its molecules.\(^5\)

You can easily measure the speed of sound yourself. One way is to watch someone hit a golf ball, chop wood, or hit a baseball. Notice that you see the event before you hear the noise. That's because the light gets to you very quickly, and then you have to wait for the sound. Estimate your distance to the person, and estimate how long it takes for the sound to reach you. If the distance is 1000 feet, then the delay should be about one second. (If you do this at a baseball game, then it is helpful to sit as far from home plate as possible.) The velocity is the distance divided by the time.

When you were young, your parents probably taught you a way to tell how far away lightening is. Namely, count how much seconds there are between the time when you see the lightening and hear the thunder, and divide by five. If there was a ten second delay, then the lightning strike was two miles away. The rule works because light travels so quickly that it covers a mile in a tiny fraction of a second. In other words, the light arrives virtually instantly. But thunder travels at the slower speed of sound: \(330\) meters/sec = \(1000\) feet/sec = 1 mile every 5 seconds (approximately) = 700 miles per hour.

The speed of light is much greater: \(186,000\) miles per second, or \(3 \times 10^8\) meters per second. Although that sounds super fast, we can express it in a way that makes it sound much slower. Modern computers take about one billionth of a second (a \(\text{nanosecond}\)) to do a calculation. In that billionth of a second, light travels only about one foot (30 cm). That’s why computers must be small. Computers must often retrieve information to do a calculation, and if the information is too far away, it has to waste several cycles to get it.\(^6\)

The Enormous Energy in Heat

The average speed of the molecules in this book is the speed of sound, but they are all moving in \(\text{random}\) directions. Suppose I made them all move in the same direction. Then the entire book would be moving at the speed of sound, 720 miles per hour. Yet the total energy would be exactly the same.

\(^5\) In a solid the sound can travel faster than the molecules, since the molecules can transmit forces over short distances even without moving from one spot to another.

\(^6\) That was a fundamental oversight in the classic movies \(\text{Forbidden Planet}\) and \(2001 – \text{a Space Odyssey}\). In the former, the computer was the size of a planet. In the latter, the computer (named "Hal") was portrayed as being large enough for a human to walk into.
This example illustrates the enormous energy that is contained in the heat of ordinary objects. Unfortunately, it is often not possible to extract that energy and use it for useful work. We'll discuss this further when we get to the section on heat engines. There is no good way to change the directions of the shaking so that all the molecules move together. Yet we can do the opposite. When the asteroid hit the Earth 65 million years ago, all the molecules were initially moving at 30 km/sec in the same direction. After the impact, the directions were all different.

When kinetic energy is turned into heat, we can think of it as coherent regular motion becoming randomized. The molecular energy changes from being neatly "ordered" (all molecules moving in the same direction) to being "disordered." The term disorder is very popular in physics. The amount of disorder can be quantified, and that value is given the name entropy. When an object is heated, its entropy (the randomness of its molecular motion) increases. I'll discuss entropy further at the end of this chapter.

**Hiss and Snow: Electronic Noise**

Radios, when tuned in between stations, sometimes give a hissing sound. What is the origin of that hiss? Old TV sets, when there is no station present, show white spots jumping on the screen that reminded people of snow. (Modern TVs sometimes just blank the screen when there is no station, so the snow is never seen.) What is that?

The surprising answer is that the snow and the hiss are due to the same thing — electrons jumping around in the electronics of your set. They are in constant motion due to heat, and when there is no other signal present, you get to watch (or listen) to them move. Even though they are not molecules, they share the energy of shaking.

Such noise can be reduced by lowering the temperature, and high sensitivity systems often have to be cooled to reduce the hiss and the snow. In the chapter on invisible light, I'll talk about a system for seeing in very low light that had such a cooling system attached. But too much cooling can cause the system to cease operation, since a transistor (discussed in chapter 12) actually depends on the fact that room-temperature electrons have some kinetic energy. Without that kinetic energy, the electrons become trapped and electricity doesn't flow. If you cool a transistor, and remove that energy, the transistor no longer functions.

Now that we have described heat as the kinetic energy of the molecules (and sometimes of the electrons too), we can address a trickier question: what is temperature?

**Temperature**
Temperature is closely related to heat. Stop for a moment and think about it. When it is 100 °F outside, it is hot. When it is below 32 °F, water freezes. But it is very tricky to state exactly what temperature is. It is what you read off thermometers. But what does it measure? The answer is surprisingly simple:

*Temperature is a measure of the hidden kinetic energy of the molecules.*

By the “hidden kinetic energy” I meant the usually unobserved energy of shaking. When we get to the section on temperature scales, I’ll give the equation that allows you to calculate the kinetic energy from the temperature.

Something is hotter if the average shaking energy of its molecules is greater. (We use the word average because at any given instant, some of the molecules may be moving faster than others, and some slower, just like dancers on a dance floor.) If two objects have the same temperature, then that means that their molecules have the same kinetic energy of vibration.

Here is a surprising consequence of what I just said. Suppose two bars, one made of iron and the other of copper, have the same temperature. Then their molecules must have the same kinetic energy, on average. Will the iron molecules and the copper molecules have the same average speed? The surprising answer is *no*. The copper molecules will be shaking faster, on average.

Remember that kinetic energy is given by \( E_{\text{kin}} = \frac{1}{2}mv^2 \). Copper and iron have different masses \( m \). So the heavier iron molecule must have a smaller velocity \( v \) in order to have the same kinetic energy \( E_{\text{kin}} \). See why temperature was once even more of a mystery than heat!

Remember this:

*At the same temperature, lighter molecules move faster (on average) than heavier ones.*

**Where is our hydrogen?**

The element hydrogen is, by far, the most abundant element in the Universe. 90% of the atoms in the Sun are hydrogen. The same is true for the large planets of Jupiter and Saturn. Yet in the atmosphere of the Earth, hydrogen gas is virtually absent. Why? Where is our hydrogen?

There is a remarkably simple answer. The Earth once had lots of hydrogen, but we lost it to space. Hydrogen in the atmosphere of the Earth would have the same temperature as the nitrogen and oxygen. Therefore the molecules of hydrogen have the same kinetic energy (on average). But since hydrogen is the lightest element (only 1/16 as massive as oxygen), it must have a higher velocity – by a factor of 4. This high average velocity
turns out to be enough for the hydrogen to escape from the Earth like a rocket! The Sun and Jupiter have much stronger gravity than the Earth, so they kept their hydrogen. We'll discuss escape velocity in more detail in Chapter 3. The Earth lost its hydrogen gas because our gravity is too weak.

**The Zeroth Law of Thermodynamics**

The key discovery that makes temperature a really useful idea is the simple fact that two things that touch each other tend to reach the same temperature. That is why a thermometer gives you the temperature of the air – because it is in contact with the air, so it gets to the same temperature. The fact that objects in contact tend to reach the same temperature was such an important observation that it was given a fancy name: the *Zeroth Law of Thermodynamics*. It probably got that name because the First Law (conservation of energy) had already been named, and this one seemed like it should precede it.

Put a hot iron object in contact with a cold copper one. Because they are touching, the fast molecules in iron now bang into the slower ones in the copper. The iron molecules lose energy and the copper ones gain energy. The temperature of the iron will drop and that of the copper will rise. Only when the temperatures are the same does the transfer of energy stop. The “flow” of heat is actually the sharing of kinetic energy. Heat (kinetic energy) is given up by the hot material to the cold one. The flow stops only when both materials have the same temperature.

This means that if you put a bunch of things in the same room and wait, that eventually they will all reach the same temperature. Of course, that doesn't work if one of the objects is a source of energy, such as a burning log. But if no energy is going in or out of the room, all objects will eventually reach the same temperature.

**The Cold Death**

Stars are very hot, and molecules in space are very cold. Eventually the stars will stop burning, and eventually everything in the Universe may reach the same temperature. By keeping track of everything, we can calculate what that temperature is. If we ignore the

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7 The average velocity of the hydrogen molecules is not sufficient for them to escape, but some hydrogen atoms have well above the average, and those are the ones we lose. Some nitrogen and oxygen molecules are lost this way too, but since their average velocity is so much lower than that for hydrogen, their loss is negligible.

8 The *first* law of thermodynamics, as you may remember from Chapter 1, is the fact that energy is conserved. We'll state the second and third laws later in this chapter. The zeroth law was added only after the other laws were articulated, and apparently everybody thought it should go first, so it got the number zero.
expansion of the Universe (see chapter 13) then that temperature turns out to be –270 C.\(^9\) Because the Universe is expanding, the eventual temperature may be even lower. Philosophers have called this the "cold death" of the Universe, and the thought of it gets some people depressed. But being cold doesn't necessarily mean life will be uninteresting. A detailed analysis made by physicist Freeman Dyson showed that even as the Universe gets very cold, life can continue, and the complexity of organized thoughts could get greater and greater. That might take additional evolution, but we have hundreds of billions of years for that.

**Temperature Scales**

The concept of temperature was invented long before it was understood. It was measured using devices called thermometers, and they were useful because people could make thermometers that would always agree, more or less. (That’s because of the zeroth law.) So temperature became a standard idea. We'll talk about how thermometers work later in the chapter.

There are two common temperature scales, the Fahrenheit Scale, and the Centigrade scale. Centigrade has recently been renamed “Celsius.”\(^10\) Celsius is also abbreviated C, just like Centigrade, and Fahrenheit is abbreviated F. The scales are defined such that the freezing point of water is 32 F and 0˚ C, and the boiling point of water is 212˚ F and 100 C.\(^11\)

We can convert between Fahrenheit and Celsius by the following rules. Let \(T_C\) be the temperature expressed in the Celsius scale, and \(T_F\) be the temperature in the Fahrenheit scale. Then:

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\(^9\) Most of the particles in the Universe are invisible very low temperature particles of light (called the cosmic microwave background) and similarly low temperature neutrinos. The cold death occurs when all the energy is shared equally, including these numerous very cold particles.

\(^10\) The name of the Centigrade scale was changed to Celsius to honor Anders Celsius, a professor of Astronomy who built some of the world’s best thermometers in the 1700s, and originally put 100 degrees between the freezing and boiling points of water.

\(^11\) An amusing historical detail is that Celsius set up his original temperature scale to put 0 at the boiling point of water and 100 at the freezing point -- exactly backwards from the way we use it today. Higher temperature was colder! It is interesting to think that it wasn’t originally obvious that higher temperature should be warmer. It is just a convention.
Here are some examples:

\[ T_F = 32^\circ F \text{ gives } T_C = 0^\circ C. \]
\[ T_C = 100^\circ C \text{ gives } T_F = 212^\circ F. \]

“Room temperature” is \( T_C = 20^\circ C \) or \( T_F = 68^\circ F \).

### Degrees

In the 20th century, it was common to refer to temperature in degrees. A temperature of 65 F was read as “65 degrees Fahrenheit” and written 65 \(^\circ\) F. However, the word degree doesn’t add any meaning, and some people were confused by it. (It has nothing to do with angles, which are also measured in degrees.) So scientists are now adopting a new convention: drop the degree symbol. Thus 32 \(^\circ\) F is usually shortened to 32 F. You’ll see it both ways. There is no physics in this; it is just notation. I’ll sometimes use the traditional terminology, just because of the fact that that is how you will hear it used most, and because it sometimes makes it clear that we are talking about temperature.

Note that Celsius degrees are bigger than Fahrenheit degrees. A change of 1 \(^\circ\) C is a change of \( \frac{9}{5} \) F = 1.8 F. As an approximation, remember:

for changes in temperature \(\Delta T\):
\[ 1^\circ C = \frac{9}{5}^\circ F \approx 2^\circ F \]

**Which is metric: C or F?** The original Fahrenheit scale was designed to make 0 F the coldest temperature that could easily be reached in a laboratory. That was done by mixing ice and salt, and that is what is called 0° F. The temperature of 100° F was originally chosen to be body temperature. (They made a slight mistake, and average body temperature is actually about 98.6° F.) On this scale, water freezes at 32° F and boils at 212° F. When the centigrade scale was officially adopted (by the French, under Napoleon) they decided that the two standard points should be the freezing and boiling points of water. So on the Centigrade scale, water freezes at 0° C and boils at 100° C. Some people think the Centigrade scale was more "metric" than the Fahrenheit scale, and that is nonsense. Both scales were based on standard points 100 degrees apart; they just chose different standard points.
**Absolute Zero**

What happens if the molecules actually come to a stop, and have zero kinetic energy? When all motion of the molecules stops\(^{12}\), we say the temperature of the material is at "absolute zero." Such cessation of motion occurs at \(-273^\circ C = -459^\circ F\).\(^{13}\)

Using this fact, we can define a new temperature scale called the "Absolute" or "Kelvin" scale (named after William Thompson\(^{14}\)). Physicists find the Kelvin scale to be very convenient, because it simplifies equations. In the Kelvin scale, the average kinetic energy \(E\) per molecule is given by a very simple equation:

\[
E = \frac{1}{2} k_b T_K,
\]

where \(T_K\) is the temperature in Kelvins (or degrees Kelvin) and \(k_b = 1 \times 10^{-23} \, \text{J} / \text{K}\) is called Boltzmann’s constant. The constant \(k_b\) is very small only because atoms are so small. *Don't bother learning this number.* It is not important to know the numerical value for the kinetic energy of the particles. It is important to know their velocity (1000 feet per second, about the speed of sound) and that if you double the temperature (on the Kelvin scale!) then you double the kinetic energy.

The most remarkable fact about this equation is that it doesn’t depend on the kind of material. That's just the zeroth law again. This is an amazing and surprisingly simple law of physics. Ponder it for a few moments. Temperature is just the hidden kinetic energy. At room temperature, the kinetic energy of the atoms in the air is identical to the kinetic energy of the atoms in this book. That fact eluded scientists for hundreds of years. The only really tricky part is that the energy must be measured per molecule. This equation begins to illustrate what physicists sometimes refer to as the “beauty” of physics. It isn’t really beauty in the traditional sense. It is just an insight, a simplicity, that is missed by people who don’t study physics.

You can convert from the Kelvin scale to the Celsius scale by subtracting 273:

\[
\frac{T_C}{^\circ C} = \frac{T_K}{^\circ K} - 273.
\]

\(^{12}\) According to the laws of quantum mechanics, the kinetic energy of a confined molecule never actually reaches zero. There is always a little bit left, because of the wave nature of the molecule. This little bit is called the "zero point energy." We ignore that residual motion in this chapter.

\(^{13}\) Don’t confuse “-459 F” with “Fahrenheit 451.” The latter is the title of a Ray Bradbury science fiction book, and is meant to be the temperature at which books burn.

\(^{14}\) Thompson was appointed to the nobility by Queen Victoria in 1892, and given the title "Baron Kelvin of Largs."
The Space Shuttle Columbia Tragedy

On February 1, 2003, the Columbia Space Shuttle broke apart in flames as it reentered the atmosphere, killing all seven astronauts on board.

The Space Shuttle always generates enormous heat when it reenters the thicker parts of the Earth's atmosphere. That's because it has very large kinetic energy, and to slow down (so it can land) it must get rid of that energy.

To calculate the energy per gram, we need to know the velocity. When the Space Shuttle orbits, it travels the Earth's circumference of 24000 miles in 1.5 hours, so its velocity is 24000/1.5 miles per hour = 16000 mph = 7000 meters per sec = 22 times the speed of sound. At the time that it began to fall apart, the Shuttle had slowed to 18.3 times the speed of sound. That is known as "Mach 18.3". We'll show why it has to move so fast in Chapter 3.

A brief calculation:

Let's calculate how hot the Space Shuttle would get if all of its kinetic energy is turned into heat. There is a trick that allows you to get the answer very quickly. We know that at room temperature (300 K) the molecules in the Shuttle are moving at about the speed of sound, i.e. at Mach 1. Suppose all the kinetic energy of the orbiting Shuttle was randomized, i.e. turned into heat. Then they would be moving at Mach 18.3 (since that is how fast the Shuttle was moving.) So as the energy of orbit turns into the energy of heat, the molecules hidden motion speeds up by a factor of 18.3.

What does that do to their hidden kinetic energy, i.e. to the temperature? Remember that the kinetic energy is \( E = \frac{1}{2} mv^2 \). So if you increase \( v \) by a factor of 18.3, you increase the kinetic energy by a factor of \( (18.3)^2 = 335 \). That means you increase the temperature by a factor of 335, from 300 K to \( 335 \times 300 \text{ K} = 100,000 \text{ K} \).

Put another way, if you move at Mach number \( M = 18.3 \), and turn your kinetic energy into heat, your temperature will rise to a temperature \( T = M^2 \times 300 \text{ K} \). This equation can be used for any Mach number \( M \).

In the above calculation, we showed that if the kinetic energy of the Space Shuttle were all turned to heating it, its temperature would rise to

\[ T = M^2 \times 300 \text{ K} \]

where \( M \) is the Mach number. For \( M = 18.3 \), this gives \( T = 100,000 \text{ K} \). That is 17 times as hot as the surface of the Sun. This is why the pieces of the Shuttle glowed so brightly. Friction with air turned them extremely hot.
There is no way to avoid this heating on reentry.\textsuperscript{15} The Space Shuttle is designed to have heat-resistant ceramic "tiles" on the bottom surface. During reentry, these tiles face the onrushing air, and glow with a temperature of thousands of degrees. They can lose this heat by conduction with the air and by radiation. They cool off by the time that the Shuttle lands.

The Shuttle contains little fuel, no explosive. It was the kinetic energy of motion, turned into heat, that destroyed the vehicle.

**Thermal Expansion: sidewalk cracks, highway gaps, and shattering glass**

When the atoms in a solid heat up (i.e. they move faster, i.e. their velocity increases, i.e. they get more kinetic energy) they tend to push their neighbor atoms further away. The effect is small, but important: most solids expand a little bit when heated. A typical number, worth remembering, is that a 1\textdegree C temperature rise makes many substances expand by somewhere between a part in a 1000 and a part in 100,000.

These sound like small numbers, but the span of the Verrazano Narrows bridge in New York City (see photo below) is 4260 feet. When the temperature changes from 20 F to 92 F, (a typical seasonal change in New York City), the length of the bridge changes by about 2 feet.\textsuperscript{16}

\textsuperscript{15} In principle, the Shuttle could have "retro-rockets" that would slow it down in the same manner that rockets sped it up. To do this, however, would take large rocket engines, stages, and fuel just as big as those used in the launch. Some day, if technology developments allow engines and fuel that are much smaller, it might prove possible.

\textsuperscript{16} To calculate this value, we take the temperature difference to be 72\textdegree F = 40\textdegree C. If we look up the thermal expansion for steel, we find that the amount is 12 parts per million for each \textdegree C, so multiply the expansion by the temperature change of 40 \textdegree C to get 480 parts per million. That sounds small, but the bridge is 4260 feet long. Multiply 480 parts per million (480 \times 10^{-6}) by 4260 to get a change in length of 2 feet.
Another effect of change in temperature is the change in shape of the bridge. Because the suspension cables get shorter in the winter cold, the height of the middle of the suspension is 12 feet higher in winter than in summer. (Why is this more than the two feet we calculated for the span? The answer is in the geometry: the cables shorten by only 2 feet, but because of the shallow way in which they hang, that makes the center rise 12 feet. Try this with a horizontal string. If you hold it tight, it is straight. But loosen it just a bit, just a centimeter, and it will sag a lot more than a centimeter.

Sidewalk cement is typically laid with grooves between squares typically five feet = 60 inches on a side. In a 1 °C temperature change, its length would change by 35 parts in a million, i.e. by \(60 \times 35 \times 10^{-6}\) inch = 0.002 inch. For a 40 °C change, that is 0.08 inch, almost a tenth of an inch. That may not sound like very much, but if there were no grooves, the concrete would be compressed and might buckle, causing random cracks. (Just as with the bridge and the string, a small expansion can cause a big buckling.) The small groove, placed by the person who paved the cement, gives room to expand and prevents the cracking. (Or, rather, it puts neat cracks in ahead of time, instead of letting ugly random cracks form.)

**Global Warming and the Rise of Sea Level**

Many climate experts believe that the temperature of the Earth is rising because of the carbon-dioxide being dumped into the atmosphere by the burning of fossil fuel. (We’ll
discuss this further in Chapter 10 on invisible light.) The predicted warming over the next 30 years is between 1.5 and 5°C, depending on which model turns out to be the most accurate.

One of the most surprising effects of the warming is the rise of sea level – not because ice melts (that would be in addition) but simply because water expands so much. The volume expansion of water is $2 \times 10^{-4}$ per degree C. For 2.5 degrees C, that amounts to $2.5 \times 2 \times 10^{-4} = 5 \times 10^{-5} = 0.0005$. The average ocean depth is about 12,000 feet. When the oceans expand, they will rise by 0.0005 of this, i.e. by about 6 feet. That would flood much of the coastal areas of the world, including much of Bangladesh and virtually all of the populated area of Florida.\(^{17}\)

This is a scary enough scenario, that people have become seriously interested in doing the calculation carefully. More detailed calculations have been done that take into account the expected temperature distribution (global warming is expected to be greatest near the poles, and least near the equator) and the variability of the expansion of water. (When the temperature of water is just above 4°C, it hardly expands at all when heated, and below 4°C, it shrinks when heated. Much of the deep ocean is close to 4°C). The 1996 report of the Intergovernmental Panel on Climate Change estimates that, taking all these things into account plus melting of glaciers, the effect would be a rise in sea level between 15 and 95 cm, i.e. between 6 inches and 3 feet. 3 feet is still enough to cover most of the populated area of Florida.

**Thermometers**

Most thermometers make use of the small expansion in order to measure temperature. They typically fill a small glass bulb with fluid, and attach a tube with a tiny long hole. When the temperature is raised, the fluid expands, and moves up the tube. Markings on the tube indicate the temperature.

Note that the thermometer would not work if *both* the glass and the fluid expanded the same amount. Thermometers take advantage of the fact that fluids can be found (e.g. mercury and alcohol) that expand more than does glass. Alcohol, died a red color, is commonly used because its expansion is particularly large. Most of the alcohol is in the bulb at the bottom. When it expands, it forces fluid into the tube. Without the bulb, the expansion would not be enough to be visible.

**Temperature in the shade vs. Temperature in the sun**

Why do meteorologists measure temperature in the shade, rather than in the sun? Aren't people more interested in the temperature in the sun! Why don't they report it?

\(^{17}\) Pieter Tans once told me that of those who live on the coast, only the Dutch would be unaffected. “We know how to build dams,” he said.
It turns out that there is a good reason. Thermometers are supposed to measure air temperature. When you place them in a room, they eventually reach the same temperature as the air; that's the zeroth law of thermodynamics. However, if you put a thermometer in direct sunlight, the red-colored alcohol absorbs more sunlight than does the transparent air. That makes the thermometer hotter than the air. Of course, heat will flow from the thermometer into the air, but if the sun keeps shining on the thermometer, the thermometer will always remain hotter. So a thermometer in the sun does not measure the air temperature. On the other hand, the temperature of the air in the shade is usually the same as that in the sun. So if you really want to know the temperature of the sun-lit air, measure it in the shade.

What happens if another object sits in the sun? It too can get hotter than the air. You've probably had the experience of walking on hot sand, or of touching a car that has been sitting out in the sun. Because these objects absorb sunlight readily, they are often hotter than the air. It is an old tradition in New York City (where I grew up) of publishing newspaper photos on a hot day showing someone frying eggs on an automobile hood. The hood is hotter than the air.

Another type of thermometer works on the principle that different metals will expand by different amount. If you take two bands of different metals, and bind them to each other, you get a “bimetallic strip.” As one side expands more than the other, the strip bends. The amount of bending will be very large for even a small amount of expansion. The bending metal can pull a lever, that moves an indicator over a temperature scale. Thermometers using bimetallic strips are used in oven thermometers and in old thermostats.

Yet a third type, called a digital thermometer (often used in medicine) takes advantage of the fact that the electrical properties of certain materials change when the temperature changes. A small circuit with a battery can measure these changes, and put the result on a digital display.

**Shattering Glass**

If you heat a glass pan in the oven, then put it in cool water, it will often crack or even shatter. A few decades ago, a special glass was developed that didn’t crack: it was trademarked as “Pyrex”, and is very popular for kitchen glass, e.g. measuring cups and pans. What is going on? Why does sudden temperature change cause some things to crack?

The glass cracks because the outside cools more rapidly than the inside, making it a different size. It starts to bend, like a bimetallic strip, but glass is brittle, and it breaks. Pyrex is a special glass that expands much less than ordinary glass; that is why it usually doesn’t break when cooled.
Why doesn’t the glass crack when initially heated in the oven? The answer is that when heated slowly, the heat passes through the glass, and all of the glass is at approximately the same temperature. It is the difference in temperature between the inside and the outside of the glass that causes the difference in expansion, and leads to the cracking.

**Tight Lids**

Tight lids on jars are such a common problem that I own several special devices to help open them, mostly large wrenches that get a good grip on the lid. But my mom taught me a different way to do it: put the lid under hot water for a few seconds. The expansion of the lid, even though tiny, is often enough to loosen the lid so it can be opened. (I’d use a rag to hold the hot lid.) This works only if the metal expands more than the glass. That happens if the expansion coefficient is greater, or if the lid gets hotter (because the water hits it) than the glass.

**Does everything contract when cooled?**

No. Cold water (below 4 °C ≈ 39 °F but not frozen) expands when it is further cooled. When it freezes into ice, it expands even more. This is a strange behavior, and it happens because water molecules start arranging themselves into mini structures, even while staying liquid.

Without this peculiar behavior of water, life on Earth might not have endured. In oceans and lakes, once the water gets colder than 4 °C, the water expands, and with its low density it floats on top of the other water. When it freezes, it expands even more, and so ice forms on the surface. This ice and layer of cold water insulates the water below, and keeps it from getting colder.

If cold water were denser than warm water, then in winter the cold surface water would sink to the bottom, and the warm water would rise to the top, where it would be chilled by contact with the cold air. If water contracted when it froze into ice, then even the ice would sink to the bottom. Eventually the entire oceans would reach the freezing point, and turn into ice, and whatever life there was in the water would be killed.

**SR-71 Spy Planes**

These planes flew so fast, that friction from the air heated the skin to over a thousand degrees C. The thermal expansion was so great, that if the wings were made in the usual way, they would crack. According to the designers (see the book “The Skunk Works” by Ben Rich), they solved this problem by making the fittings of the plane loose – almost like the cracks placed in concrete. A good tight fit was obtained only when the metal expanded, at high speed. A tricky consequence of this was the fact that the planes leaked
fuel (through these loose fittings) until the outside heated up sufficiently. (I know – this is hard to believe. Read Ben Rich’s book.)

**Conduction**

When two objects come in contact, the touching (collisions of surface molecules) allows them to share kinetic energy. The zeroth law implies that the hotter object (greater kinetic energy per molecule) will lose some of its kinetic energy and the cooler object will gain some. Eventually they will be at the same temperature. But this doesn't happen instantly. Moreover, the rate is different for different materials. We say that different materials "conduct heat" at different rates.

Let's look at one of the "quandaries" at the beginning of the chapter. Even though both are at room temperature, a plastic cup and one made of glass feel different. The glass one seems cooler. (If you've never noticed this, find two such cups now, and do the experiment -- or as soon as is convenient.) But why should that be? If both objects were sitting together in the room, they were at the same temperature, right?

Yes, the plastic and the glass were at the same temperature. But plastic and glass conduct heat at different rates. Your finger is warmer than room temperature, because you are generating heat in your body – at an average rate of about 100 watts. When you touch the glass, it conducts the heat away rapidly, and so the temperature of your finger tip drops slightly. That is what your nerves sense: not the temperature of the glass, but the temperature of your skin. When you touch plastic, the heat is not conducted away as rapidly, so you skin doesn’t cool as much. You think (incorrectly) that the glass is cooler than the plastic. In fact, they are the same temperature. The glass, however, cools your warm skin faster than the plastic does.

**Solid, Liquid, Gas and Plasma**

At low temperatures, the shaking of the molecules is low, and the molecules tend to stick together in a rigid form we call a *solid*. When the substance gets hotter, the molecular motion increase to the point that the bonds to nearby molecules are weakened. The molecules still stick, but they can now slip past each other. When they reach this point, we say we have a *liquid*.

The most remarkable thing about this change is that it happens so abruptly. Water at 31 F is a solid, and water at 33 F is a liquid. The difference in energy for rigid sticking vs. slip sticking is small, but it is the same for all the water molecules. The change from solid to liquid is called a change in "phase."

As we continue to heat the water, the molecular shaking increases, but until the temperature reaches 212 F (= 100 C), the molecules slip but they still stick. At 212 F, the shaking is finally enough to overcome the attractive forces between the molecules, and
they break apart. This is the phenomenon called boiling, and the escaped molecules are now a gas.

Even below 212 F, some molecules will have sufficient energy to break away. This happens because not all the molecules have the same energy; some are moving faster, and some slower. The faster ones are the ones that can break away. When they do that, and leave the surface, then the molecules left behind are the slower, colder ones. That's why evaporation makes the liquid cooler—it's just because the hotter molecules are leaving.

At even hotter temperatures, collisions between the molecules are sufficient to break them apart into individual atoms. If the atoms are themselves broken apart, so that electrons are knocked off their surfaces, then we call the gas a plasma. A plasma consists of electrons (with negative electric charge—see Chapter 4) and the remaining atom fragment (which has a net positive charge) is called an ion. A plasma has no net electric charge because it is a mixture of negatively charged electrons and positively charged ions.

Solids, liquids, and gases are commonplace, but many people think plasmas are exotic. They are more common than you might guess. A candle flame is a plasma. The gas inside a fluorescent light bulb is a plasma. The surface of the Sun is a plasma. A bolt of lightning is largely plasma.

**Exploding TNT**

Let's think again about what happens when TNT (trinitrotoluene) explodes. According to the energy table in Chapter 1, the chemical energy that is released is 0.65 Calories per gram of TNT. When TNT explodes, it suddenly converts 0.65 Cal per gram into heat. This new thermal energy is much greater than its prior thermal energy, which amounted to only 0.004 Cal per gram. 

For room temperature, we take $T_K = 300K$. The energy per molecule is given by the equation we already discussed: $E = \frac{1}{2} k_B T_K = 2 \times 10^{-23} \frac{J}{K} \times T_K$. Putting in the numbers, this equation gives the heat energy per molecule $= 2 \times 10^{-23} \frac{J}{K} \times 300K = 6 \times 10^{-21} J = 1.4 \times 10^{-24} Cal$. TNT has $2.6 \times 10^{21}$ molecules in one gram. So the thermal energy in one gram of TNT is the energy per molecule times the number of molecules per gram:

$$E_{TNT} = 1.4 \times 10^{-24} \frac{Cal}{Molecule} \times 2.6 \times 10^{21} \frac{Molecules}{gram} = 0.004 \frac{Cal}{gram}.$$ 

So the thermal energy at room temperature is much less than the chemical energy released in the explosion.

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18 The word plasma was originally used in biology, and was appropriated for physics by Nobel Laureate Irving Langumuir. If you are interested, see *The Birth of "Plasma"*, L. Tonks, Am. J. Phys., 35 (1967), p.857.

19 For room temperature, we take $T_K = 300K$. The energy per molecule is given by the equation we already discussed: $E = \frac{1}{2} k_B T_K = 2 \times 10^{-23} \frac{J}{K} \times T_K$. Putting in the numbers, this equation gives the heat energy per molecule $= 2 \times 10^{-23} \frac{J}{K} \times 300K = 6 \times 10^{-21} J = 1.4 \times 10^{-24} Cal$. TNT has $2.6 \times 10^{21}$ molecules in one gram. So the thermal energy in one gram of TNT is the energy per molecule times the number of molecules per gram:

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So the thermal energy at room temperature is much less than the chemical energy released in the explosion.
energy increases by a factor of 167. If the molecules didn't break apart (they do - and that complicates it a little), the absolute temperature would suddenly become 167 times greater than the prior temperature (300 K). That makes the temperature $167 \times 300\,\text{K} = 50,000\,\text{K}$. Note that if we convert back to Celsius: 50,000 K is $(50,000 - 273) \approx 50,000$ C (rounding to the nearest 1000).

50,000 C is very hot, much hotter than the surface of the Sun (which is about 6000 C). Nothing is a solid at 50,000 C. The forces between the molecules are not strong enough to hold them together. That means that our gram of TNT is suddenly converted into a very hot gas, perhaps even into a plasma.

What will that hot gas do? Even at normal room temperatures, gases take typically 1000 times the volume of a solid. So just the fact that it turns into a gas makes it expand by a factor of 1000. But since it is hot, it expands even more -- by another factor of 167 (the ratio of temperatures before and after). We'll discuss that extra factor of 167 in the next section. But for now, accept that figure. Put that factor on top of the factor of 1000, and we get a total expansion in volume of 167,000. (This is only a rough estimate.)

To summarize: here is our picture of what happens when TNT explodes. The solid material is suddenly converted into a hot gas. The hot gas expands rapidly until its volume goes up by a factor of 167,000. The expanding gas pushes everything out of the way. Any material nearby picks up the velocity of the gas. Terrorists typically surround the explosive with a pipe, or pieces of metal (e.g. nails). When the metal fragments fly out at high speed, they are what do the most harm.\(^{20}\)

Gas Temperature and Pressure – the "Ideal Gas Law"

Why did the heated gas in the last section expand by an additional factor of 167? It helps to understand the difference between a solid and a gas. In a solid, the atoms bounce back and forth, but never leave their relative position. As the solid gets hot, this added bouncing makes the solid expand. But when the energy of the molecules becomes sufficiently great, the atoms push their way out. At high temperature the molecules no longer stay in the same place, but move much more freely. They bump into other molecules, and they bounce against any walls in the containers that they are in. The bouncing tends to push the walls outward. A force must be applied to the walls to keep them from moving.

The pressure of a gas is defined as the force it exerts on one square meter of area. The key result is:

$$P = \text{const.} \times T_k$$

\(^{20}\) The military has built "fragmentation bombs" and "fragmentation grenades" based on the same principle. The colloquialism "to frag" originally meant to attack someone with a fragmentation grenade.
This equation is part of the "ideal gas law." It is called ideal because most real gases deviate from it a little bit, yet it is usually a good approximation. \(^{21}\)

The importance of this law is as follows: if you double the absolute temperature, you double the pressure of the gas (if you keep the volume fixed). If you raise the absolute temperature by a factor of 167 (our TNT example) then the pressure increases by a factor of 167. That’s why hot gases exert so much pressure.

Airbags literally explode open!

The airbags that are used to protect you during an automobile crash are balloons that inflate very rapidly, in a thousandth of a second, in between the time that the crash is detected by the automobile electronics, and the time that your head would smash into the windshield. How can you fill a balloon that rapidly? The answer is, naturally, with an explosion. Airbags contain about 50 to 200 grams of an explosive called sodium azide. Its molecules consist of one atom of sodium and three of nitrogen; it has the chemical formula NaN\(_3\). When triggered by an electric pulse, it explodes into sodium metal and nitrogen gas. The released gas inflates the balloon.

**Sautéing, and Leidenfrost Layers, and Firewalking**

Have you ever seen a drop of water land on a hot sauce pan, and seem to float above the surface and move about as if there were no friction? If not, try it. Put on a pair of glasses to protect your eyes. You’ll see the drop sizzle, and then float just above the surface of the pan.

This happens because the rapid heating of the water turns it into a gas, and pushes the drop away from contact with the pan. The gas has very little friction, and so the droplet moves over the surface. The gas also conducts heat very poorly, since it is a thousand times less dense than the water (so there are 1000 times fewer molecules present to carry the kinetic energy from the sauce pan to the water).

The thin layer of gas that insulates the drop of water is called a “Leidenfrost layer” after the Josef Leidenfrost, the scientist who, in the 16\(^{th}\) century, was the first to understand why water droplets floated on hot pans.

In one of your lab classes we will demonstrate this effect with liquid nitrogen. Nitrogen is a gas, approximately 79% of air, and it turns to liquid when cooled to 77 K = −196 C = −321 F. Pour some on a table, and watch the little droplets of liquid nitrogen scoot over the table top, suspended on thin layers of nitrogen gas.

Some people believe that the Leidenfrost effect can explain "firewalking", the ability of people to walk barefoot over hot coals without burning their feet. If the skin of your foot
is moist (e.g. from sweat), and you step on a hot coal, the water is very rapidly boiled into a thin layer of gas. The water vapor from the sweat has a temperature of 100°C; it penetrates into the hot coals, and prevents the much hotter gases from the interior from reaching the feet. Although the hot water vapor is hot, it is also a poor conductor of heat, so it doesn’t heat the foot very quickly.

Look up firewalking on the web; you will find lots of commercial organizations that will lead you through a firewalking ritual as part of a self-improvement and confidence building program. (If you can walk on fire without being burned, you can do anything…) But I don’t recommend you try walking on hot coals without professional supervision. I would guess that the professionals first make sure your feet are adequately damp (e.g. from walking on moist sand near the sea) and they use porous coals (which the water vapor can penetrate). Something you can try with relative safety: next time you are at the beach on a hot day, and the sand is too hot to walk on comfortably, wet your feet, and try again. You’ll discover that you can walk a few tens of meters before the sand becomes unbearably hot again. Of course, the temperature of the sand didn’t change; just the flow of energy into your feet. And be careful; even hot sand can scald your feet. If you never get the leave the city, you can try the same thing on a hot sidewalk. But carry some sandals with you in case your feet begin to burn.

**Explosions under the Hood**

We’ve talked about turning energy (e.g. energy of motion) into heat, but can we do the opposite? There is a huge amount of energy hidden as heat. Can it be turned into useful energy?

Yes. Exploding TNT turns chemical energy into heat, the heat causes the material to turn into hot gas, and the expanding hot gas can rip apart rock. That counts as useful work.

We can also tame this process to do some more gentle work, like running an automobile. Gasoline and air are injected into a chamber called a cylinder (because of its shape) making an explosive mixture. A spark (from the spark plug) ignites the mixture, it explodes, and the mixture turns into a hot gas. The high pressure from this gas pushes a piston, which in turn pushes a series of gears that turn the wheels.

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Engineers sometimes like to distinguish between an "explosion" and a "conflagration." In an explosion, the surface of burning moves faster than the speed of sound. In this precise terminology, the burning of gasoline in an automobile is a conflagration, not an explosion. But I won't use this fine distinction.
The figure above shows a model of an automobile engine. This image was borrowed from http://206.117.169.65/engine.htm. It is an animated GIF image, and when run by a web browser, it shows the cycles of the engine. Go to the web site to see it in operation. At the top is a spark plug. Gas and air are introduced through the valves; the spark plug ignites the mixture, forcing the piston down in the cylinder. At the end of its motion, another valve is opened; the cylinder moves upward (carried by the momentum of an attached flywheel it is attached to) to expel the burned gases, and the cycle repeats.

The explosions in an automobile are generally kept small, so that they won’t rip the engine apart. Your car probably has four to eight cylinders, and these are run in sequence to provide a fast series of bursts that approximate continuous power.

Any engine that runs by turning heat into mechanical motion is called a "heat engine." Nuclear submarines and nuclear ships (some of our aircraft carriers are nuclear) are also run by a “heat engine”, although without explosions. Nuclear power is used to heat water to steam, and the steam is run through a turbine (a fancy fan) to make it spin. That spinning motion is conveyed to the propeller to push the submarine (or ship) forward. We'll talk more about creating heat from nuclear energy in Chapter 4.

**Wasted Energy**

In an automobile engine, the chemical energy from the gasoline and air mixture is turned into heat, and the pressure from the hot gas pushes the piston. But not all of the energy turns into useful work. Some of the heat is conducted away to the outside air and is "wasted." For typical automobiles, only about 20% to 30% of the chemical energy is
converted into useful propulsion.\textsuperscript{23} The rest is wasted – as heat that escapes, or has to be removed. In fact, gasoline engines waste so much energy that special cooling systems are built-in to get rid of the wasted heat. That is what the “radiator” in the front of the car does: cool water, by letting air blow by it; next, use the cool water to remove waste heat from the engine (so it doesn’t “overheat”); and, then, send the hot water back to the radiator to cool off.\textsuperscript{24}

It is possible to use the energy more efficiently, but there are surprising limits. As we will see in the next section, there are limits to how well a heat engine can perform.

\section*{Limited Efficiency of Heat Engines}

Here is a puzzle: The thermal energy of water at room temperature is about 0.04 Cal per gram. That is small, but it is five times as much as in a battery. And water is cheap. Why not use the thermal energy in water as a fuel?

It turns out that there is a very fundamental theorem that limits how much of such heat can be turned into useful energy (e.g. kinetic or potential energy). This theorem was one of the greatest achievements of the theory of heat. To understand this theorem, you first have to realize that heat can be extracted (turned into useful energy) only when it is flowing from a hot region to a cold region. For example, when gasoline burns, it is hotter than the surrounding air, and that allows it to expand and push against a piston. If the surrounding air were just as hot as the exploded gasoline, it would have a similar pressure and the piston would not move. Heat engines depend on such a temperature difference to do their work.

\textsuperscript{23} Assume an automobile gets 30 miles per gallon, as it travels 50 miles per hour over a level road. Although the auto has a peak power of 150 horsepower, assume that it uses only about 50 horsepower under these conditions. Combining these numbers, you can easily show that the rate of gasoline use is about 10,000 grams per hour. With 10 Cal per gram, the energy in the gasoline being used is about 30 Cal/second = 123 kW. But the energy the engine actually delivers is only 50 hp = 37 kW. So the energy efficiency is $\frac{37}{123} = 0.30 = 30\%$.

\textsuperscript{24} If the radiator stops working, the engine gets very hot (it "overheats"), the lubricating oil decomposes, and without lubrication, the metal pistons no longer slide smoothly in the metal cylinders; they scrape and eventually bind. We use an ironic word for the process of the metal binding to other metal: we say the engine “freezes” – even though it all happened because of the high temperature.
Let the hot temperature (e.g. of the exploded gasoline) be $T_H$ (in degrees Kelvin!) and the temperature of the gas after it has been cooled be $T_C$. The amazing theorem is that the efficiency of the engine is given by the following equation:

$$\text{Efficiency} \leq 1 - \frac{T_C}{T_H}.$$ 

The symbol $\leq$ means "less than or equal to". Perfect efficiency is 1 (= 100%). Thus, for example, if the gasoline explodes at 1000 K, and is cooled to 500 K before it exhausts from the cylinder, then the efficiency of the engine will be less than or equal to 

$$1 - \frac{500}{1000} = 0.5 = 50\%.$$ 

This is a remarkably simple rule, and it is always true when trying to extract energy from heat. It is not relevant for batteries or solar cells that extract energy directly from chemicals or from light. But it shows why heat engines, to be efficient, must be hot.

Let's go back to the puzzle: why not extract heat energy from room-temperature (300 K) water? Imagine a device that can do this: a boat, that scoops water out of the sea, tries to extract energy from it, and then dumps the water out the back end. If the water has the same temperature afterwards as before, then $T_C$ and $T_H$ are equal and the efficiency is 

$$1 - \frac{300}{300} = 0.$$ 

So no energy is gained. To gain energy, the water must be cooler afterwards. However, there is a limit to how much energy you can gain because water freezes at $T_C = 273$ K. This limits the efficiency to 9%.

So you need a temperature difference in order to extract any useful energy from heat. This is so important, that the fact has been given another fancy name: the Second Law of Thermodynamics. To have high efficiency, you have to have a large temperature difference (e.g. between the hot exploded gasoline and the cool gas ejected outdoors).

**Volkswagen Beetle -- and the Efficiency Equation**

In the 1960s, the Volkswagen company introduced the car that was commonly known as the “Beetle” or the “bug”. At a time when other cars averaged 6 to 15 miles per gallon (mpg), it got 30 mpg. That was, in part, because it was little. But it also ran its engine at a higher temperature, a temperature at which higher efficiency was obtained, according to the efficiency equation. If $T_H$ gets very large, then the ratio $T_C / T_H$ gets very small, and the efficiency $1 - \frac{T_C}{T_H}$ gets close to 1, i.e. to 100% efficiency.

The Beetle was originally thought to have another advantage: the car was believed to produce very little air pollution. That’s because at the high temperature of the engine, virtually all the carbon particles in the exhaust were burned into carbon dioxide. The

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25 Prior to this equation, I usually used the symbol $T_C$ to mean the temperature measured on the Celsius or Centigrade scale. Here, $T_C$ is the “cold” temperature measured on the absolute or Kelvin scale. Try not to be confused.
result was the virtual total absence of “smoke” at the back exhaust. But a few decades later, people began to worry about other kinds of pollution, in particular, nitrous oxides (NO and NO₂). These had not been considered pollution in 1966! It turns out that at high temperatures, ordinary air (N₂ and O₂) react chemically to form nitrous oxide, and nitrous oxide is more important in the formation of smog than are carbon particles. The Beetle produced huge amounts of nitrous oxides, because of its high engine temperature. The nitrous oxide production could not be reduced without reducing the temperature of the engine, and if they did that, then the efficiency of the engine would go down. When new legislation limited the nitrous oxides allowed from new cars, the old bug was phased out. It was replaced by a design uses an air-cooled engine that operates at low temperatures.

Refrigerators and Heat Pumps

A heat engine requires a temperature difference. In an automobile engine this is created by burning (exploding) gasoline. As the hot gas expands, it does useful work (i.e. it turns the wheels of the car). It is possible to reverse this process: to take mechanical motion, and use it to create a temperature difference. The device that does this is called a refrigerator or a "heat pump."

A typical refrigerator works by using a mechanical force to reduce the pressure in a chamber. Then the gas law equation, \( P = \text{const.} \times T \), implies that the temperature of the gas will decrease. That cool gas can be used to freeze ice, or just to cool a room. That is how refrigerators and air conditioners work.

The mechanical force that reduces the pressure must push the piston against the room air pressure. This motion slightly heats the air. So in a refrigerator, not only is one side being cooled, but the other side is being heated. Energy is conserved, so any heat that leaves the refrigerator must result in energy transferred elsewhere, usually to the room air. Thus, refrigerators heat the rooms that they are in. Air conditioners are designed cool a room and put the extra heat outside. That's why air conditioners must be placed in windows or other locations with access to the outside. You can think of an air conditioner as a device that uses mechanical motion (usually from an electric motor) to pump heat from inside the room to the outside.

The reverse also works. On a winter day, you can take an air conditioner, install it backwards, and use it to pump heat from the cold outdoors into a warm room. When used in this fashion, the device is usually called a heat pump. Heat pumps are widely used in cold parts of the United States.

Here is a puzzle with a surprising answer. Suppose you have a gallon of fuel, and a cold house. What is the best way to heat your home? You can burn the fuel, and use the heat produced. But here is a much better way: use the fuel in a heat engine, and use the mechanical motion that is produced to run a heat pump. The heat pump will extract heat from the cold outdoors, and pump it into the room. It turns out that the heat pump
method will put typically three to six times more heat into your room than if you were to just burn the fuel and use the heat emitted. This factor over burning is called the "coefficient of performance" or COF.

Does that mean that we are wasting fuel when we heat our homes by burning fuel (gas, coal or wood) instead of using that fuel to run a heat engine/heat pump system? The surprising answer is yes. But an engine/pump system is more complicated and its costs more. It generally isn't used unless the outside temperature is very cold, since otherwise it is cheaper to buy more fuel than it is to buy the expensive engine/pump system. But as we run out of fossil fuel, and it becomes more expensive, we can expect to see much wider use of engine/pump heating systems.

**Laws of Thermodynamics**

Here is now a complete list of the "Laws of Thermodynamics"

0th Law: objects in contact tend to reach the same temperature
1st Law: energy is conserved (if you consider all the forms, including heat)
2nd Law: heat flows only from a higher temperature to a lower one; you can’t extract heat energy without a temperature difference
3rd Law: you can never reach absolute zero

The 0th law can also be interpreted as saying that all objects in contact with each other tend towards “equilibrium”: once they all reach the same temperature, no further change occurs. The 2nd law is sometimes stated in terms of “entropy” or “disorder.” We will explore this connection shortly. The 3rd law is something we have not mentioned previously. When combined with the 2nd law, it says that it is hard to extra energy from objects near absolute zero. From our expression for the efficiency of a heat engine, the 3rd law also says it is impossible to have a perfectly efficient engine.

**Heat Flow: conduction, convection, and radiation**

Heat energy moves from one place to another in three ways, called conduction, convection, and radiation.

**Conduction**: energy flows by contact. Hot molecules transfer energy to cooler ones by direct contact. A good conductor is something that transfers heat rapidly from one molecule to the next. Metals are usually good conductors, as is glass. Plastic is a poor conductor. If you want to insulate something from heat, you use a poor conductor. If you want a pan that is heated at one point to distribute that heat over its whole surface, you make it out of a good conductor (e.g. aluminum or copper).
**Convection:** energy is carried by a moving material, usually a gas or a liquid. When the hot material reaches some cold things, it usually transfers its energy by contact, i.e. by conduction. Example: an electric heater in your room warms the nearby air (by conduction). That air then moves throughout the room (convection), warming things that it touches (by conduction). A fan can help convection. Hot air also tends to rise (see Chapter 3) and that starts the air in a room circulating on its own; that's called "natural convection." A convection oven uses circulating air to heat food.

**Radiation:** energy moves through empty space, carried by (possibly invisible) light. When you stand in sunlight, you are warmed by radiation from the sun. When you stand in front of an infrared heat lamp, you are warmed by the invisible infrared radiation. (We'll discuss such invisible light in much more detail in chapter 10.) A microwave oven cooks by radiation. Microwaves penetrate into food, so they will cook the insides of some foods as rapidly as they cook the outsides.

The word radiation is used for virtually any energy that flows through space. This includes nuclear radiation (which can cause cancer; see chapter 4), visible light, ultraviolet light (which can cause sunburn, see chapter 9), and microwaves.

**Entropy and Disorder**

I mentioned earlier that the 2\textsuperscript{nd} law is sometime phrased in terms of “disorder.” The degree of "disorder" can be quantified by a number called the *entropy*, denoted by $S$. Another equivalent version of the 2\textsuperscript{nd} law is that, when heat flows, the net entropy of the Universe tends to increase. This subject receives a great deal of attention from philosophers, and so it is worth a bit of further discussion.

When entropy changes due to heat flow, the calculation is simple: When heat flows into an object, its numerical increase in entropy is $\Delta S = \frac{Q}{T}$, where $Q$ is the amount of heat (usually measured in joules) and $T$ is the temperature. When heat leaves an object, the entropy of that object decreases by $\frac{Q}{T}$.

When heat flows from a hot object (with temperature $T_H$) to a cold object (which has temperature $T_C$), the total change in entropy of the combined system is

$$\Delta S = \frac{Q}{T_C} - \frac{Q}{T_H}$$

The first term will always be bigger than the second one (since $T_C$ is smaller than $T_H$) and so the total entropy will increase. If heat could flow the other way, from cold to hot, the total entropy would *decrease*; but this is forbidden by the 2\textsuperscript{nd} law. So, the 2\textsuperscript{nd} law is
equivalent to saying that the total entropy decreases. The Universe is becoming more and more disordered.

It is important to realize that the entropy of an individual object can go up or down; it is the total entropy of the Universe that is always increasing. My goal with this book is to decrease the entropy in your brain. (That is a fancy way of saying that I hope you learn something.) As you learn, you will radiate heat, and that will increase the entropy of the world around you. The net entropy of the Universe goes up, but I hope that your own entropy goes down.

When an object gives off heat, its entropy goes down. The heating of the surroundings more than makes up for that, so the total entropy of the Universe increases. The entropy of the Earth is decreasing with time, as is the entropy of the Sun. The Sun is emitting visible light; the Earth is emitting infrared light (see chapter 10) and as a result, the total entropy of the Universe goes up.

Some philosophers (and some physicists) have argued that the increase in entropy of the Universe is what determines the direction of time, i.e. why we remember the past and not the future. (That really is a deep question, not as trivial as it sounds.) But it can also be argued that it is the local decrease in entropy (i.e. when we learn things) that gives us the sense of time.

Have fun thinking about these ideas. There are several popular books devoted to the subject.

The second and third laws of thermodynamics can be reformulated as follows:

Second Law: The entropy of the Universe tends to increase
Third Law: The entropy of an object goes to zero at $T = 0$ K.

Understanding how these reformulations are equivalent to the original statements is part of the advanced study of thermodynamics and statistical mechanics.

Quick Review

Atoms, the basic constituents of matter, are about $10^{-8}$ cm in diameter. There are about 50,000 of them in the diameter of a red blood cell, which is about the smallest object visible with visible light. Heat is the shaking of molecules, the fact that they have kinetic energy. The velocity of shaking is comparable to the velocity of sound, about 1000 ft/sec = 330 meters/sec. For solids, the atoms remain in the same location despite
this violent shaking. The effects of shaking can be observed in “Brownian motion.” It also makes itself evident in electronic noise such as hiss.

If two objects have the same temperature, that means that the average kinetic energy of the molecules in the two objects is the same. However, the speed of the molecules is not equal. Given equal kinetic energies, an object with light molecules will have the faster ones. The lightest molecules of all, those of hydrogen gas ($H_2$), move so fast that most of them have escaped the gravity of the Earth and are no longer present in the atmosphere.

Temperature can be measured on the Fahrenheit scale, or the Celsius (Centigrade) scale. But more useful for physics is the Absolute or Kelvin scale, for which 0 K corresponds to a kinetic energy per molecule of zero. A change of 1 K is equal to a change of 1 C which is equal to a change of $9/5$ F $\approx 2$ F.

Most objects expand when they get warm, by an amount of typically a part per 1000 to a part per 100,000 for each degree C. This is used for thermometers, but it also results in sidewalk cracks, and it could cause substantial sea level rise if global warming warms the oceans.

Heat can be transferred by conduction, since atoms in contact with others can share their kinetic energy. Gases expand when they get hot. A good approximation is the “ideal gas law” that says the gas pressure is proportional to the absolute temperature. Heat can also flow by radiation and by convection.

An explosion occurs when an object gains so much energy that it becomes a very hot gas. It is the high pressure of the gas, and the resulting rapid expansion, that make up an explosion. Such explosions also occur in the cylinders of “internal combustion engines,” and we use them to supply energy to our automobiles.

Energy converted to heat cannot always be converted back efficiently. The limit is the efficiency equation, $\text{efficiency} \leq 1 - \frac{T_c}{T_H}$. Such heat is often considered wasted, and may result in the ultimate “heat death” of the Universe.

The four major laws of thermodynamics are:

0. Objects in contact tend to reach the same temperature,
1. Energy is conserved,
2. Extracting useful energy from heat requires a temperature difference, and
3. No object can be made to have $T = 0$ K.
Energy can be used to extract heat from an object. That is the basic principle of the refrigerator, the air conditioner, and the heat pump.

Entropy is a measure of the disorder in molecules. Warm objects, by their shaking, have more disorder, and therefore higher entropy. Whenever heat flows, the entropy of the universe increases, although the entropy of an object (such as your brain) can decrease. Indeed it does, when you learn something.