New Mexico Solar Energy Association

Energy Concepts Primer

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This primer is intended to fill in important background information about basic energy physics in a conceptually deep but mathematically simple way.

Note: If you're short on time, try reading only the highlighted portions of text.

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What *is* energy?

This section covers the concept of energy itself, what it actually ***is***. In the next sections, we'll discuss its various forms, it properties, how its transferred, how we obtain it, and how we use it.

Most of us have an intuitive concept of energy that goes something like this:

Energy is the stuff we need to accomplish physical actions such as walking, lifting a glass, heating some water, or powering a television set.

Although this definition is correct, it's a bit indirect because it really only conveys to us what energy is ***used*** for, not what energy ***is***, or even how it ***behaves*** (for example, what happens to it after you use it?).

A curious person might still ask questions like: Is energy a thing? Or is it a property or a condition of a thing? How do we really define it? How was it discovered? What are its properties? These are some of the questions we will try to answer in this and following sections, as completely, briefly, and simply as possible.

With perhaps the exception of energy in the form of light, energy is not a thing per se. Rather, energy refers to a *condition* or *state* of a thing.

As we will discuss in more depth later, a book sitting on a table, for example, possesses energy ("potential energy") because of its *condition* of being able to fall if nudged off the table. A ball flying through the air has energy ("kinetic energy") because of its relative velocity with respect to the ground, and it also possesses potential energy because of its height above the ground.

But people speak of energy as if it’s a thing. Moreover, we all know that energy can be stored, bought and sold, and transported. The reason that energy has all these aspects is, unlike many "conditions" that objects may be subject to, ***energy is conserved***; the condition of having energy is always passed from one object to another, never created anew or destroyed. In this way, energy is pretty unique among conditions.

A good example of how energy is passed along from object to object is a water wave. A water wave gives the impression that there is an object moving across the water because the shape of the water doesn't change very much. But there really is not an object moving - rather, the movement itself of the water molecules is passed from each collection of water molecules to the next through the forces between the water molecules.

Similarly, people are familiar with heat flowing from one object to another. For a long time, because molecules are far too small to see, people thought that heat might be a kind of fluid-like substance, which some called "caloric fluid" that flowed from one thing to another. Nowadays, we know that heat energy is the microscopic motion of molecules, and that this *state of motion*, not the molecules themselves, is what "flows" from hot objects to cold objects.

The Scientific Concept of Energy

To understand the concept of energy a little more deeply, one needs to first understand the concept of "work" as defined by the branch of science called physics.

Suppose you push something, say, your couch, across your living room floor. Then the measure of the "work" you do, as defined by the branch of science called physics, is equal to the force you pushed with, multiplied by the distance over which you did the pushing:

Work = Force x Distance.

Suppose you just push on the couch *without* moving it. Are you doing any work on the couch in this case? No! Although you may feel like you're doing work (you may get tired), you're not, because you haven't exerted the force *through a distance* (that is, the distance in this example is simply zero).

Notice that because work is defined as the multiplicative product of force and distance, knowing just the amount of work doesn't tell you whether you pushed with a little force over a long distance, or a lot of force over a short distance --- you can accomplish the same amount of work either way.

Now we can give our first scientific definition of energy:

The *energy* of an object, or of a system, is how much *work* the object or system can do on some other object or system.

In other words, energy measures the *capability* of an object or system to do *work on another* system or object.

Consider a ball flying through the air for example. If the ball collides with another ball, the ball will exert a force on the second ball for a moment, which does work on the second ball and causes it to move. The newly acquired kinetic energy of the second ball after the collision is equal to the amount of work exerted on it by the first ball.

In the example above of pushing a couch, you're able to do work on the couch because your body has a certain amount of **chemical energy** in your body from the food you eat. This chemical energy is released to generate **force** via your muscles, which you then direct to push the couch across floor. The change in your body's stored chemical energy is exactly equal to the work you do on the couch, plus any heat energy generated in your body while you do the work.

There are a number of ways in which a system or object can possess energy, i.e. the capability to do work, and each way corresponds to having a different *form* of energy. The following sections will describe these different forms in more detail. But keep in mind that no matter what the form, energy always means the capability to do work, that is, exert a force through a distance on some object. Sometimes the path to extracting this work from an energy source is difficult and complicated, and compromised by practical considerations involving entropy (discussed in a later section), yet extracting work is always possible in principle.

What are the different forms of energy?

Energy has a number of different forms, all of which measure the ability of an object or system to do work on another object or system.
In other words, there are *different ways* that an object or a system can possess energy.

Here are the different basic forms:

Kinetic Energy:
Consider a baseball flying through the air. The ball is said to have "kinetic energy" by virtue of the fact that its in motion relative to the ground. You can see that it is has energy because it can do "**work**" on an object on the ground if it collides with it (either by pushing on it and/or damaging it during the collision).

The formula for Kinetic energy, and for some of the other forms of energy described in this section will, is given in a later section of this primer.

Potential Energy:
Consider a book sitting on a table. The book is said to have "potential energy" because if it is nudged off, gravity will accelerate the book, giving the book kinetic energy. Because the Earth's gravity is necessary to create this kinetic energy, and because this gravity depends on the Earth being present, we say that the "Earth-book system" is what really possesses this potential energy, and that this energy is **converted** into kinetic energy as the book falls.

Thermal, or heat energy:
Consider a hot cup of coffee. The coffee is said to possess "thermal energy", or "heat energy" which is really the collective, microscopic, kinetic and potential energy of the molecules in the coffee (the molecules have kinetic energy because they are moving and vibrating, and they have potential energy due their mutual attraction for one another - much the same way that the book and the Earth have potential energy because they attract each other).

Temperature is really a measure of how much thermal energy something has. The higher the temperature, the faster the molecules are moving around and/or vibrating, i.e. the more kinetic and potential energy the molecules have.

Chemical Energy:
Consider the ability of your body to do work. The glucose (blood sugar) in your body is said to have "chemical energy" because the glucose releases

energy when chemically reacted (combusted) with oxygen. Your muscles use this energy to generate mechanical force and also heat. Chemical energy is really a form of *microscopic potential energy*, which exists because of the electric and magnetic forces of attraction exerted between the different parts of each molecule - the same attractive forces involved in thermal vibrations. These parts get rearranged in chemical reactions, releasing or adding to this potential energy.

Electrical Energy:
All matter is made up of atoms, and atoms are made up of smaller particles, called protons (which have positive charge), neutrons (which have neutral charge), and electrons (which are negatively charged). Electrons orbit around the center, or nucleus, of atoms, just like the moon orbits the earth. The nucleus is made up of neutrons and protons.

Some material, particularly metals, have certain electrons that are only loosely attached to their atoms. They can easily be made to move from one atom to another if an electric field is applied to them. When those electrons move among the atoms of matter, a *current* of electricity is created.
This is what happens in a piece of wire when an electric field, or *voltage*, is applied. The electrons pass from atom to atom, pushed by the electric field and by each other (they repel each other because like charges repel), thus creating the electrical current. The measure of how well something conducts electricity is called its *conductivity*, and the reciprocal of conductivity is called the *resistance*.

Copper is used for many wires because it has a lower resistance than many other metals and is easy to use and obtain. Most of the wires in your house are made of copper. Some older homes still use aluminum wiring.

The energy is really transferred by the chain of repulsive interactions between the electrons down the wire - not by the transfer of electrons per se. This is just like the way that water molecules can push on each other and transmit pressure (or force) through a pipe carrying water. At points where a strong resistance is encountered, its harder for the electrons to flow - this creates a "back pressure" in a sense back to the source. This back pressure is what really transmits the energy from whatever is pushing the electrons through the wire. Of course, this applied "pressure" is the "voltage".

As the electrons move through a "resistor" in the circuit, they interact with the atoms in the resistor very strongly, causing the resistor to heat up - hence delivering energy in the form of heat. Or, if the electrons are moving instead through the wound coils of a motor, they instead create a magnetic field, which interacts with other magnets in the motor, and hence turns the motor. In this case the "back pressure" on the electrons, which is necessary

for there to be a transfer of energy from the applied voltage to the motor's shaft, is created by the magnetic fields of the other magnets (back) acting on the electrons - a perfect push-pull arrangement!

Electrochemical Energy:
Consider the energy stored in a battery. Like the example above involving blood sugar, the battery also stores energy in a chemical way. But electricity is also involved, so we say that the battery stores energy "electro-chemically". Another electron chemical device is a "fuel-cell".

Electromagnetic Energy (light):
Consider the energy transmitted to the Earth from the Sun by light (or by any source of light). Light, which is also called "electro-magnetic radiation". Why the fancy term? Because light really can be thought of as oscillating, coupled electric and magnetic fields that travel freely through space (without there having to be charged particles of some kind around).
It turns out that light may *also* be thought of as little packets of energy called *photons* (that is, as particles, instead of waves). The word "photon" derives from the word "photo", which means "light".

Photons are created when electrons jump to lower energy levels in atoms, and absorbed when electrons jump to higher levels. Photons are also created when a charged particle, such as an electron or proton, is accelerated, as for example happens in a radio transmitter antenna.

But because light can also be described as waves, in addition to being a packet of energy, each photon also has a specific frequency and wavelength associated with it, which depends on how much energy the photon has (because of this weird duality - waves and particles at the same time - people sometimes call particles like photons "wavicles"). The lower the energy, the longer the wavelength and lower the frequency, and vice versa.

The reason that sunlight can hurt your skin or your eyes is because it contains "ultraviolet light", which consists of high energy photons. These photons have short wavelength and high frequency, and pack enough energy in each photon to cause physical damage to your skin if they get past the outer layer of skin or the lens in your eye. Radio waves, and the radiant heat you feel at a distance from a campfire, for example, are also forms of electro-magnetic radiation, or light, except that they consist of low energy photons (long wavelength and high frequencies - in the infrared band and lower) that your eyes can't perceive. This was a great discovery of the nineteenth century - that radio waves, x-rays, and gamma-rays, are just forms of light, and that light is electro-magnetic waves.

Sound Energy:
Sound waves are compression waves associated with the potential and kinetic energy of air molecules. When an object moves quickly, for example the head of drum, it compresses the air nearby, giving that air potential energy. That air then expands, transforming the potential energy into kinetic energy (moving air). The moving air then pushes on and compresses other air, and so on down the chain. A nice way to think of sound waves is as "shimmering air".

Nuclear Energy:
The Sun, nuclear reactors, and the interior of the Earth, all have "nuclear reactions" as the source of their energy, that is, reactions that involve changes in the structure of the nuclei of atoms.

In the Sun, hydrogen nuclei fuse (combine) together to make helium nuclei, in a process called **fusion**, which releases energy. In a nuclear reactor, or in the interior of the Earth, Uranium nuclei (and certain other heavy elements in the Earth's interior) split apart, in a process called **fission**. If this didn't happen, the Earth's interior would have long gone cold!

The energy released by fission and fusion is not just a product of the potential energy released by rearranging the nuclei. **In fact, in both cases, fusion or fission, some of the *matter* making up the nuclei is actually converted into *energy*. How can this be?** The answer is that ***matter itself is a form of energy!*** This concept involves one of the most famous formula's in physics, the formula,

$$E=mc^2.$$

This formula was discovered by Einstein as part of his "Theory of Special Relativity". In simple words, this formula means:

The energy intrinsically stored in a piece of matter at rest equals its mass times the speed of light squared.

When we plug numbers in this equation, we find that there is actually an incredibly huge amount of energy stored in even little pieces of matter (the speed of light squared is a very very large number!). For example, it would cost more than a million dollars to buy the energy stored intrinsically stored in a single penny at our current (relatively cheap!) electricity rates. To get some feeling for how much energy is really there, consider that nuclear weapons only release a small fraction of the "intrinsic" energy of their components.

What are the properties of energy?

So far, we have learned that energy is a measure of the capability of an object or system to do work, and we have also learned about the basic different forms of energy.

But these concepts *still* don't quite do justice to the full concept of energy, for energy has a number of very special additional properties we have not fully discussed yet. If you think about these carefully, and don't take them for granted, you'll realize that they don't follow from simple intuition. Rather, these properties had to be discovered or proven somehow. We'll explore briefly how these properties were proven in the next section. In this section, we'll first review them:

These properties are;

1. **Energy can be transferred from one object or system to another through the interaction of forces between the objects** (unlike the condition of, say, being the color red, which is intrinsic to the object in question).
2. **Energy comes in multiple forms: kinetic, potential, thermal (heat), chemical, electromagnetic, and nuclear energy.** (as discussed in the previous section)**.**
3. **In principle, energy can be converted from any one of these forms into any other, and vice versa, limited in practice only by the Second Law of Thermodynamics** (we discuss the Second Law, that is "entropy", in a later section)**.**
4. **Energy is always conserved, that is, it is never created anew or destroyed - this is called the First Law of Thermodynamics.** Thus, when an object does work on another object, the energy can only be converted and/or transferred, but never lost or generated anew. In a sense, energy is like perfect money - transferred but always preserved, assuming no inflation or deflation!

Although most people are aware of these facts nowadays and take them for granted, these are really amazing properties if you stop and think about them. How was anyone ever able to prove such properties? These properties go far beyond the intuitive concept of energy given at the beginning of this primer.

You may find this hard to see now, because we generally take these ideas for granted. But for thousands of years, people didn't have a clearly defined concept of energy, and didn't know, for example, that there is a definition of "energy" which refers to a quantity that is always conserved.

Moreover, even after kinetic energy and potential energy became understood, it still took people *centuries* to figure out that heat is just another form of energy.

Before our present understanding of physics evolved, it was still a logical possibility that the Universe might have been constructed quite differently, such that energy, in the sense of power to modify the world, would not have been conserved and/or things in even everyday life might have been controlled by some kind of supernatural beings.

We can now see easily that such a world would likely look very different from our own, because the basic properties of energy are actually responsible for "constraining" many aspects of our world: Everything from the branching structures of trees to the way that our bodies and the planets move are all strongly constrained by the properties of energy.

How was energy defined and discovered in the first place?

To explore this question, we'll consider the ***six most basic forms of energy*** in a *little* more detail. These are:

- **Kinetic Energy**
- **Potential Energy**
- **Thermal (Heat) Energy**
- **Chemical Energy**
- **Electromagnetic Radiation (Light)**
- **Nuclear Energy**

In the process, we will hopefully shed a little more light on how energy is defined, and how these concepts were discovered by humans.

The Discovery of *Mechanical Energy* (the kinetic and potential energy of ordinary objects):

As described in the previous section on the various forms of energy, **kinetic energy is the energy an object possesses by virtue of its motion.** Anything that is moving or rotating possesses kinetic energy. The faster an object moves or rotates, the greater its kinetic energy. **But how do we define kinetic energy mathematically, as something we can quantify?** Well, for a simple particle of mass **m** (say, measured in kilograms) moving with some particular velocity **v** (say, in meters per second), the kinetic energy is defined as one-half of the particles mass times the square of its velocity (actually the magnitude of its velocity, its "speed", but we won't be pedantic here),

$$\mathbf{E_{kinetic} = (1/2)\ m\ v^2.}$$

To see first how this formula "behaves", note from the formula that if either the velocity or the mass is zero, then the kinetic energy must be zero, and that if neither are zero, the kinetic energy will be larger if either the mass or velocity is increased (assuming both are nonzero to begin with). Intuitively, you can think of kinetic energy as a measure of the work (or damage!) that something can do if it collides with something else; the larger the speed and/or the larger the mass, the larger the kinetic energy, and thus the greater the impact.

Below, after we define "potential energy", we'll discuss how the formula above was discovered. But for the moment, notice just the following obvious thing again: Kinetic energy is defined by a *specific formula*. This formula was discovered by people who were trying to describe the behavior

of the world with mathematical language; kinetic energy is not an intuitive, or vague, or mystical concept. This is true for all the forms of energy that we discuss here --- they have precise mathematical definitions and meanings. Energy can be *quantified*.

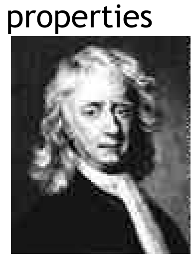
Potential energy, like kinetic energy, is also a measure of the work an object or system can exert on another object or system. Imagine a book falling off a table and crushing an egg. This is work being done to the egg by the book (pretty messy!) This potential work is a consequence of the position of the book relative to the floor.

More specifically, it is the force of gravity that accelerates the book, giving it kinetic energy. So, as we noted in a previous section, because gravity, and hence the Earth, is a crucial component, the potential energy is really a condition of the *book-Earth system*.

So how do we *define* potential energy in this case? For the book sitting on the table, its potential energy is defined as the mass of the book times the acceleration of gravity **g** (which is about 10 meters per second squared at Earth's surface), and also times the height **h** of the table,

$$E_{potential} = m\ g\ h.$$

Again, as for kinetic energy, we see that there is a well defined mathematical formula that defines potential energy.
So, how then did people actually come up with these formula's for the kinetic and potential energies, and how did they prove the various special properties of energy? **Amazingly, it took many people lots of hard work over at least a millennium to overcome various misconceptions and to discover the simple formulas above. First, some people, most notably Galileo Galilei and Isaac Newton (Newton's picture appears at right), gradually figured out how forces are related to acceleration --- this information is summed up by Isaac Newton's famous Laws of Motion**, which we list here for completeness:



Newton's Laws of Motion:

1. An object at rest will remain at rest and an object in motion will remain in motion at constant velocity unless acted upon by a net force.
2. The net force on an object is equal to its mass times its acceleration (F=ma).
3. For every action there is an equal and opposite reaction.

Although most people are now familiar with these laws, they're really not all that obvious. The philosopher Aristotle, for example, wrote that all objects eventually come to a natural state of rest. From a practical point of view, he was correct, because most objects in our human experience do just that, they eventually stop, because they are subject to forces, such as friction with the air, and these forces generally bring objects in motion to rest with respect to the ground.

But this observation hid something deeper - that is, the crucial and not so obvious fact that objects *not* subject to interactions with other objects will simply keep moving unchanged. The world had to wait until Galileo, many centuries after Aristotle, to finally grasp this fact. Why was it so hard? Because its an *abstract* notion - in the real world, its impossible to completely turn off the interactions.

To analyze the consequences of these laws, Isaac Newton and Gottfried Liebniz both developed (independently) the body of mathematical techniques known as the calculus and applied it to analyze these laws. In the course of this analysis, they, and many people who followed them, found that **it was *extremely useful to formalize certain combinations of variables with special names that we now identify with the various different forms of energy*.**

Thus, to give a short answer, (mechanical) energy was "discovered" in the course of mathematically analyzing the equations derived from Newton's Laws.
More specifically, this was possible because it was found that Newton's Laws led, with the application of calculus, to formulas in which the parameter of time did not appear *explicitly*.

To see a concrete example, and how the particular names for various forms of energy arose, consider again a simple mass m, such as book, which finds itself in Earth's gravitational field. We'll ignore air friction, to keep things really simple. Knowing ahead of time the definitions of kinetic and potential energy (which is really cheating!), we can add up the potential and kinetic energy as defined above, to get the total energy:

$$\textbf{Total Energy} = \textbf{Potential Energy} + \textbf{Kinetic Energy}$$
$$= m\,g\,h + 1/2\,m\,v^2.$$

(We read this as follows: "Energy equals mass times the acceleration of gravity times height, plus one-half the mass times velocity squared". Note that the multiplications are not indicated *explicitly* with an "x" - they are simply implied by the notation. Only the addition operation is noted explicitly: This convention makes the notation much simpler)

This is in fact a correct formula to calculate the total energy of the book at any moment. ***But what happened historically, before anybody knew how to define "energy", is that this equation was derived by "integrating" Newton's First Law (F=ma)***. "Integrating" is the fundamental process of calculus.

For those who want to see how this works in detail, we offer two options:

- A non-calculus derivation : See Appendix I (this requires some rudimentary familiarity with algebra)
- A calculus derivation : See Appendix II (still quite simple)

Surprisingly, as the derivations show, despite the fact that this quantity depends both on h and v, both of which change with time (say, as the book falls), *it was found that this quantity equals a constant - i.e. it doesn't depend explicitly on time* (that is, the variable time doesn't appear explicitly in the equation one gets from Newton's laws that contains the expression for the energy):

Great Discovery! $(m\ g\ h + 1/2\ m\ v^2) = \text{constant}$

Now you might say to yourself "well, of course the energy doesn't contain the time variable, because we didn't include it when we wrote it down!". But this would be incomplete - Remember, we only wrote down the left hand side. How would we know to set this equal to a constant? To show this, we need to derive the complete expression from Newton's equations, and Newton's equations *do* involve time explicitly, so there is no a priori way to know that you would arrive at an expression that didn't!

But, you might say, how can this be? Don't h and v depend on time when the book is falling? And right you would be: What is meant that although the variables h and v both change with time as the book falls under the force of gravity, they both change in *exactly* the right way for the total energy, as given by the formula above, to stay always at the same, constant value!

In other words, h and v don't change in just any arbitrary way. They change exactly together in a way that keeps the energy expression constant.

Amazing you say, but how could this be exactly? Let's look at this more closely to see how it works. Before the book begins to fall, the speed v equals zero, so the kinetic energy is zero, and so the total (initial) energy just equals the initial potential energy:

Initial Energy = m g h, where h = table height.

Suppose that this energy is 5 Joules (the definition of a Joule, a basic unit for energy, is covered in a later section - just accept this term for now). As the book falls, it starts to pick up velocity, and therefore v, and its kinetic energy, begins to increase. But simultaneously, the potential energy of the book begins to decrease because the book's height h starts to decrease.

The mathematical discovery that the total energy is constant tells us that the book falls in exactly such a way that the *sum* of the potential energy and kinetic energy remains exactly equal to 5 Joules. After the book has fallen (say, at the instant just before it hits the floor), its potential energy is now zero (because its height h above the floor equals zero), but the total energy is *still* 5 Joules, and the final kinetic energy is equal to this value:

$$\textbf{Final Energy} = \textbf{Initial Energy} = 1/2\ m\ v^2$$

Because the total energy doesn't change, we infer that the (initial) potential energy must have been completely ***converted*** into the (final) kinetic energy.

Note that the definitions of kinetic energy and potential energy were defined *after* the discovery that such a constant-in-time combination ($m\ g\ h + 1/2\ m\ v^2$) existed. Because there is such a quantity, and *only* because there is such a quantity, does it make sense to break things down and call the combination ($m\ g\ h$) "potential energy", and the other combination ($1/2\ m\ v^2$) "kinetic energy". If you couldn't add these things up into something that stayed constant in time, then these definitions wouldn't be useful! So the definition of energy expressions are "wholistic" in a sense. Finally, people also analyzed these new physics equations to show that when objects interact, i.e. exert forces on each other, then the work exerted by one object on another, defined as

$$\textbf{Work} = \textbf{Force} \times \textbf{Distance},$$

is exactly equal to the loss in energy that the object experiences while doing that work. Likewise, this work is equal to the energy that the object being acted on gains. This discovery is called the "work-energy theorem" in physics texts, and is the fundamental connection between the concepts of energy and work. Moreover, its the reason that energy is *conserved*. Without this, the concept of energy might be interesting, but not very *useful*.

In retrospect, it is really quite amazing that such a constant-in-time combination ($m\ g\ h + 1/2\ m\ v^2$) of the variables h and v even exists in the first place. Is this combination special to the particular case of a mass in Earth's gravitational field? Not all all! It turns out that there are such combinations for all physical phenomena known to us . There are very deep

reasons for why this is so, and these are briefly discussed at the end of this section.

Discovery of Heat:
For more than a century after Newton, people didn't know that heat, which is now known to be the microscopic motion of molecules, was also a form of energy. They suspected instead that maybe it was some kind of substance not related to energy that was contained in things and could flow between things, and was released when things were burned or worn away by friction.

Some people called this supposed substance "caloric fluid". They started to suspect that there was more to the picture when somebody observed that when attempting to bore a cannon, one could grind and grind and make a lot of heat, but not grind away much of the cannon. Thus, it appeared that the "caloric fluid" was endless, and therefore it was hard to see how it could be coming through the material of cannon itself. Rather, it seemed to be produced somehow from the *process* of grinding the cannon.

Finally, an English physicist named James Prescott Joule 1818-1889, through very careful experiments, proved that heat is actually a form of energy by showing how it could come from conversion of other forms of energy, such as mechanical or chemical energy, and that when heat is considered in the calculation of the total energy, the total energy in processes involving heat is conserved.

Discovery of electromagnetic radiation and nuclear energy properties:

We now discuss how electromagnetic radiation (light) and nuclear energy (the so-called "rest-mass" energy of matter) came to be known.

Electromagnetic radiation and rest-mass energy may be thought of as representing two physical extremes of energy in nature. The phrase "rest-mass energy" refers to the *intrinsic* energy that an object has by virtue of its simply having mass, whereas light is a "pure energy state", and has zero "rest-mass". Ordinary objects that have both rest-mass and kinetic energy can be thought of as being in a state somewhere between these two extremes.

We use the phrase "rest-mass", because Einstein's Special Theory of Relativity tells us that the mass of an object is not actually constant, but actually increases with an object's velocity (a strange and wonderful implication of this theory). Here, we are specifically concerned with the relativistic energy that an object has when at rest, hence the term "rest-mass" energy.

Einstein came up with his theory of special relativity when he attempted to explain certain inconsistencies between the theory of electromagnetic waves, which had been developed earlier in the nineteenth century by Faraday, Hemholtz, Maxwell, and others, with the mathematical properties of space and time as implied by Newton's Laws. Newton's Laws implied that all reference frames that only differ by a constant relative velocity should be equivalent, so that the laws of physics should look the same in all of these frames. But the equations for electromagnetic waves seemed to violate this idea.

These inconsistencies were particularly troubling because both Newton's Laws and the electromagnetic theory were by then well grounded in experiment. At the heart of the matter was the experimental finding that the speed of light was apparently independent of an observer's reference frame, which seemed consistent with the electromagnetic theory, but seemed at odds with Newtonian theory. **In the process of resolving this contradiction, Einstein deduced, much to everyone's great and continuing fascination, that *matter itself is a form of energy*, the precise amount of this rest mass energy being given by his famous formula,**

$$\mathbf{E=mc^2,}$$

where m is an object’s mass, and c is the speed of light. As stated in the section on the various forms of energy, this formula tells us that a truly enormous amount of energy is bundled up inside ordinary matter. For example, it would cost over a million dollars to buy the amount of energy from a utility contained in the rest mass of a single penny!
Do we see any of this energy at use in the everyday world? *Yes!* A small fraction of that energy is released in nuclear reactions in nuclear reactors and nuclear weapons. More significantly, **the energy given off by the Sun comes mostly from rest-mass *converted* into energy when hydrogen nuclei in the Sun fuse to form helium nuclei (fusion).**

Einstein's theory should not be viewed as something different from the results deriving from Newton's Laws. Rather, Newton's Laws can be shown to be limiting case when velocities much less than the speed of light are considered. In other words, Einstein actually *extended* Newton's theory to large velocities, but in doing so, he changed our ideas about space and time forever.

Radiation:
Electromagnetic radiation, or light (although only some of it is visible to our eyes) may be thought of as pure form of energy. This includes visible light, the warmth you feel at a distance from a fire, and radio and television waves.

It is valid to think of light as consisting of packets of pure energy, called photons, that travel through space at about 186,282 miles per hour. Again, it is because of Einstein that we know that we can think of light as being the "pure energy state". This is because Einstein's theory also shows clearly that light, although made of discrete packets, has *zero* rest mass.

Electromagnetic radiation is generated, for example, when the electrons in an atom jump to a lower energy level by emitting a photon, or when charged particles are accelerated back and forth in a radio transmitter's antenna.

Historically, the classical theory of light, upon which Einstein's work was largely based, was developed following a long period of research on electricity and magnetism. Initially, light was thought to be little "corpuscules" of energy, as suggested by Newton (for reasons which eventually proved erroneous).

Then, in the nineteenth century, it was shown that light actually corresponds to electromagnetic waves, that is, coupled electric and magnetic fields which propagate in space via a kind of push-pull self-perpetuating manner. This discovery revealed how accelerating charged particles can generated light, and led to the invention of radio, and many other devices.

A little later on, around the turn of the century, however, it was found by Einstein and others that light *also* can be thought of as coming in discrete packets of energy (which we now call photons), as well as waves. The fact that light behaves both as particles and as waves is a strange and difficult to understand conceptual duality which underlies much of the theory of quantum mechanics in modern physics. This duality, in fact, lies at the heart of the deepest mysteries of present day particle physics.

The Reason there is Energy Conservation in our world:
To conclude this section, let us take up the question of just why it is that the equations of physics should have led to the conserved quantity that we call energy in the first place? Is this just an accident? Nowadays, we have a deeper understanding of why there is such a quantity. It turns out that the true reason for such a quantity is the following innocent looking statement:

- *The laws of physics do not change with time*

From this very simple assumption, the principle of conservation of energy can be shown to hold. The first person to fully appreciate this fact was the great mathematician, **Emmy Noether**, who first explained this fact in 1905, the same year that Einstein published his theory of special relativity.

The fact that the invariance, or symmetry of the laws of physics with respect to time could lead to something as concrete and useful as conservation of energy is really quite profound. As Noether showed, basic symmetries lead to many other laws of physics as well. Conservation of momentum, for example, another principle of physics, is a consequence of the fact that the laws of physics do not vary from place to place. Thus, symmetries allow us to derive very powerful "laws of nature" on very general grounds.

How is energy transported from place to place and transferred between objects?

The most obvious and trivial way in which energy is *transported* is when an object that possesses energy simply moves from one place to another. For example, a baseball flying through the air is a simple form of energy transport.

Kinetic energy can also be *transferred* from one object to another when objects collide. This is also pretty trivial, except that we also know that the total energy, including any heat or other forms of energy generated during the collision, is conserved in this process, regardless of the relative sizes, shapes, and materials of the objects.

In general, the important modes of transfer for renewable energy technology are:

- **Light propagation in space**
- **Light propagation in materials:**
  - **Transmission:** ***Transparent or translucent***
  - **Reflection:** ***Coherent or diffuse***
  - **Absorption**
- **Heat propagation in materials and in space:**
  - **Conduction**
  - **Convection**
  - **Radiation**
- **Electrical**

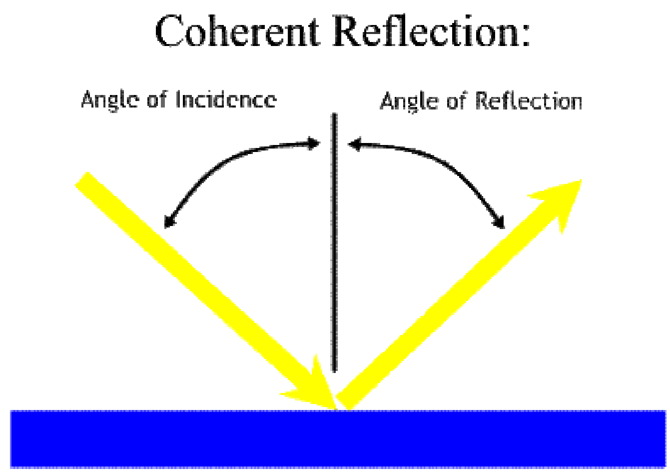
***Note the two "triads" above: (transmission-reflection-absorption & conduction-convection-radiation). You should memorize these and know what they mean!**

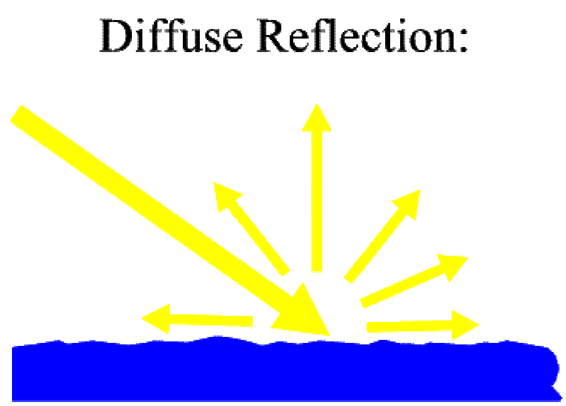
Light

Light (essentially pure energy that can be thought of as either "photons" or electro-magnetic waves) propagates by itself in a vacuum at very high speed (the speed of light that is! Always the same value in a vacuum).

Light interacts with *materials* in various ways that impact its transfer. In general, light is either:
Transmitted: It passes *through* an object - an object is either *transparent* (the light passes straight through), or *translucent* (the light passes through, but its direction "scattered" by the material).

Reflected: The light bounces off. Reflection can either be *coherent* (the angle of incidence equals the angle of reflection) or *diffuse* (the reflected direction is randomly scattered):





Absorbed: The light enters the material but does not pass through - Instead, its energy is converted into the form we call "heat", that is, microscopic vibrations of the material, or is absorbed by chemical reactions triggered by the light (photochemical effect).

Heat

There are three important ways that heat energy can be transported or transferred, called *conduction*, *convection*, *and radiation*. The first two refer to transfer of the thermal energy, whereas the last is really a

conversion **of energy to a different form, (photons of light) and the subsequent travel (transport) of those photons.**

<u>Conduction</u>**: The "diffusion" of thermal energy (heat) through a substance,** which occurs because hotter molecules (those that are vibrating, rotating, or traveling faster), interact with colder molecules, and in the process transfer some of their energy. For example, conduction of thermal energy is what makes the handle of a metal frying pan on the stove get hot, even though the handle is not exposed to the flame. **Metals are excellent conductors of heat energy, whereas things like wood or plastics are not good conductors of heat. Those that are not so good conductors are called insulators.**

The rate H, at which heat conducts through a slab of material across a fixed temperature difference ΔT, for example, from the inside of a warm house to the outside through a wall, **is given by the area A of the surface, times the temperature difference ΔT, divided by the thermal resistance R,**

$$H = (A \ \Delta T) / R.$$

R is also called the "R-factor" of the material. When considering the insulating power of the walls of a house, R is likely to have units of square feet divided by BTUs per hour ($ft^2/(BTU\text{-}hr)$). BTU stands for British Thermal Unit, and is the amount of energy needed to raise the temperature of one pound of water one degree Fahrenheit. Technical discussions involving conduction may also refer to the thermal conductivity K of a material, which is related to the R-factor by

$$R = L / K,$$

where L is the thickness of the material. Thus, if you look up the thermal conductivity of some material, then you can calculate the R value for a slab of that material with thickness L.

<u>Convection:</u> **The transfer of heat energy by the movement of a substance, such as a heated gas or liquid from one place to another. For example, hot air rising to the ceiling is an example of convection (in this case called a convection current).**

<u>Radiation</u>: In general, you are probably familiar with the fact that the word "radiation" applies to both the light waves (photons), and also rays consisting of other subatomic particles, such as electrons (beta rays) and helium nuclei (alpha rays), that are emitted by radioactive materials.

In the context of heat transfer, however, the term "radiation" refers just to light (electro-magnetic waves), and in particular, to the surprising fact that

***all* objects, even those that are in equilibrium (at equal temperature) with their surroundings, continuously emit, or radiate electromagnetic waves (that is, light waves) into their surroundings. The source of this radiation is the thermal energy of the materials, that is, the movement of the object's molecules.**

The amount of light wave radiation radiated by ordinary objects is surprisingly large, even though we usually don't notice it. For example, an object at 70 degrees Fahrenheit (room temperature), radiates about 460 watts per square meter of its surface! If this is true, you might wonder, then why doesn't everything grow cold right away, and why don't we feel this radiation?

In fact, if an object is suddenly placed in outer space, far away from any strong energy input, then the object would indeed grow cold quite rapidly by the radiation process. Normally, however, an object is completely surrounded by other objects of the same temperature (such as by the air itself), and these objects also radiate energy at the same rate. Thus the energy loss from radiation leaving the objects is balanced by the incoming radiation coming from the others. We don't feel the effects of the radiation because of this balance, unless we happen to stand between objects that have different temperature, for example, if we stand next to a wall that was being warmed by the Sun right after the Sun goes down.

To give you a feel for how much the *imbalance* of radiation between objects is in such cases, a temperature difference of about 20 degrees Fahrenheit leads to a *net* radiation transfer from the hotter object to the cooler of about 11 watts per square meter, which is enough to notice, yet still not much compared to the total radiation coming from each object.

As another example, if the sky is cloudy then heat radiating from the ground will largely be absorbed and reradiated back to Earth by the clouds, keeping the air near the surface warm. On a clear night, however, the ground and nearby air can cool very dramatically by radiating out into space, and you will sometimes hear people call this effect "radiation cooling".

The Black-Body spectrum of radiation from objects:
For those that are curious about how to calculate the amount of energy that is radiated, it is interesting to know that the spectrum of light radiated by objects, that is, how much energy is radiated at each frequency, has approximately the same mathematical form for all objects, and thus depends only on the *temperature of the object and not the specific kind of material*.

The spectrum is called the "black-body spectrum", because it is most perfectly exhibited by objects that absorb all the light falling upon them (which means they are perfectly *black* in color). For relatively low temperatures, such as room temperature, most of the black-body spectrum is at long wavelengths of light, that is, in the infrared or longer wavelengths, which are invisible to the human eye, while at high temperatures the spectrum lies at shorter wavelengths, and can become visible if the temperature is very high.

For example, an ordinary object sitting on a desk *appears* not to radiate anything (although it does), because most of its radiation is at wavelengths longer that light waves in the visible range. On the other hand, when an electric stove burner starts to glow red, it does so because it's reaching a temperature at which the black body spectrum is starting to strongly overlap the region of visible light.

It is very interesting to note that the Sun itself is, to a very good approximation, also a black-body radiator, and that the black-body spectrum of the Sun largely lies in the visible because the Sun is so hot. For any temperature, the wavelength at which the blackbody spectrum has its peak is given by "Wien's Displacement Law",

Peak wavelength in micrometers = 2900 / T,

where T is the temperature in Kelvin degrees. For the Sun, which has a surface temperature of about 6000 Kelvin, we find that the Sun's peak wavelength is about .5 micrometers, which corresponds roughly to the color yellow, approximately in the middle of our visible range. Thus, not surprisingly, we find that our eyes are well adapted to the peak wavelengths given off by the Sun!

The *total* amount of energy radiated per second, that is, the total *power* of the radiation, also has a simple formula, which gives the power as a function of the temperature of the body raised to the fourth power,

$$P = s\ e\ A\ T^4.$$

This is called the Stefan - Boltzmann Law. In this equation, the parameter s is called the Stefan-Boltzmann constant, equal to 5.67 x 10-8 watts/(meter2 - degree Kelvin), A is the surface area of the object, and e is the "emissivity" of the object, which ranges for 0 to 1. Because the temperature is raised to the fourth power, then an object with twice the (absolute) temperature of another object will radiate 16 times more strongly!.

Finally, it is interesting to know that this law, along with the form of the black-body spectrum and Wien's Displacement Law above, can be explained only by using the theory of physics called "quantum mechanics", and therefore is actually a very deep result of science.

In fact, quantum mechanics arose during attempts to explain the experimentally measured form of the blackbody spectrum, which contradicted the predictions of Newtonian (classical physics). Newtonian physics actually predicted, absurdly, that objects would radiate at *infinite* power, so people realized that there must be something wrong with Newtonian physics at microscopic scales.

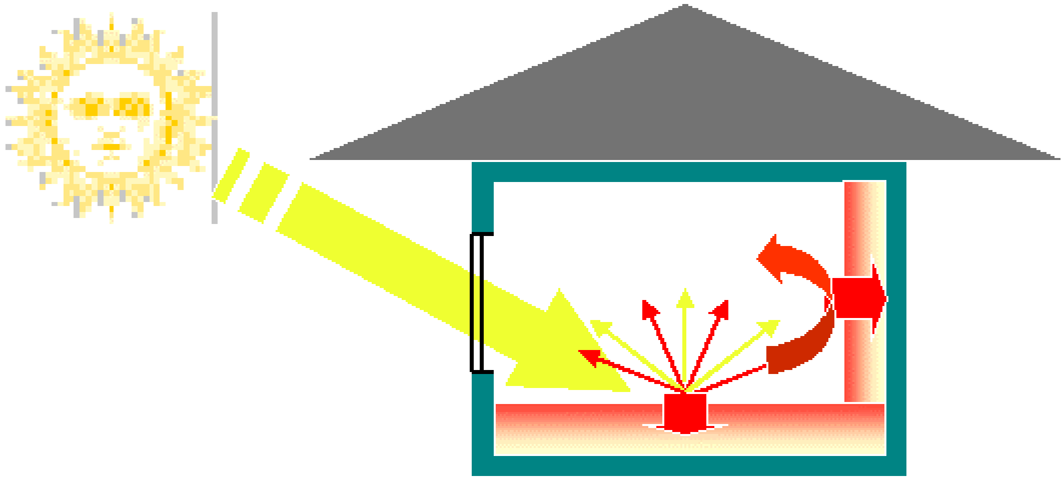
Convection, Conduction, and Radiation, all at once

As a good example of conduction, convection, and radiation, all happening at once, consider sitting by the side of a hot fire, holding a metal rod in the fire with a marsh mellow on it. The rod gets to hot to hold after awhile, because heat conducts down the rod to the handle. Likewise, you can see that there is hot air rising above the fire, carrying smoke. The energy carried by the hot air is an example of convection. Finally, you can feel your face and body get hot from being near the fire. This isn't likely to be because hot air is coming to you from the fire, because the fire is actually drawing air *into* the fire. The heat you feel is actually coming from radiation - that is, the light given off by the fire.

Transmission-Reflection-Absorption & Conduction-Convection-Radiation all at Once

Consider a passive solar home in the winter (see figure below):

- Light *propagates* to the window:
- It is *transmitted* through the window (which is either translucent or transparent)
- The light hits the floor and is either *reflected* or *absorbed* (after several reflections, almost all is eventually absorbed. A tiny bit is reflected back out the window!)
- The floor (and other surfaces where the light hits), are heated up by the *absorption* of light.
- Some of this heat *conducts* into the material
- Some of this heat is *re-radiated* (at infrared wavelengths), back into the room.
- Air near the surfaces is heated by this *re-radiation* and by contact (*conduction*) with the wall.
- The heated air rises (*convection*).



Electrical Energy:
Finally, energy can be transferred by electrical transmission. Within a wire this is accomplished through electric fields associated with electrons in the metal wire. The electrons literally push on each other, and convey force through the wire, which thereby transfers energy. For example, the electro-chemical processes in a battery create positive and negative electric charges at the battery contacts that push on, and hence force, the free (moveable) electrons in the wires to move.

Electrical energy is converted to heat when some of the electrons encounter resistance - that is, when the electrons are pushed through materials causing heat, that is, cause the atoms of the material to start vibrating. Alternatively, the movement of electrons may give rise to electric and magnetic fields (such as in coils of a motor), which do work, such as turning the motor shaft.

How is energy converted?

Energy can be converted from one form into another in three basic ways:

1. **Through the action of forces. This category has several important special cases:**
    i. **Gravitational Forces** - when gravity accelerates a falling object, its converts its potential energy to kinetic energy. Likewise, when an object is lifted the gravitational field stores the energy exerted by the lifter as potential energy in the earth-object system.
    ii. **Electric and Magnetic Force Fields** - Charged particles, upon which electrical fields exert forces, possess potential energy in the presence of an electric field in a way similar to that of an object in a gravitational field. These force fields can accelerate particles, converting a particle's potential energy into kinetic energy. Likewise, charged particles can interact via the electric and magnetic fields they create, transferring energy between them, and in the case of an electrical current in a conductor, cause molecules to vibrate, i.e. converting electrical potential energy into heat.
    iii. **Frictional Forces -** The macroscopic (large-scale) energy of an object, that is, the potential and kinetic energy associated with the position, orientation, or motion of the *entire* object, *not* counting the thermal or heat energy of the system, can be converted into thermal energy (heat), whenever the object *slides* against another object. The sliding causes the molecules on the surfaces of contact to interact via electromagnetic fields with one another and start vibrating.
2. **When atoms absorb or emit photons of light.** When light falls on an object, an incident photon may either pass through the object, be reflected by the object, or be absorbed by the atoms making up the object. If most of the photons pass through, the object is said to be ***transparent***. Depending on the smoothness of the surface on the scale of the photon's wavelength, the reflection may be either ***diffuse*** (rough surface) or ***coherent*** (smooth surface).

    If the photon is absorbed, the photon's energy may also be split up and converted in the following ways:

    i. **photothermal effect:** the energy absorbed may simply produce thermal energy, or heat in the object. In this case the photon's energy is converted into vibrations of the molecules called ***phonons,*** which is actually heat energy.

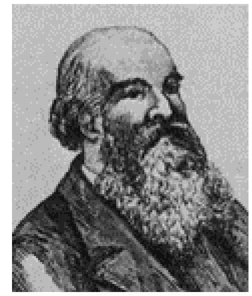
ii. **photoelectric effect:** the energy absorbed may be converted into the kinetic energy of conduction electrons, and hence electrical energy.

iii. **photochemical effect:** the energy may bring about chemical changes which effectively store the energy.

3. **When nuclear reactions occur**, that is, when there are rearrangements of the subatomic particles that make up the nuclei of atoms. There are two basic types: **Fusion** - when nuclei combine, and **Fission** - when nuclei split apart.

How is electrical energy measured, and how well does the Sun provide?

Electrical Units of Energy



In the so-called "International System of Units", which are based on metric units, and which form the basis for the electrical units we use, both work and energy have the same unit, called the "Joule". "Joule" sounds the same way as the word "jewel" (as in diamonds and emeralds). The Joule is named after the English physicist James Prescott Joule (pictured at right) who lived from 1818 to 1889. Joule played an important role in generalizing the notions of mechanical energy that followed from Newton's Laws. In particular, he showed that heat is a type of energy.

To understand the definition of a Joule, we first have to understand a definition of the unit of force used in the International System of units, which is called the "Newton", after the English physicist Isaac Newton. A Newton of force is defined to be the force that can accelerate a mass of 1 kilogram (about 2.205 lbs), such that it picks up 1 meter per second of velocity during each second that the force is exerted. Thus, after one second, the 1 kilogram mass is going 1 meter per second, after two seconds, 2 meters per second, and so on.

Now recall that "work" is defined as force times distance (see the first section of this primer - "What is energy?"), and also that energy has the same units as work. **A Joule is the amount of energy we expend as work if we exert a force of 1 Newton of Force over a distance of one meter.** Intuitively, 1 Joule is about how much energy it takes to lift 1 lb about 9 inches.
When we talk about powering appliances in our home with electricity, we are not usually interested in how much energy an appliance uses per se, but rather the *rate* of energy use, or in other words, how much energy *per unit time* the appliance draws. This quantity is called the "power":

Power = Energy / Time

In particular, for electrical power we use the "Watt" (named after the scientist James Watt):

1 Watt = 1 Joule / Second.

It is important not to confuse power and energy, although they are closely related. Just remember that power is the ***rate*** at which energy is delivered, not an amount of energy itself. With simple algebra, can turn the formula above for power around to solve for energy instead, and write:

Energy = Power x Time.

For example, using the definition of the word watt given above, a 100 watt light bulb is a device that converts 100 joules of electrical energy into 100 joules of electromagnetic radiation (light) every second. **If you leave a 100 watt light on for one hour, that is, 3600 seconds, then the total energy you used was:**

Energy = Power x Time
= (100 Joules/Second) x (3600 Seconds)
= 360,000 Joules

Watts are a very convenient unit when working with appliances, for example, for specifying the power of light bulbs. But there are also times when you are interested in the total energy use, for example, when you are calculating how much your utility bill is going to be. You can see that its not so convenient to work with Joules to specify total energy use in practical situations, because you get such large numbers, like the 360,000 Joules figure above. So, when it comes to working with total *energy* use (as opposed to the *power* you need to run something), people like work with another unit, called the "kilo-watt hour":

1 kilo-watt hour = the energy delivered by 1000 watts of power over a one hour time period.

This is the amount of energy you would use to run a typical hair dryer for one hour. To see how many Joules this is, we calculate:

Energy = Power x Time
= (1000 Joules/Second) x (3600 Seconds)
= 3,600,000 Joules = 3.6 million Joules!

That's a lot of Joules! So you see that kilo-watt hours is a much better unit for large amounts of energy.

To give you a feeling for how much power the Sun provides, consider that on a sunny day, at solar noon, the sunlight at the surface of the Earth delivers about 1000 watts (one kilowatt) per square meter. A typical photovoltaic solar cell can convert about 15% of this to electricity, that is, about 150 watts (the best cells in the laboratory can go somewhat higher, up to about 34%, or 340 watts).

Now lets ask how much power you would need to power your home. Assuming 15% percent efficient solar cells (so that we can capture 150 watts per square meter when the sun is shining), the total power will be given by:

Power = (Area of solar panels) x 150 watts/m^2

Plugging this into the formula above for energy, and the hours of sunlight for the time, we find:

Energy generated per day = (Area of solar panels) x 150 watts/m^2 x (hours of sunlight)

Assuming that the energy generated per day is equal to the energy used per day, and solving for the Area, we find:

Area of panels required = (Energy used per day)/(150 watts/m^2 x (hours of sunlight))

US residences presently use about 14 kilo-watt-hours of electrical energy a day on average (which is probably unnecessarily high and could be easily lowered by switching to more efficient appliances). Suppose you have five good hours of sunlight during the day. Then, using the formula above, **the area in solar panels you would need to obtain the average household draw of 14 kilo-watt-hours per day would be:**

Area needed = 14,000 watt-hours / (150 watts/m^2 x 5 hours)
= 18.6 square meters = 200 square feet

It can be seen that this figure is an area of 10 feet by 20 feet, much less than the roof area of a typical house. Therefore, the Sun provides ample power for household electricity!

Amps and Volts

Finally, some people may wonder about how **amps and volts** fit into all this. **Voltage**, measures how much electrical energy is delivered if a certain charge, that is, a certain number of electrons, are transmitted through a circuit. In other words, it tells you that such and such an amount of energy will be delivered if such and such a number of electrons pass through the circuit. The number of electrons is measured with the unit of a **Coulomb**, which consists of 1.6×10^{19} electrons.

Amps are a measure of how many coulombs *per second* are being transmitted, which is call the **current**. Thus, a current of one amp in a wire means exactly 1.6×10^{19} electrons per second are flowing past any given point in the wire.

A voltage of 1 volt means that 1 joule of energy will be delivered for each coulomb of charge that flows through the circuit. A voltage of 2 volts means that 2 joules of energy will be delivered for each coulomb, and so one. Since current is the number of coulombs per second, and power is the number of joules per second (watts), we see that:

Power (in watts) = Joules/Second
= (Joules/Coulomb) x (Coulomb/Second)
= volts x amps
= number of Watts

Suppose now, for example, that we want to know how much current, in amps, that a hair dryer draws. Suppose that the hair dryer is rated to draw 1100 watts of power. In a typical house with alternating current (say, from a utility line) the power outlets in the wall supply 110 volts (at least in the USA). By turning the formula above around to solve for amps, we see that a 1100 watt hair dryer draws about:

amps = Power / volts = 1100 watts / 110 volts = 10 amps.

If the fuse for the outlet limits the amperage to about 15 amps (fuses are rated by the maximum current that can flow through them), then we see that if we plugged two of these hair dryers in at the same time, they would together draw 20 amps, and the fuse would blow!

How is thermal (heat) energy measured, and how well does the Sun provide?

The basic unit for thermal energy in home heating applications is the "therm", which is defined to be 100,000 BTU's:

1 therm = 100,000 BTUs

BTU stands for British Thermal Unit and is the amount of energy required to raise the temperature of 1 lb of water one degree Fahrenheit. Intuitively, you can think of a BTU as approximately equivalent to the heat given off by burning one match head.

A BTU is equivalent to1055 Joules, and from this you can calculate that a therm is about 105,500,000, or 105.5 million Joules!

To get a feeling for how much energy a therm is, a home furnace is typically rated at somewhere around one therm per hour.

Typical annual heating loads, for a house with 1,800 ft^2, as calculated from the Book "Homegrown Sundwellings," by Peter Van Dresser, 1977 (a great book now out of print), are:

- **Phoenix, Arizona: 389 therms**
- **Santa Fe, New Mexico, 1,444 therms**
- **Great Falls, Montana: 1,728 therms**

It is very interesting to compare this with the annual "insolation" (energy from the Sun - not to confused with insulation, which measures resistance to heat flow) falling on the same surface area:

- **Phoenix, Arizona: 12,600 therms**
- **Santa Fe, New Mexico, 12,110 therms**
- **Great Falls, Montana: 8,870 therms**

It can be seen that there is abundant solar energy for heating homes, even in Montana. Thus, we see that a home in Santa Fe should be designed to capture about 10% of the available insolation, and the homes in Phoenix and Montana should capture less and more, respectively. The art to building a home to capture just the right amount of this energy without overheating is called *passive solar design*.

What is entropy?

The word entropy is sometimes confused with energy. Although they are related quantities, they are distinct.

As described in previous sections, *energy* measures the capability of an object or system to do work.

***Entropy*, on the other hand, *is a measure of the "disorder" of a system*. What "disorder refers to is really the *number of different microscopic states a system can be in*, given that the system has a particular fixed composition, volume, energy, pressure, and temperature. By "microscopic states", we mean the exact states of all the molecules making up the system.**

The idea here is that just knowing the composition, volume, energy, pressure, and temperature doesn't tell you very much about the exact state of each molecule making up the system. For even a very small piece of matter, there can be trillions of different microscopic states, all of which correspond to the sample having the same composition, volume, energy, pressure, and temperature. But you don’t know exactly which one the system is in at any given moment - and that turns out to be important.

Why should it be important, after all, if you know the bulk properties. Isn't that all one usually needs? It turns out that no, in fact if you want to, say, exact energy from say steam and convert it to useful work, those details turn out to be crucial! (More on this below).

For those that are technically inclined, the exact definition is

Entropy = (Boltzmann's constant k) x logarithm of number of possible states
= k log(N).

Since the logarithm of a number always increases as the number increases, we see that the more possible states that the system can be in (given that it has a particular volume, energy, pressure, and temperature), then the greater the entropy.

Again, because we can't see which particular microscopic state a system is in, people often like to say that entropy is quantitative measure of how *uncertain* or *ignorant* one is about the exact, detailed, microscopic state of a system. Or, another popular way of saying this is that entropy measures the microscopic *disorder* of a system.

As a simple example, suppose that you put a marble in a large box, and shook the box around, and you didn't look inside afterwards. Then the marble could be anywhere in the box. Because the box is *large*, there are many possible places inside the box that the marble could be, so the marble in the box has a *high* entropy.

Now suppose you put the marble in a tiny box and shake up the box. Now, even though you shook the box, you pretty much know where the marble is, because the box is *small*. In this case we say that the marble in the box has *low* entropy.

The same idea applies to the arrangements of atoms of a gas in a jar at room temperature. The smaller the jar, the lower the entropy. But keep in mind that we also have to consider the *velocities* of the gas particles to have full knowledge of their states. The higher the temperature of the gas, the faster the gas particles are moving on average, so the wider the range of possible velocities for the gas particles, and hence, the more uncertainty we have about the velocity of any particular particle. Thus, higher temperature, as well as greater volume, mean higher entropy.

Scientists say that entropy, like energy, volume, temperature, and pressure, is another *thermodynamic state variable* of a system. It turns out that, for a simple system, if you know any two of these state variables, then the others are all determined. Although the word entropy might seem like a mysterious concept, its really not. Remember that its really just a measure of the number states a system can be in, given the constraints on the system.

What is entropy good for? Knowing the entropy of a system can tell us many things about what can and can't happen. In particular, it's the basis for the **second law of thermodynamics: the Universe evolves such that its total entropy always stays the same or increases (The first law of thermodynamics is conservation of energy).**

Why is this so? In fact, the basic idea of entropy is simple to understand. Suppose you are floating out in space and you have a jar containing a particular gas, say argon. When you open the jar for a moment, the argon will almost certainly escape out into space. After the argon has escaped, its entropy is greatly increased (and it continues to increase as the gas expands). How do I know that the entropy increased? This is because the number of states that the argon gas can be in when it occupies a much larger volume is much greater than when its confined to the jar. So, the entropy of the gas increases when the argon escapes.

But why must the argon escape? Well, in fact, prior to opening the jar, if you arranged the microscopic states of the argon molecules in just the right way, you could open the jar for a moment and *not* have the argon escape. The point is that it is highly *improbable* that the argon is in one of these special non-escaping states when you open the jar - most of the states lead to the gas escaping.

This is really the content of the second law - that if you begin not knowing the microscopic state of a system, then the system is more than likely to evolve to state where you are even *more* ignorant of its exact microscopic state. Just knowing the thermodynamic state variables of a system, such as its temperature and pressure, means you are in fact ignorant about the initial exact microscopic state - all you can know from the state variables is the number of possible microscopic states it can be in, i.e. the entropy. Hence, for most situations we encounter, chances are that entropy will increase with time.

It is very interesting to compare the behavior of entropy compared to energy. Unlike energy, entropy *can* be created (but not generally destroyed). In fact, your body is creating some right now as it generates heat.

One of the reasons that your body temperature has to be higher than the surrounding air, or that you have to sweat off water if it isn't, is that you have to get rid of the extra entropy (otherwise, you would become disorganized and eventually die). The energy that your warm body radiates carries away the extra entropy. It does this because losing this energy decreases the number of microscopic states that the atoms and molecules of your body can be in. Another practical example of entropy is the following. Suppose we want to use a source of heat, say, from steam generated by heating water, to drive some kind of turbine. Then, it turns out, by considering entropy, that the maximum efficiency of our process will be less than 100%. The reason that this is so is because when heat is brought into the turbine, it carries with it some entropy.

We can't keep this entropy in the turbine, because the turbine would become microscopically disordered and eventually break. So, some heat energy has to be released to the outside world to get rid of this entropy to protect the turbine. The heat released for this purpose therefore can't be converted into work (otherwise it wouldn't be available anymore to release as heat). We get rid of the unwanted entropy by rejecting this heat to the outside world at a lower temperature than we brought the heat in at. The reason for the lower temperature is that the heat released into a low temperature environment carries out more entropy from the turbine than the entropy this same amount of heat carries into the turbine at a high temperature. This is because heat disrupts a cold system more than a hot one, because the hot one is already more disordered. Thus, we must only sacrifice some of the heat carried into the turbine to get rid of the entropy imported into the turbine by that heat in the first place.

One can see from this discussion, however, why power plants need a cold temperature environment to dump their waste heat.

Now this all might seem a little too abstract. Here's another way to look at it: The kinetic energy of the steam molecules is large (because the steam is hot), but the directions of the molecules are disordered. Somehow, to convert all of the energy of the steam into useful work, you'd have to line them all up in the same direction (at least, say, one at a time or in groups). But you're ignorant of the exact configuration at any given instant, right? And even if you weren't, how are you going to get in there and actually do it for each molecule? Clearly, the microscopic disorder is a barrier. This shows why being ignorant of those details might seem minor intuitively, but actually has real consequences for real things you would like to do!

This example above demonstrates how heat energy, because it can't be *completely* converted to mechanical energy in a turbine, is, in a sense, of *lesser quality* than mechanical energy. People have in fact rated the quality of energy in this sense for many different sources. Solar electric energy captured by photovoltaic cells, in particular, is energy of very high "quality". Virtually all of it can be converted to mechanical energy.

Entropy can also be applied to many other situations. For example, it can be used to predict the direction that a chemical reaction will proceed in.

Photosynthesis

It is important to realize that we are everywhere surrounded by solar collectors - plants! Plants convert solar energy into chemical energy by photosynthesis, that is, by absorbing carbon dioxide (CO_2) which they combine with water (H_2O) and energy from sunlight to produce oxygen (O_2) (thereby supplying *us* with oxygen), and combustible sugars, which are made of carbon and hydrogen.

The efficiency of photosynthesis is not so great - roughly about .3 %, or about 3 watts per square meter. However, over half a billion years, this has resulted in the huge deposits of fossil fuels we are presently dependent on.
To learn more about photosynthesis, a good place to start is the Arizona State University Photosynthesis program website:
http://photoscience.la.asu.edu/photosyn/default.html

Appendix I: Non-Calculus Derivation for Potential Energy

Because the acceleration is constant, when we drop the book, it begins to fall (downwards) and its velocity increases (in the negative direction, if up is defined as the positive direction) in a simple linear way with time:

$v = - g t$

In other words, the velocity's magnitude increases proportionally with time t, and the proportionality constant is simply "g", the acceleration of gravity, by *definition*. For example, given that the acceleration g is about 10 meters per second squared, then after 1 second, the velocity is 10 meters per second, after 2 seconds its 20 meters per second, after 3 seconds its 30 meter per second, and so on.

Thus you can see that this simple formula gives the *instantaneous*, or *momentary* value of the book's velocity at any given time t you choose.

Now, most people are familiar with the notion that "distance equals velocity times time":

Distance = Velocity x Time

So, you might suppose that we could write:

$h = h_{initial} + v t$

Here, we are using "h" for distance, which in this case refers to the "height", or distance of the book above the ground. The symbol "$h_{initial}$" represents the initial height of the book (which is a constant).

This is *almost* correct, but strictly speaking, this formula only holds if the velocity in question is either *constant* (which is not true in our case), or alternatively, its true if we use the *average* velocity v_{avg} that the book had during any particular time *interval* from t=0 till time $t=t_{final}$. Hence we should really write:

$h = h_{initial} + v_{avg} t_{final}$,

where v_{avg} is the average velocity that corresponds to the particular value of t_{final} used.

So how do we calculate v_{avg}? This is the crucial step! (Its exactly here that we really avoid the tools of calculus).

Because the *instantaneous* velocity is given by v = g t (from above), a nice linear relationship, it follows that the *average* velocity v_{avg} for the interval ending at $t=t_{final}$ must equal to the velocity at the *mid-point* of the time interval (at $t = 1/2\ t_{final}$):

$v_{avg} = - g \times (1/2\ t_{final}) = - 1/2\ g\ \ t_{final}$

Putting this back into our formula for h above, we obtain:

$h = h_{initial} + v_{avg}\, t_{final} = h_{initial} + (- 1/2\ g\ \ t_{final}) \times t_{final}$

or,

$h = h_{initial} - 1/2\ g\ (t_{final})^2$

So now we have figured out some really significant - that the books height decreases according to the *square* of the time. This is exactly what always occurs to a position variable for something under *constant* acceleration.

Now you can actually begin to understand the energy equation above, that is, **Total Energy = m g h + 1/2 m v^2 = constant**. Specifically, we know from the equation above that h is related to time squared. But from our earlier equation, we know that v^2 is *also* related to time squared (one's sees this by simply squaring the equation v = g t: $v^2 = g^2\ t^2$). So, it must be that h is related to v^2, as the energy equation suggests.

Now, to actually get the energy equation, we just rearrange our new formula ($h = h_{initial} - 1/2\ g\ (t_{final})^2$), and also a formula relating t_{final} and v, (that is, $v = g\ t_{final}$) to eliminate the explicit appearance of t_{final} in the equation.

First, we move the term containing t_{final} to the left side (for those who want rigor, this is accomplished by *adding* $1/2\ g\ (t_{final})^2$ to both sides). We obtain:

$h + 1/2\ g\ (t_{final})^2 = h_{initial}$

Now note that we have

$v = - g\ t_{final}$

(This is just the formula for the instantaneous velocity, as above, at the particular time t_{final}.)

We can rearrange this to read:

$t_{final} = - v_{avg} / g.$

Substitute this expression into $h + 1/2\ g\ (t_{final})^2 = h_{initial}$, we obtain:

$h + 1/2\ g\ (- v_{avg} / g)^2 = h_{initial}$

We're almost there!

The second term simplifies:

$1/2\ g\ (- v_{avg} / g)^2 = 1/2\ (v_{avg})^2 / g$

(Note that the -1 disappears because it gets squared)

Now our equation now reads:

$h + 1 / 2\ (v_{avg})^2 / g = h_{initial}$

Now we simply multiply both sides through by mg (just the mass times acceleration - a constant), to get

$m\ g\ h + 1/2\ m\ v^2 = m\ g\ h_{initial}$

This is our hard-earned energy equation! Note that the right hand side is a constant - its the initial potential energy (which equals the total potential energy).

Appendix II: Calculus Derivation of Potential Energy

We Integrate Newton's First Law (F=ma) to obtain the expression for energy conservation for a book falling off a table

The force F in this case is constant, F=mg, m being the mass, g being the (constant) acceleration of gravity. So that F=ma is in this case gives:

$mg = - m\, dv/dt$

where v is the velocity (dv/dt being the "derivative" of v with respect to time, which is therefore the acceleration a), and the minus sign comes because gravity is pulling down and we are defining positive velocity as up.

Multiplying both sides by dt, and integrating both sides (choosing the simplest integration limits $v_1 = 0$, $v_2 = v$, $t_1 = 0$, $t_2 = t$) gives:

$mg\, t = - m\, v$

Replacing v with dh/dt (i.e. the vertical coordinate of the book is h - its height off the floor), and multiplying through by dt, we have:

$mg\, t\, dt = - m\, dh$

Integrating again (same limits for t as before, and $h_1 = h_{table}$, $h_2 = h$) we have

$mg\, 1/2\, t^2 = - m\, (h - h_{table})$

From the first integration above (mgt = mv), we obtain $t = - v/g$ (this equation tells us simply that $v = - g\, t$, i.e. the velocity increases downwards linearly with time, as it should under a constant force). Substituting this into the result of the second integration (to eliminate the explicit time dependence), we have

$m\, g\, 1/2\, v^2 / g^2 = - m\, (h - h_{table})$

and multiplying through by g, and adding (m g h) to both sides, this yields our desired result:

$m\, g\, h + 1/2\, m\, v^2 = m\, g\, h_{table}$ (i.e. the energy equals the *initial* potential energy, which is obviously a constant)

Note that what made this all possible was the fact that we could eliminate the explicit time dependence - this is really a deep consequence of the symmetry of physical law with respect to time. If the force had depended on time explicitly, for example, obtaining a constant energy would not generally have been possible.