PEARSON NEW INTERNATIONAL EDITION

# Physics: Concepts and Connections

Art Hobson

Fifth Edition

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Concepts and Connections
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into the system on which work is done. So work is an energy transfer from the system doing the work into the system having work done on it. I'll call this

### The Work-Energy Principle

Work is an energy transfer. Work reduces the energy of the system doing the work and increases the energy of the system on which work is done, both by an amount equal to the work done.[5]

> It takes about 8 solid light-years of lead to stop half the neutrinos emitted in a typical nuclear decay. They move like "greased lightning" through matter.... If you make a fist, there are thousands of neutrinos flying through it right now, because the entire universe is filled with neutrinos.... Another proposal, made tongue-in-cheek, is for a neutrino bomb, a pacifist's favorite weapon. Such a bomb would explode with a whimper and flood the target area with a high flux of neutrinos.... [T]he neutrinos would fly harmlessly through everything.
>
> Heinz Pagels, in *The Cosmic Code*

**How do we know that energy is conserved even in nuclear processes?** Early in the twentieth century, nuclear physicists investigated a form of "radioactive decay" known as beta decay, a process in which a nucleus spontaneously creates an electron and spits it out of the nucleus. This alters the original nucleus. If energy is conserved, the nuclear energy of the original nucleus should equal the nuclear energy of the altered nucleus plus the energy of the ejected electron.

But measurements showed that the energy was larger before than after! Being reluctant to conclude that energy was not conserved, physicists hypothesized that some undetected particle was also ejected along with the electron. It was thought that when this other particle's energy was included, the energies would balance. Although the hypothesized particle had not been detected, it was thought that its energy could be directly measured by surrounding the nucleus with a large cylinder of lead. The unseen particle would surely be slowed down and stopped inside a sufficiently thick cylinder and so deposit its energy in the lead, causing a temperature rise in the lead.

But there was no measurable temperature increase. Perhaps energy was *not* conserved in beta decay. This is where the matter stood from 1914 to 1930. By 1929, some physicists, such as Niels Bohr, were suggesting that energy conservation didn't apply to the nucleus. But others didn't accept this suggestion, and in 1930 Wolfgang Pauli hypothesized that the new particle was so penetrating that it could pass right through the thick lead without depositing any energy and that energy would be found to be conserved once the elusive particle was found.

This set off a search for such a particle. Before long, physicists found other indirect evidence (other than beta decay), and they gave the hypothesized particle a name: "neutrino." It was finally detected directly in 1956. Experiments showed that, as Pauli had predicted, energy was conserved once the neutrino was included in the balance.

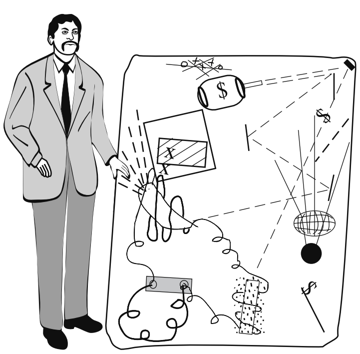

**Figure 9**
"A remarkable device," Farswell Slick remarks. Would you buy a supertranspropulsionizer from this man?

CONCEPT CHECK 12 Farswell Slick (**Figure 9**) invites your investment in a business venture to manufacture his remarkable "supertranspropulsionizer." His diagrams show a dazzling array of superconductors, lasers, liquid-helium coolants, and fancy computers. Slick informs you that this ultimate propulsion system will accelerate spaceships to nearly lightspeed for interstellar travel. Amazingly, no fuel supply is needed, either on board or outside the spaceship. The principle involved, he explains, is "bremsstrahlung superconduction" (BS). With BS, the device operates in a continuous cycle that both accelerates the spaceship and "feeds back" some of its laser light to maintain, for as long as may be desired, the operation of the transpropulsionizer itself. Should you invest?

[5] There is another worklike process by which energy can be transferred, called "heating." Heating is thermal energy transfer due to a temperature difference and can be thought of as microscopic work. When expanded to include not only ordinary work but also heating, the work–energy principle is called "the first law of thermodynamics." We won't need the first law of thermodynamics in what follows.

## 6 TRANSFORMATIONS OF ENERGY

Everything that happens can be described as an energy transformation. This section describes the energy transformations involved in some familiar processes.

Once again, drop your book to the floor (it's coming in for a lot of rough treatment in this chapter!). You've studied this process up until its impact with the floor. Where is the energy after impact? Conservation of energy says it can't just vanish. Going through our eight forms of energy, there's only one plausible candidate: thermal energy. The impact must warm the book or the floor. This temperature rise is hard to detect, but you can demonstrate the same effect by driving a nail into a board with a hard hammer blow. Feel the nail before and after the blow. Try several blows.

We can summarize the energy transformations in the following way:

GravE (at the top) → KinE (just before impact) → ThermE (after impact)

Let's add the effects of air resistance. Since air resistance slows the book, the falling book has less kinetic energy than it did before. But this energy is not lost—you can't lose energy. It must be transformed into thermal energy. The air and book must warm a little as the book falls.

Until the work of Joule and others around 1850, scientists had long believed that the work going into forces such as air resistance and friction, work that produces warming, was lost. Thus, it was believed that energy tended to decrease in most systems, rather than being conserved. The key to uncovering conservation of energy was discovering that warming represented an energy increase in a then-unknown form of energy, namely, thermal energy.

**How do we know that energy is conserved even when thermal energy is involved?** I asserted above that air warms when you stir it with a falling object. James Prescott Joule (Figure 4) did an experiment like this in the 1840s, using water instead of air. He placed a paddle wheel in a tub of water, stirred the water with the paddle wheel, and measured the temperature rise in the water.[6] He quantified the experiment by allowing a falling weight attached to a cord to turn the paddle wheel. The weight's energy loss is then its weight multiplied by the distance fallen. Joule found that the water's temperature rise was precisely proportional to the gravitational energy lost. This showed that the lost gravitational energy went directly into a temperature rise, in other words into thermal energy.

Energy concepts were murky in Joule's day because scientists didn't understand that warmth (thermal energy) actually is a form of energy. Joule clarified matters by showing that work is precisely convertible to thermal energy. This breakthrough showed that the principle of energy conservation extends to processes involving thermal energy, a microscopic form of energy that lies outside of Newtonian physics.

Joule showed that a particular amount of work, about 4200 J, produces a 1°C rise in the temperature of 1 kilogram of water. This amount of energy is the dietitian's **Calorie.**[7] Although the Calorie is often used to measure thermal energy, Joule's work showed that it is really a general energy unit, equivalent to 4200 joules.

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[6] When you stir hot water in open air, the water cools because of evaporation. In Joule's experiment the stirring occurred inside a closed container that prevented evaporation.

[7] The dietitian's Calorie is always spelled with a capital *C*. Physicists use "calorie" (lowercase *c*) to denote the energy needed to raise 1 gram of water by 1°C.

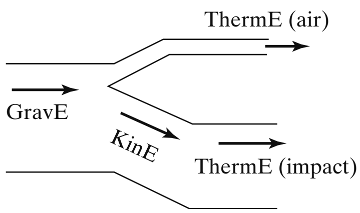


**Figure 10**
Energy flow diagram for a falling book, with air resistance. The "pipe" widths correspond to the amounts of energy involved in various parts of the process. Since energy is conserved, the pipe widths match up at each intersection.

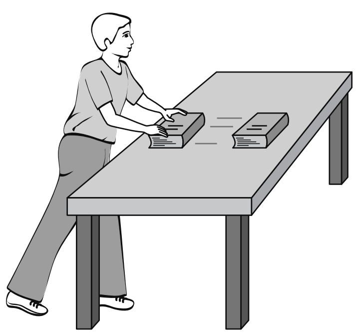

**Figure 11**
What energy transformations occur when you briefly push a book and then let it slide?

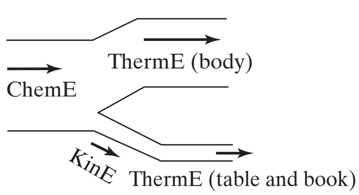


**Figure 12**
Energy flow diagram for a book that is given a quick push and allowed to slide across a surface while coming to rest. The pushing process is very inefficient, with most of the initial chemical energy going into warming your body rather than into the book.

Back to the falling book (it's remarkable what you can learn just by thinking carefully about a falling book): Just before impact, all the energy has been converted to kinetic energy of the book and thermal energy of the air and book. Since air resistance has only a small effect on the motion, thermal energy must form only a small fraction of the total. Finally, the impact converts the pre-impact kinetic energy to thermal energy of the floor and the book.[8]

As a helpful way to visualize energy transformations of all sorts, I'll use **energy flow diagrams.** For example, **Figure 10** shows the energy of the falling book transforming as though it were water flowing through pipes, beginning as gravitational energy, then transforming into kinetic energy and a little thermal energy of the air (note the smaller pipe), and finally transforming entirely to thermal energy. Since energy is conserved, the pipe widths match up at each intersection.

Now give your book a quick hard push so that it slides across your tabletop, sliding to rest (**Figure 11**). Where does the energy come from for this process, and in what form is it? (...Time out, for thinking.)

... It comes from your body, in the form of chemical energy. **Figure 12** shows the energy flow diagram for this process. Most of the initial chemical energy used to push the book turns into thermal energy in your body. The small amount that goes into the book then winds up as thermal energy produced while the book slides to rest. You might have noticed how frequently the various forms of energy transform into thermal energy.

Energy transformations in animals provide many interesting examples. The energy that enables you to do useful work comes from foods and is stored in your body as chemical energy. Dietitians measure this stored chemical energy in Calories. For example, a 70 Calorie slice of bread gives you 70 Calories of stored chemical energy that can then provide 70 Calories of work and thermal energy.

When animal chemical energy is used to do work, only a small fraction actually transforms into useful work. We say that such a process is "inefficient." A "highly efficient" process, on the other hand, is one in which most of the initial, or "input," energy is transformed into useful "output" energy and the wasted fraction is small. Quantitatively, the **energy efficiency** of any energy transformation is the fraction of the input that appears as useful output:

$$\text{energy efficiency} = \frac{\text{useful output energy}}{\text{total input energy}}$$

It is usually expressed as a percentage. The energy efficiency of typical human muscular activities is only about 10%.

Energy being one of this text's four major themes, you will encounter many more energy transformations and energy flow diagrams in future texts.

CONCEPT CHECK 13 The energy transformation during photosynthesis is (a) KinE → ThermE; (b) ThermE → KinE; (c) KinE → ChemE; (d) ElectE → ChemE; (e) RadE → ChemE; (f) ChemE → RadE.

[8] And you can hear the impart. A small fraction of the energy is transformed into the energy of sound, a form of kinetic and elastic energy of the air.

CONCEPT CHECK 14 While a wooden matchstick burns, the energy transformation is (a) ThermE → ElectE + RadE; (b) ElectE → ThermE + RadE; (c) KinE → ChemE + RadE; (d) ChemE → KinE + RadE; (e) ThermE → ChemE + RadE; (f) ChemE → ThermE + RadE.

CONCEPT CHECK 15 Robin Hood shoots an arrow from his bow. Beginning just *before* he draws the bow, the energy transformation is (a) ChemE → ElastE → KinE; (b) ThermE → ElastE → KinE; (c) ElastE → ChemE → KinE; (d) ChemE → KinE → ElastE; (e) ElastE → KinE; (f) ThermE → ElastEly.

## 7 POWER: THE QUICKNESS OF ENERGY TRANSFORMATION

What's the difference between running and walking up a flight of stairs? Your gravitational energy increases by the same amount in both cases. So the work you do is the same. And yet your body knows there's a difference between running and walking upstairs. The difference is that you do the work in less time when you run.

There's a word for this notion of how quickly work is done. It's called **power.** Quantitatively, power is the work done per second—in other words, the work done divided by the time to do it:

$$\text{power} = \frac{\text{work done}}{\text{time to do it}}$$

Because work is an energy transformation, power can be thought of as the rate of transforming energy.

Suppose you run up one flight of stairs and then walk up a second, identical flight of stairs in twice the time it took to run up the first flight. You do the same work for each flight, but your power output during the first flight is double your power output during the second flight. The difference is a power difference, not an energy difference.

The unit of power is the joule per second (J/s). It differs by an all-important "per second" from the unit of work or energy. Power is such a popular concept that its unit is given a special name. The joule per second is called the **watt** (W), in honor of the eighteenth-century developer of the steam engine, James Watt. The kilowatt (kW) is 1000 watts, and the megawatt (MW) is 1 million watts.

Think of several everyday devices: automobile, lightbulb, electric blender, toaster, and so forth. These can be understood as energy transformers; they transform energy from one form to another form that you can use. An important feature is often the rate at which the energy is converted. For example, to get a certain lighting level from a lightbulb, the bulb must convert a certain number of joules per second to visible light. So lightbulbs and other devices must be rated in power units (watts) rather than energy units. A popular power unit for automobile engines and other heat engines is the horsepower, equal to about 750 watts.

**Table 1** gives the power transformed by typical household electrical appliances. The numbers give the power consumed only during the time that the appliance is turned on. Total electric energy consumption, perhaps over one day or over one year, often tells quite a different story. For example, one ordinarily uses a toaster for only a short time each day, so its daily energy consumption is low even though its 1200 W power consumption is high. And refrigerators, although their power consumption

**MAKING ESTIMATES** What's your power output while running up a flight of stairs? If the energy efficiency of this process is 10%, what's your (chemical) power input, in watts and in Calories/second?

can be as low as 300 W, are leading household energy consumers because they operate for so many hours every day.

Although home energy use over the course of a year determines how much energy a power plant must deliver, energy use during so-called peak times has a special impact on the need for new plants. Each electric plant has a maximum power output, its power rating, usually one hundred or more megawatts. The plant's actual power output is largest at times such as hot afternoons when many people are running air conditioners. If the power peak approaches the plant's rating, the plant will cut its output by reducing the supply to all customers, causing lightbulbs and other appliances to dim in a "brownout."

Because industrial societies waste enormous amounts of energy, there are countless opportunities today for electric power companies to save customers' money, enhance company profits, and protect the environment, all with no reduction in services, by finding ways to avoid building expensive new power plants. Pressures

**Table 1**

Power consumption of household appliances while the appliance is turned on and consuming electric energy

| Appliance | Power (W) |
|---|---|
| Cooking range | 12,000 |
| Clothes dryer | 5,000 |
| Water heater | 4,500 |
| Air conditioner, window | 1,600 |
| Microwave oven | 1,400 |
| Dishwasher (incl. hot water) | 1,200 |
| Toaster | 1,200 |
| Hair dryer | 1,000 |
| Refrigerator, frostless | 600 |
| Refrigerator, not frostless | 300 |
| TV, color | 350 |
| Stereo set | 100 |

**SOLUTION TO MAKING ESTIMATES** Suppose that you weigh 500 newtons (110 pounds), the vertical height of one flight of stairs is 4 meters (measure it!), and you run up one flight in 5 seconds (try it!). The work done to lift yourself and the power output are

$$\text{work} = \text{weight} \times \text{height} = 500 \text{ N} \times 4 \text{ m} = 2000 \text{ J}$$
$$\text{power} = \text{work} \div \text{time} = 2000 \text{ J} \div 5 \text{ s} = 400 \text{ W}$$

This is a large power output for a human being, as you will discover if you do the experiment. To produce this output at 10% efficiency, you must convert chemical energy at a rate of 4000 W, or 4000 J/s. In Cal/s (1 Cal = 4200 J), this is $4000/4200 \approx 0.95$ Cal/s, your **metabolic rate** in this example. If you could maintain this rate for an hour (3600 s), you would "burn up" (transform) $3600 \times 0.95 = 3400$ Calories, the energy content of a big steak.

for new plants arise when existing plants can no longer provide the electricity needed during periods of peak demand. Energy-efficient devices can provide the same services (the same amount of light, for example) with less energy. Because such efficiency measures are usually far cheaper than the cost of building new plants, many power companies are actively seeking and providing new energy-efficiency opportunities. For example, because it's usually far cheaper to warm a house with additional insulation than with additional electricity, many power companies provide services and low-cost loans to encourage customers to insulate their homes. Everybody wins: the customer, who gets a warmer home cheaper; the power company, for which the insulation is cheaper than a new plant; and the environment, which benefits from reduced resource consumption and less pollution.

Pricing is another way to reduce the need for new power plants. If electric companies charge higher rates at peak power times, balanced by reduced rates during off-peak periods, people have an incentive to switch their power use from peak to off-peak times. This reduces the need for new power plants, and the resulting financial savings can reduce customers' electrical bills while increasing company profits.

The most useful energy unit for measuring your home's electric energy consumption is the **kilowatt-hour,** the amount of energy transformed when a power of 1 kilowatt operates for 1 hour. Since 1 kilowatt is 1000 joules/second and 1 hour is 3600 seconds,

$$1 \text{ kilowatt-hour} = 1000 \text{ J/s} \times 3600 \text{ s} = 3.6 \times 10^6 \text{ J}$$

If a known power in kilowatts operates for a known number of hours, it's easy to figure the number of kilowatt-hours of energy consumed: Just multiply the number of kilowatts by the number of hours.

Electricity costs about 10 cents per kilowatt-hour. That sounds pretty cheap for 3,600,000 joules. How cheap? For instance, how far could 3,600,000 joules lift a 1000 newton (225 pound) person? Since the work done in lifting an object is the object's weight times the distance through which it's raised, the 3,600,000 J must equal 1000 N times the distance. So the distance is 3,600,000 J divided by 1000 N, or 3600 meters—nearly 12,000 feet! That's a lot of lifting for just a dime. Electricity is phenomenally cheap, and we use a lot of it. The average U.S. household consumes about 1.4 kilowatt-hours of electric energy every hour!

Society's use of energy is a crucial topic today for many reasons, including global warming, pollution, national security, declining energy resources, nuclear power issues, and environmental destruction.

CONCEPT CHECK 16 You press a 500 N weight from your shoulders up to arms' length, a distance of 0.8 m, during a period of 2 seconds. How much work did you do? (a) 800 W. (b) 800 J. (c) 400 W. (d) 400 J. (e) 200 W. (f) 200 J.

CONCEPT CHECK 17 In the preceding question, your power output is (a) 800 W; (b) 800 J; (c) 400 W; (d) 400 J; (e) 200 W; (f) 200 J.