From the **Energy** issue of **Exploring** magazine, Vol.18, No. 4, Winter 1994.
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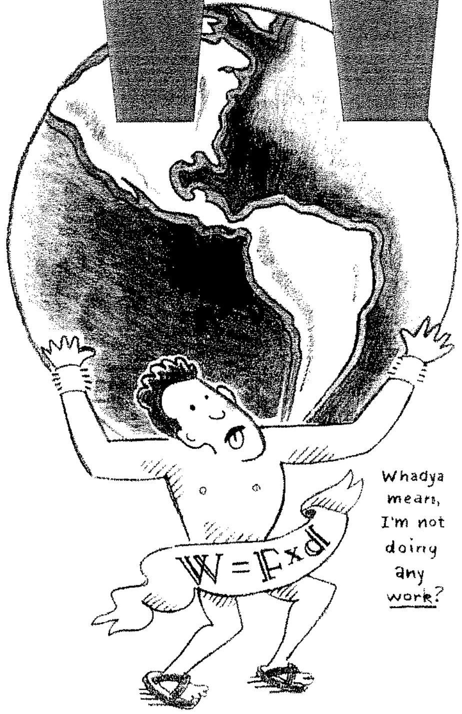
WATT'S A JOULE?

UNDERSTANDING ENERGY AND POWER

BY DON RATHJEN



RAISE ONE HAND AS HIGH OVER YOUR HEAD AS YOU CAN. KEEP IT UP THERE AS YOU READ THIS ARTICLE!

Raising your hand will let you physically experience some of the ideas that physicists hold about energy, work, and power, the subjects I'll be talking about in this article.

Virtually everything you do—whether physical or mental, by hand or by machine, active or sedentary—involves energy. To a physicist, life is really a complex series of energy transactions, in which energy is transformed from one form to another or transferred from one object to another.

Take, for example, an apple tree. The tree absorbs light energy from sunlight, converting the light energy into chemical potential energy stored in chemical bonds. The tree uses this energy to build leaves and branches and fruit. When an apple falls from the tree to the ground, its energy of position (stored as gravitational potential energy) is converted to kinetic energy, the energy of motion, as it falls. When the apple hits the ground, kinetic energy is transformed into heat energy. When you eat the apple, your body converts its chemical energy into the movement of your muscles. If your muscles are tired, and you decide to drive your car instead of walking, the engine of your car takes gasoline (which contains chemical energy stored long ago by plants) and converts it into heat. Then it takes that heat and converts it into motion, or kinetic energy.

So far I've used the word *energy* a bundle of times. What is energy? Unfortunately, it isn't really that easy to define. So we'll have to talk a bit more before we can get a handle on it.

HEY, HOW'S YOUR ARM?

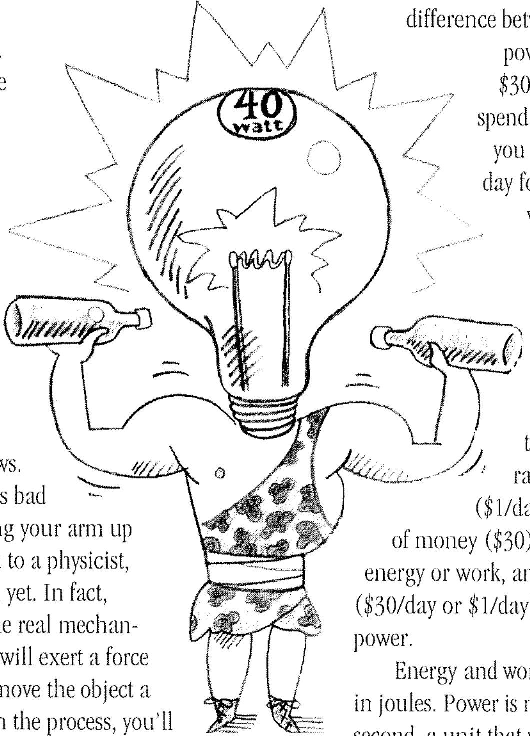
Getting tired yet? Your arm, of course, weighs something. When you hold it over your head, you have to exert a force to support it, and you get tired. You might even describe this activity as "a lot of work." A physicist, however, would disagree. It isn't that physicists are callous (some are and some aren't). But when physicists talk about work, they are talking about something very specific that they call mechanical work. A physicist defines work (W) as the force (F) multiplied by the distance (d) over which it is exerted. This is expressed as $W = F \times d$. Work is measured in units called joules (pronounced "jools").

When you hold your arm over your head, you aren't moving anything. But mechanical work involves both force and distance, and there isn't any distance. Ergo, you're doing no mechanical work. Zero. Nada.

Of course you're certainly doing what might be called "biological work." If you stand for a period of time with your arm upraised, you will eventually have to eat another peanut-butter sandwich to replenish the energy you are consuming through the metabolic process. But physicists don't talk about biological work; they talk about mechanical work. And they talk about energy, which they define as "the ability to do work."[1]

So there you have it—your definition of energy! It may seem a little devious or circular, and not very satisfying. Defining this stuff we call energy is difficult, because energy isn't something you can get your hands on. It's an idea, a concept, an abstraction. To quote a college textbook: "Energy is not a 'thing' or a 'substance,' but a concept that has been developed to describe in specific terms how fast something is moving, where it is, how hot it is, and so on. . . . Energy is really an abstraction, a mental bookkeeping device that we have invented." (Robert Romer, *Energy: An Introduction to Physics.* Freeman, 1976, pp. 3, 89.)

I realize that this may muddy rather than clarify the definition of energy for you at this point. But don't throw up your hands in despair. Oops! . . . I forgot! . . . you've already got one of them up there!



OK—YOU CAN PUT YOUR ARM DOWN.

That's the good news. But don't relax! There's bad news, too. Since holding your arm up doesn't qualify as work to a physicist, you're not off the hook yet. In fact, you're about to do some real mechanical work. That is, you will exert a force on an object that will move the object a certain distance. And in the process, you'll learn the difference between work, energy, and power.

Got a couple of two-liter soda bottles around? If they're empty, just fill them with water—it won't make any difference whether they hold water or soda for what you're going to do with them. Screw on the caps and put the bottles on the floor. Now pick them up, one in each hand, and lift them up one meter (about three feet) in one second (the time it takes you to say "one-thousand-one"). Do it again. And again.

The bottles always have the same weight, and you always lift them the same distance. That means that each time you lift them you always do the same amount of "work." (Remember our definition of work: force multiplied by distance, or $W = F \times d$.)

It doesn't matter whether you lift them rapidly or slowly; it's the same amount of work. But if you lift them rapidly, you are doing the work in a shorter period of time. That's what physicists call power. Energy is the ability to do work, but power is the rate at which you do it. In physics-ese, power (P) is equal to work (W) divided by time (t), or $P = W/t$. Therefore, when you lift the bottles faster, your work is the same, but your power is greater.

Here's another way to understand the difference between energy and power. Suppose you had $30. You could choose to spend it all in one day, or you could spend $1 each day for thirty days. Either way, you end up spending the same amount of money. But in the first case your rate of spending was high ($30/day), while in the second case your rate of spending was low ($1/day). The total amount of money ($30) is analogous to energy or work, and the rate of spending ($30/day or $1/day) is analogous to power.

Energy and work are both measured in joules. Power is measured in joules per second, a unit that we call a watt. When you repeatedly lifted the bottles one meter in one second, you experienced what it felt like to expend energy at the same rate as a 40-watt light bulb.[2] Since the power of an average laborer's daily work has been calculated at 75 watts, you should be able to raise and lower the bottles virtually all day long.

SO WATT?

What does all this have to do with the kind of energy that your local utility company delivers to your home? Well, envision a huge building with row upon row of benches filled with people just like yourself. In fact, imagine 25,000 such individuals. But instead of lifting soda bottles, they're turning cranks by exerting about the same amount of effort. (Since they're still exerting a force through

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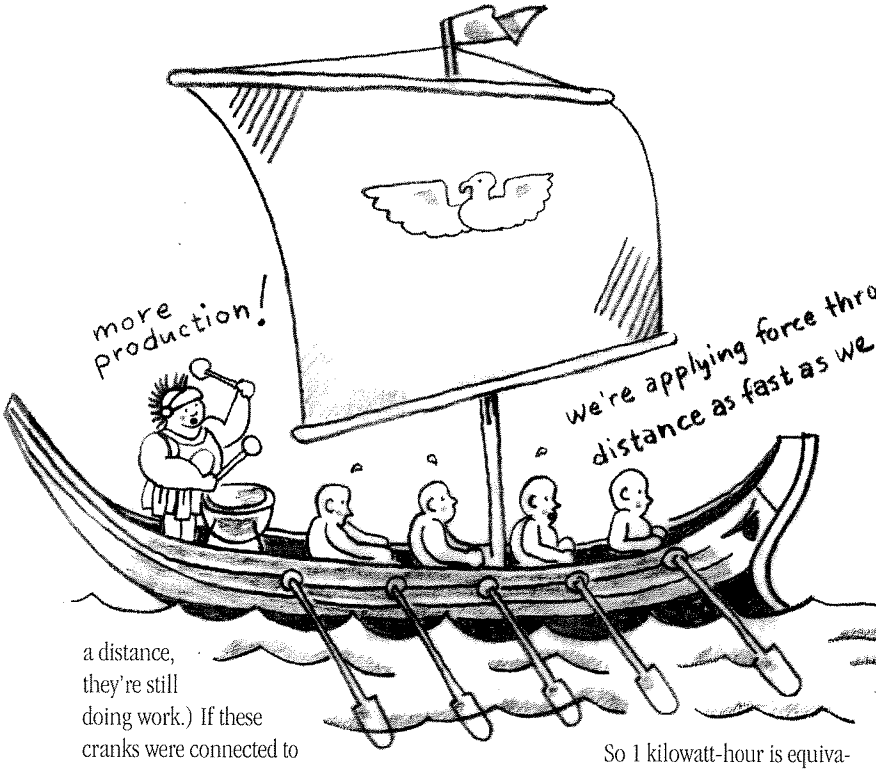
[1] Whenever you do work, you automatically transform energy from one form to another or transfer energy from one object to another. Work is the link between force and energy. Likewise, if you allow energy to change from one form to another or transfer from one object to another, work is done. Work becomes a way to calculate the amount of energy transformed or transferred.

[2] Here's the calculation for the power involved in lifting the two soda bottles. One liter of water has a mass of 1 kilogram, which here on earth weighs about 10 newtons. (The newton is the metric unit for force, and is equivalent to about a quarter of a pound.) That means a 2-liter bottle of water weighs 20 newtons. The unit of work is the newton-meter, or joule. One joule of work is done when a force of 1 newton is exerted for a distance of 1 meter. When you lift a 20-newton soda bottle 1 meter, you do 20 joules of work. The unit of power is the joule per second, or watt. When you do 20 joules of work in 1 second, your power is 20 watts. If you have a bottle in each hand, your power is 40 watts.



a distance, they're still doing work.) If these cranks were connected to electrical generators, then you would be looking at a 1 megawatt (1 million watts) powerhouse.

Ever been inside a powerhouse? How do you know that this isn't the way your electricity is generated? That's how the Romans made their ships move: by people power. The power expended by each galley slave could be rated in watts, as could the power of a modern-day member of a crew in a racing shell, or any person rowing a boat. Or walking. Or riding a bicycle. Even as you read this, you radiate heat at about 100 watts.

But wait a minute. When you get your monthly utility bill, you don't get charged for joules or watts. Your bill tells you how many kilowatt-hours of electricity you used, and how many therms of gas. What gives?

One kilowatt-hour means you are using energy at the rate of 1 kilowatt (1000 watts, or 1000 joules per second) for a period of 1 hour. An hour is 3,600 seconds. If you use 1000 joules each second for an hour, that's 3,600,000 joules.

So 1 kilowatt-hour is equivalent to 3,600,000 joules. Do you see why your utility company prefers kilowatt-hours? Charging by the joule would be kind of like buying gasoline for your car by the drop rather than by the gallon. Of course, they could just as easily call a kilowatt-hour 3.6 megajoules (3.6 mJ) or 3,600 kilojoules (3,600 kJ).

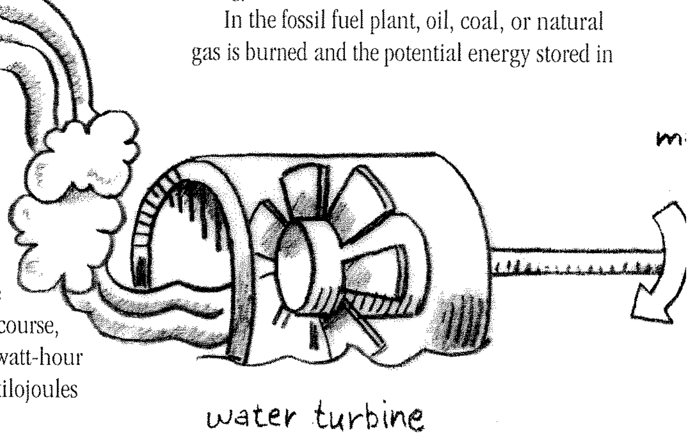
And now for your gas bill, which is in therms! Wait! Don't leave! A therm is a unit used by utilities to stand for approximately 100 million joules. So if you used 10 therms of gas, you've used 1 billion joules!

IT'S TIME TO PLUG IN.

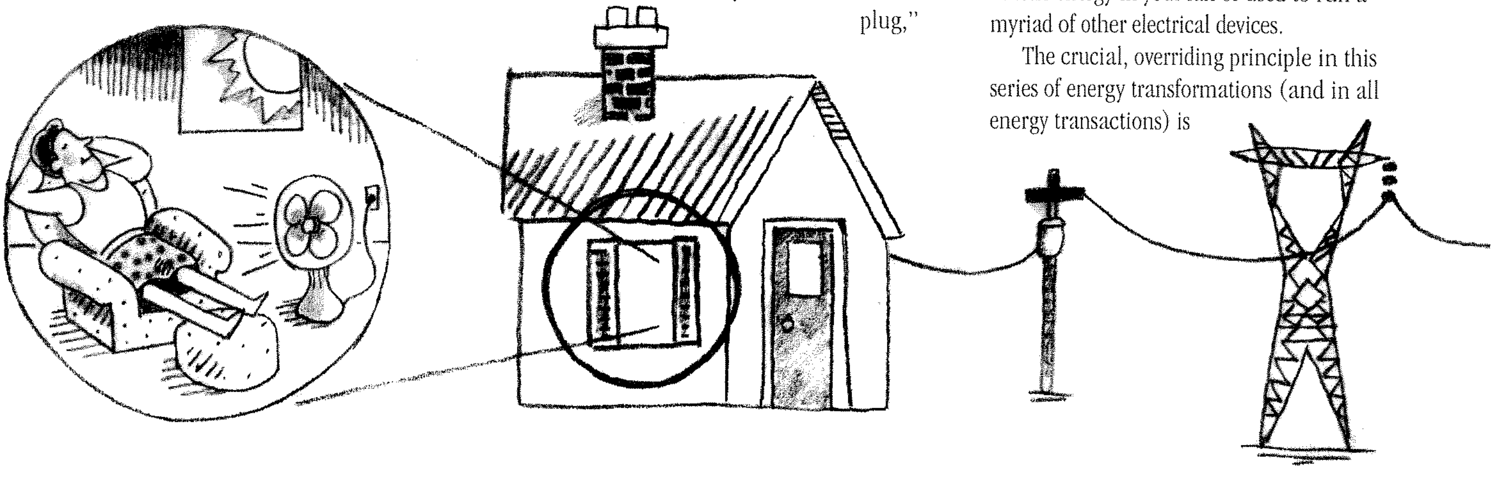
Since we're talking about your utility bill, did you ever wonder where the electricity in your house comes from? The easy answer is "from the plug," of course. But where does the plug get it? For a closing shot at clarifying the concept of energy itself, we'll consider your electricity as an example of energy and its transformations.

Your public utility generates electricity by burning a fossil fuel (coal, oil, or natural gas), operating a nuclear reactor, or using water, wind, or solar energy. For simplicity, we'll limit our discussion to fossil fuels. But similar stories, with different details, could be told for the other energy sources.

In the fossil fuel plant, oil, coal, or natural gas is burned and the potential energy stored in the chemical bonds of the fuel is transformed into heat energy, which boils water and produces steam. The steam turns the turbine of an electrical generator, and the heat energy is transformed into the kinetic energy of the spinning turbine. The generator spins coils of wire in a magnetic field, transforming its kinetic energy into electrical energy. The electricity is sent through wires to your house. Once there, it can be transformed into heat in your toaster or kinetic energy in your fan or used to run a myriad of other electrical devices.

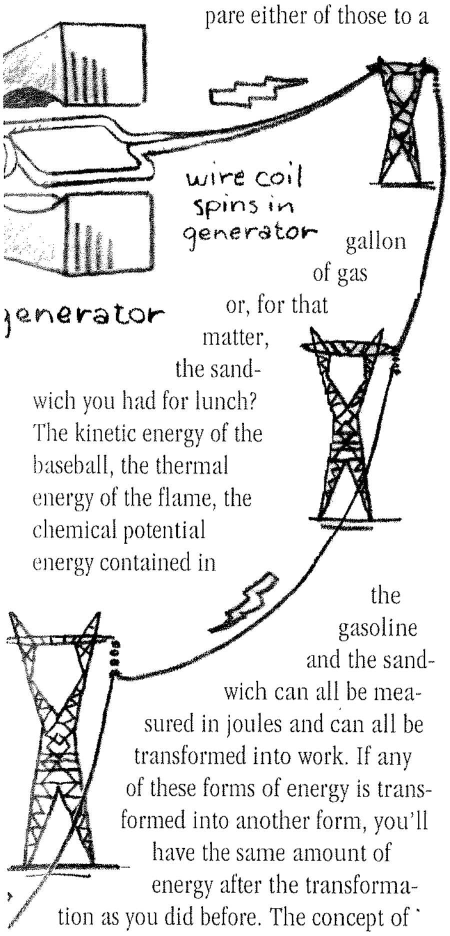


The crucial, overriding principle in this series of energy transformations (and in all energy transactions) is

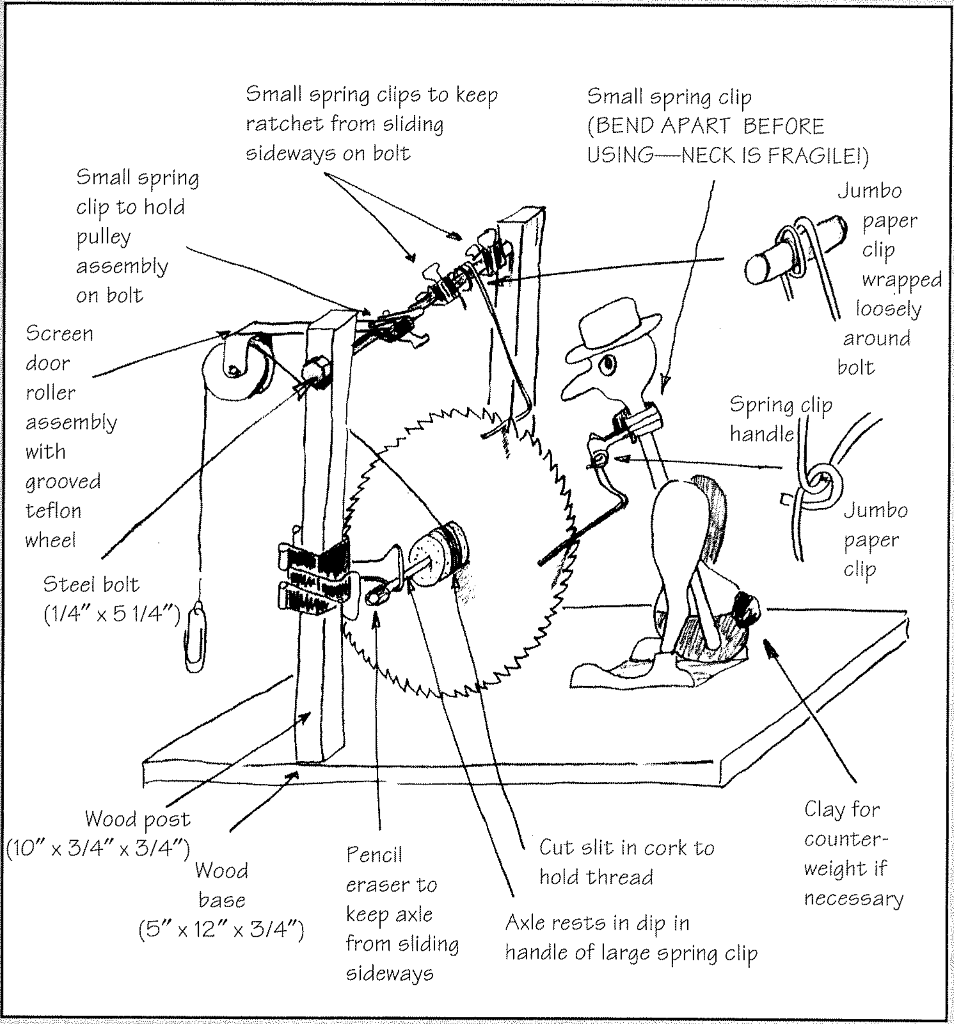


that energy may change form, but it can't be created or destroyed. In the textbook definition I cited earlier, energy was associated with bookkeeping. What's amazing about this bookkeeping is that it always balances. If you add up all the energy that's around after an energy transformation, you always end up with the same amount of energy you started with, though the form may have changed.

This principle is one of the cornerstones of physics. It provides a way to link some very diverse phenomena. How is a baseball speeding toward home plate like a candle flame? How can you compare either of those to a gallon of gas or, for that matter, the sandwich you had for lunch? The kinetic energy of the baseball, the thermal energy of the flame, the chemical potential energy contained in the gasoline and the sandwich can all be measured in joules and can all be transformed into work. If any of these forms of energy is transformed into another form, you'll have the same amount of energy after the transformation as you did before. The concept of energy—and the realization that energy cannot be created or destroyed—has allowed physicists to recognize the relationships among things that seem, at first glance, to be unrelated, a step toward understanding the essential unity of nature.



DUCKPOWER SPECIAL



Fitting 15 clowns in a car is a circus performance. But fitting 150 horses under the hood of a car is a routine part of daily life. Our car engines are seemingly crammed with horses. *Horsepower* is a familiar term, but where does it come from, what does it mean, and what does it have to do with the dipping duck toy shown here?

Before the invention of the steam engine, animals were the primary source of power. Horses or oxen pulled carriages and wagons, or turned in endless circles harnessed to devices that lifted water or ground grain. Dogs or reindeer pulled sleds. People rowed boats, pulled rickshaws, or carried sedan chairs and stretchers.

After the invention of the steam engine, it was natural to compare the newfangled mechanical monsters to their animal predecessors. How many horses would it take to do the job of a particular steam engine? Economic justification to invest in one of these new contraptions could be readily understood in terms of how many horses it could replace. The average power that could be exerted by the average horse became the standard of power. Thus we have the term *horsepower*.

With this equine background, let's cut now to the avian heart of the matter. I'd like to introduce an alternative unit of power—duckpower! A dipping duck toy, like the one pictured here, can lift a weight. In the high school physics class that I teach, students calculate the power that the dipping duck exerts—a single "duckpower." They can then figure out the horsepower of the duck—or even the duckpower of a horse.

Take a look at the picture. This is our experimental setup. Note that we aren't allowing our dipping duck to horse around and duck any heavy lifting. When everything goes according to plan, the dipping duck turns the toothed wheel a little bit on every dip, lifting the paper clip a small distance. The ratchet keeps the wheel from turning backwards when the duck rises. As this process is repeated over and over, the paper clip is eventually lifted a significant distance.

Lifting the paper clip involves exerting a force (the weight of the paper clip) through a distance (the distance the clip is lifted). This happens to be the physicist's criterion for accomplishing mechanical work. And since the duck does the work over a period of time, its power (the rate at which it does work) is also specified. You are now dealing with duckpower!

In my class, careful observation of the duck's exertion revealed that it lifted the paper clip a distance of 4.4 cm (almost 2 inches) in 30 minutes. With these three items—force, distance, and time—we can calculate the power expended by the duck in lifting the paper clip. To avoid arousal of latent math anxiety (accompanied by massive instantaneous loss of readership), I'll skip the arithmetic and the unit conversions and just say that this translates into roughly a millionth of a watt, or a billionth of a horsepower. One duckpower is therefore equal to a billionth of a horsepower. So it would take a billionth of a horse to do the work that the duck did in the same period of time. Put another way, it would take a billion dipping ducks to replace one horse!

If you are a teacher or other warped individual who would actually like to "do the numbers" (and units), see the calculations in the Box o' Math at the right. For more information on watts, joules, work, and power, read "Watt's a Joule?" on pages 4 to 7.

WHAT MAKES THE DUCK DIP?

When the duck is manufactured, most of the air is removed from inside the duck's body. The gas that remains is largely the vapor of the red liquid, which vaporizes very easily.

To start the duck dipping, you need to get the fuzzy coating on the duck's head wet. The duck starts dipping when the water evaporates from the fuzzy coating.

Evaporation is a cooling process. (When you step out of the shower, for example, you feel chilly because water is evaporating from your body.) The evaporating water cools the vapor inside the duck's head. This condenses the vapor back to liquid and reduces the pressure in the duck's head.

After the vapor in the duck's head condenses, the pressure of the vapor in the duck's body is higher than the pressure in its head. So liquid is forced from the body up the tube toward the head. As the liquid climbs in the tube, the duck's head gets heavier as its body gets lighter, and the duck begins to tip forward.

When the duck finally dips into the water, a clear passage is opened between the head and the body, allowing the pressures to equalize and the liquid to fall back down into the body. The bird returns to the upright position and the whole process repeats.

This seemingly endless repetition of the dunking maneuver, with no apparent source of energy or fuel, has traditionally resulted in the dipping duck being erroneously described as a "perpetual motion" machine. But think for a minute—will the duck actually run forever? When will it stop? Right! It stops when it runs out of water—that is, when its head dries out. Evaporation of water from the duck's head is crucial to its operation. When this stops, the duck stops. And this, dear reader, is where this article stops. Yes, you have it! The duck stops here!

BOX O' MATH

To calculate duckpower, we needed to know how much a paper clip weighs. So we heaped paper clips on a postal scale until it read one ounce. Then we divided one ounce by the number of paper clips and learned that one paper clip weighs 0.07 ounce. In the metric system, the unit of weight is the newton, and 1 newton is equivalent to about 3.5 ounces. We divided 0.07 ounces per paper clip by 3.5 ounces per newton and got about 0.02 newtons per paper clip.

In 30 minutes, the duck lifted the paper clip 4.4 centimeters. To use these numbers in our calculations, we have to change the minutes to seconds and the centimeters to meters. These values then become 1800 seconds and 0.044 meters.

Work (W) is equal to force measured in newtons (N) times distance measured in meters (m). The unit of work is the joule (J). Work done by the duck is 0.02 N times 0.044 m equals 0.0009 J.

Power is equal to the rate at which work is done, or work (joules) divided by time (seconds). The unit of power is the watt (W). For our dipping duck, 0.009 J divided by 1800 s equals 0.0000005 W, or five ten-millionths of a watt. We can round this off very roughly to about a millionth of a watt.

One horsepower is equivalent to 746 watts. Dividing the power of our dipping duck in watts by 746 gives its power in horsepower: 0.0000005 W divided by 746 equals 0.0000000007 hp, or seven ten-billionths of a horsepower. In very round numbers, this is about a billionth of a horsepower.