Chapter 2

CONCEPTS

Children are naturally curious about and fascinated by mechanisms. They love to take things apart to reveal the secrets hidden inside. That's one reason the study of mechanisms is an engaging and inexpensive way to introduce several of the big ideas of science and technology to young children. This chapter describes the concepts—those big ideas—that children are exploring when they investigate mechanisms. You'll revisit the challenges and puzzles you worked with in Chapter 1 in the context of these concepts and children's learning. In Chapter 3, you'll find activities that let children use their hands and their minds to explore these ideas directly. And in Chapter 4, you'll see how some teachers applied these ideas in their classrooms through their work with mechanisms.

Mechanisms Are Systems

A *system* is a collection of interconnected parts, functioning together in a way that makes the whole greater than the sum of its parts. A *mechanism* is a particular kind of system—one that converts one type of motion to another. A bicycle has one mechanism that converts pedaling to forward motion, another mechanism for operating the brakes, and yet others for changing gears. The human body is itself a system that abounds in smaller systems—including mechanisms that use muscles to transmit motion to limbs and other body parts.

By looking at mechanisms as systems, even young children can begin to build their understanding of how the world works by handling questions like these:

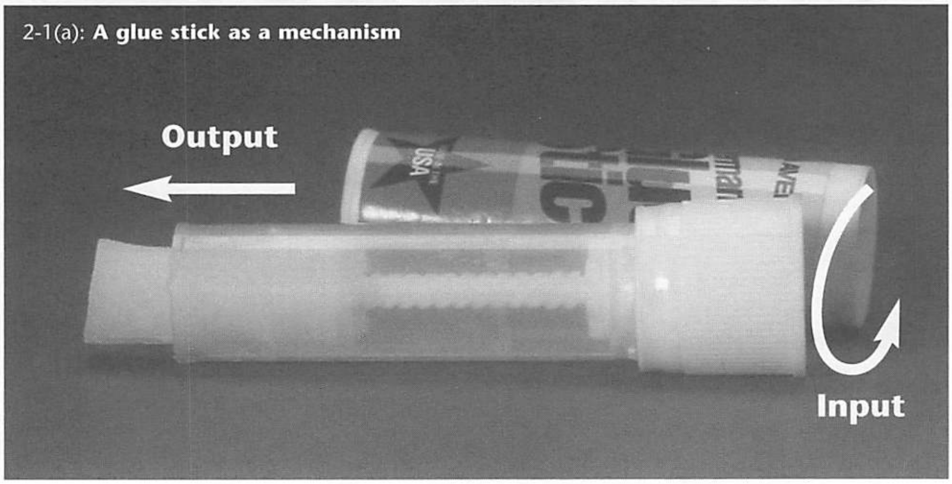
- What is the purpose of this system as a whole? What does it do?
- What are its parts?
- How are the parts connected to one another?
- How does each part function in relation to the whole?

Every mechanism can be understood in terms of these three basic elements:

- the *input*—the motion that causes the system to operate;
- the *output*—the motion that is the result or effect of the input;
- the process that changes the input into the output.

Look at a glue stick, for example. It is a simple mechanical system that takes one kind of motion and transforms it into another. Remove the cover from a glue stick and examine the tube. To use the glue, you turn a knob at one end and the glue comes straight out the other end. (A lipstick tube works the same way.) Inside the tube is a mechanism that takes the motion you supply by turning the knob—the input—and transforms it into the motion that makes the glue come out—the output. The input and output motions are different. The input motion travels around in a circle at one end of the glue or lipstick case. The output motion travels in a straight line and moves most of the length of the stick.

2-1(a): **A glue stick as a mechanism**



Making Things Happen

Unless a system is broken, it has a process that converts the input into the output. Another way of saying this is that there is a cause-and-effect relationship between the input and the output. The idea that one thing causes another is the basis for scientific prediction: if the cause is present, you can predict that the effect will occur.

As Piaget demonstrated, even young children have very definite ideas about cause and effect, but many of these ideas are at variance with the conclusions of science. When he asked five- through eight-year-old children what makes clouds move, their answers included "by themselves," "God," "the sun," "the moon," "rain," "night," "the air from the trees," etc.

In science education, cause-and-effect is often introduced by developing the formal method of a controlled experiment. For example, if some classroom plants thrive better than others, it might make sense to do a controlled experiment to determine precisely why. The controlled experiment is a method of establishing cause-and-effect when the cause is not immediately obvious. However, children below the upper elementary grades may not be developmentally ready to handle the concepts of a variable, a controlled variable, an experimental variable, and so on.

Simple mechanisms offer more direct opportunities for learning about cause-and-effect. Just by playing with a mechanism, even very young children can usually figure out what causes what. By choosing mechanisms of increasing complexity, teachers can introduce children to more complicated examples of cause-and-effect sequences.

Taking It Apart, Piece by Piece

What does it mean to say, "I understand how this mechanism works"? Let's consider the example of a glue stick again. Some brands of glue stick have a case that is semi-transparent, as shown in Figure 2-1 (b). As you turn the knob at the right, you can see that it turns a screw inside the tube that runs the length of the stick. As the screw turns, a kind of nut rides left or right on it, depending on the direction of turning. The glue sits in a platform attached to the nut, so that turning the knob and screw forces the platform to move left or right.

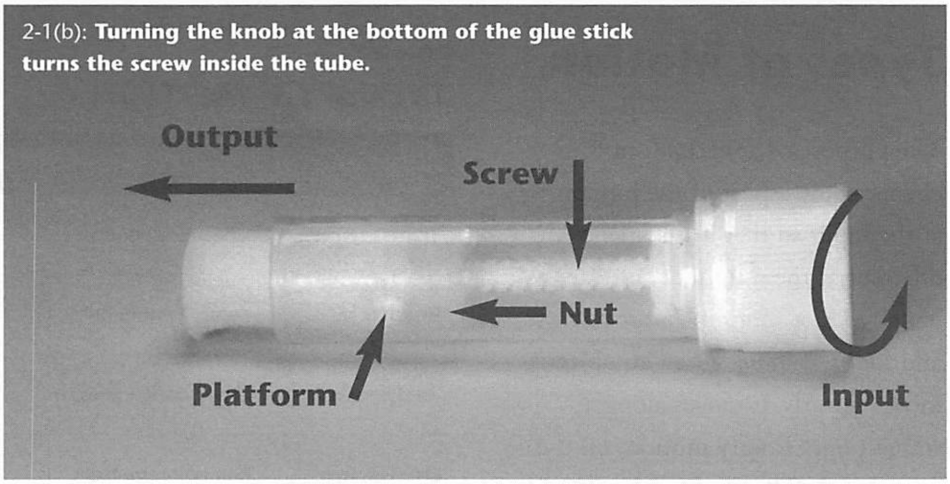
This explanation of a glue stick consists of a step-by-step description of what all the parts do, how they transmit motion from one to the next, changing the input into the output.

A nail clipper is somewhat more complicated than a glue stick. It has about the same number of parts as a glue stick, but the parts are not as tightly connected and their relationships are not quite as clear.

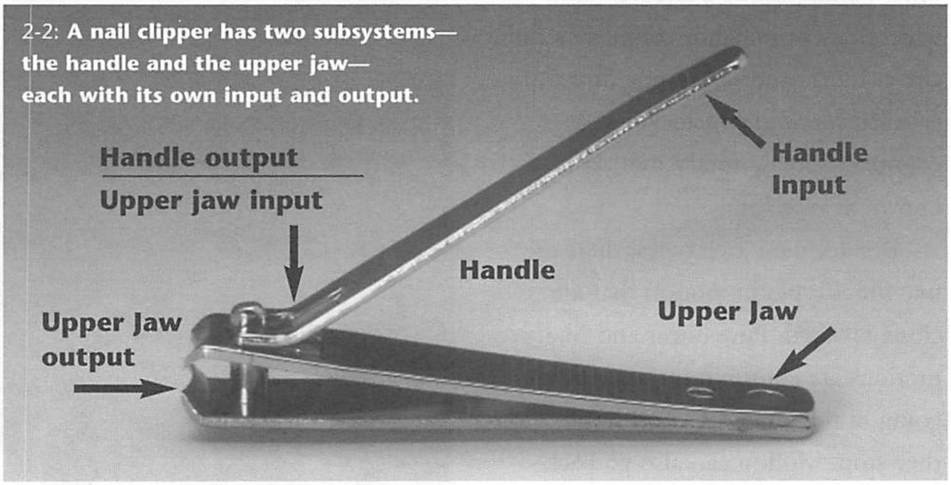
In analyzing a nail clipper, it is useful to divide the device into two sub-systems or modules—the handle and the upper jaw—each with its own input and output. (See Figure 2-2.) The output of the handle is the input to the upper jaw. In other words, the two parts are in series: the tail of one is attached to the head of the next. In this example, a more complicated mechanism can be analyzed by decomposing it into a sequence of simpler mechanisms.

Dividing a complex system into simpler ones is a very important technique in dealing with systems, and for problem solving in general. The same idea is behind modular home construction, stereo component systems, software "add-ons," and solving math problems by the "divide-and-conquer" strategy. It is also a basic strategy in design: solve the problem one part at a time, and then combine the parts.

2-1(b): **Turning the knob at the bottom of the glue stick turns the screw inside the tube.**



2-2: **A nail clipper has two subsystems—the handle and the upper jaw—each with its own input and output.**



Science and Math Concepts in Mechanisms

Types of Motion

The purpose of a mechanism is to change some aspect of the motion at the input so that it is somehow different at the output. There are two basic types of motion: *linear motion* and *rotary motion.* When an object moves linearly, it moves along a straight line. Rotary motion, on the other hand, follows a circular path, which may or may not complete a full circle. Linear motion in one direction is called *translation.* Clockwise or counterclockwise rotary motion is known as *rotation.*

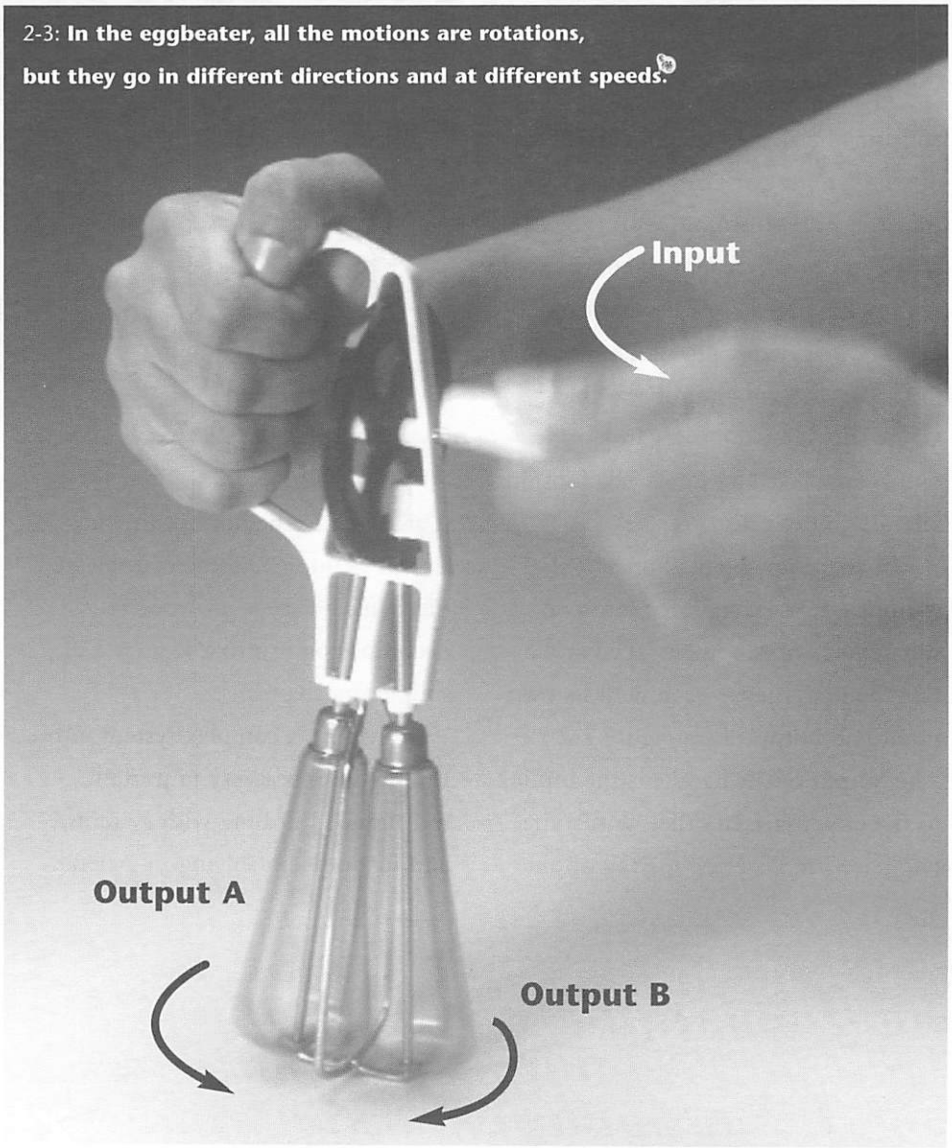
Besides these two types, there are two other types of motion that are closely related. Pure linear and rotary motions are continuous—they keep going in the same direction until they stop. Motion can also go back-and-forth. Back-and-forth motion in a straight line is called *reciprocating motion,* while rotary back-and-forth motion is known as *oscillating motion.* A summary of all four types, with examples, can be found in Table 2-1.

Some mechanisms are designed to convert one of these four types of motion to another. For example, the screw mechanism in a lipstick container or glue stick converts the rotation of the knob to the translation of the lipstick or glue. Something similar happens in a door lock, which converts

Table 2-1

TYPES OF MOTION

Type	Description	Diagram	Examples
Translation	Linear continuous	→	zipper, slide bolt, push button
Rotation	Rotary continuous	↻	Steering wheel, fan blades, faucet handle, can opener
Reciprocating	Linear back-and-forth	↔	sewing machine needle, bicycle pump, piston
Oscillating	Rotary intermittent	↺↻	windshield wipers, oscillating fan, lawn sprinkler


2-3: **In the eggbeater, all the motions are rotations, but they go in different directions and at different speeds.**

the rotary motion of a key to the linear motion—the translation—of the bolt. A windshield wiper linkage converts the rotary motion of a motor to the oscillating motion of the wiper blades.

There are also many mechanisms that do not change the type of motion, but rather change its speed, direction and/or location. In the eggbeater shown in Figure 2-3, all the motions are rotations: two at the output and one at the input. The eggbeater takes one rotation and produces two rotations in opposite directions. Notice that the outputs are different from the input in several ways:

- There are two outputs and only one input;
- The two outputs go in opposite directions;
- The input rotation is vertical, while the output rotations are horizontal;
- The outputs rotate faster than the input.

Mechanisms are often designed to magnify the force available for a job. The nail clipper of Figure 2-2, for example, transforms a relatively small amount of effort at the handle into the much greater force needed to cut the nail. This transformation depends on the use of levers, which we shall explore in detail shortly.

"Ins and Outs of Inputs and Outputs" in Chapter 3 is an activity designed to explore types of motion.

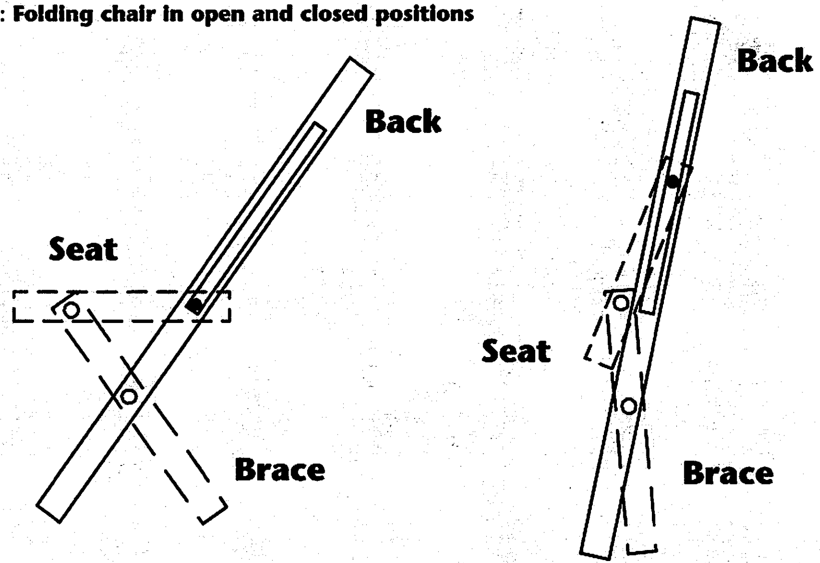
Links and Joints

Most of the common mechanisms we will consider are composed of two kinds of components: links and joints. A link is a rigid bar, frame, or plate that can move only as a unit. Consider, for example, the folding chair shown in profile in Figure 2-4. This is the same device shown in Figures 1-33 and 1-34. It consists of three links: the back, the seat and the diagonal brace.

The chair could never fold and open if these links were simply glued together. Instead they are connected by joints, which allow rotary or linear motion. In the diagram, you can see the three joints, represented by circles. Two of the joints—those connecting the seat and brace, and the brace and back—are pin joints, which only allow rotation. Some other examples of pin joints are the human elbow, a door hinge, and a toilet-paper-roll holder.

The third joint of the folding chair—the one connecting the back and seat—is a roll-slide joint. Notice how the pin-in-slot arrangement allows both translation and rotation. If you compare the positions of the seat in the open and closed positions, you can see how the seat has to both rotate counter-clockwise and slide up in order to fold up. You can find more roll-slide joints in umbrellas, scissor jacks, foot-pedal pumps, ironing boards, and drafting tables. A folding umbrella has a slider that rides along the central shaft. Attached to the slider are links that are vertical in the folded position, and gradually become horizontal as the umbrella unfolds. Each of these links is connected to the central shaft by a roll-slide joint. (See Figure 2-5.)

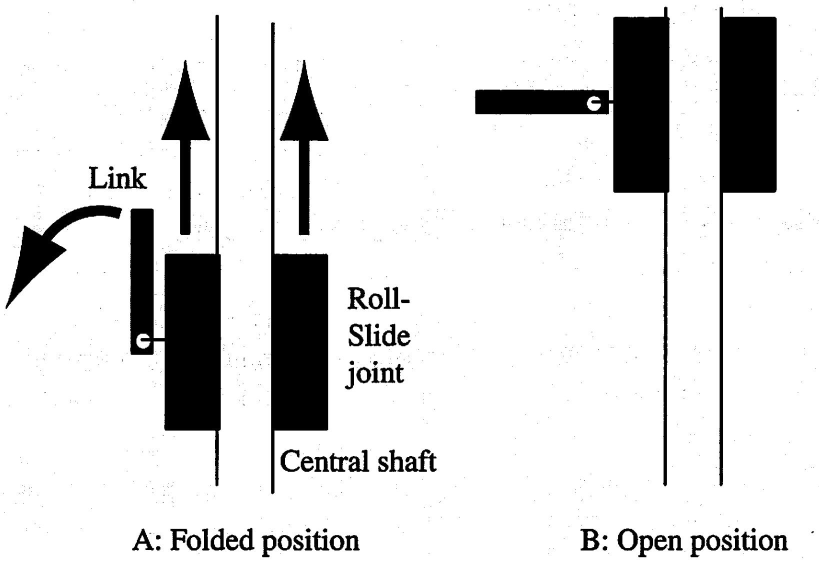
2-4: Folding chair in open and closed positions



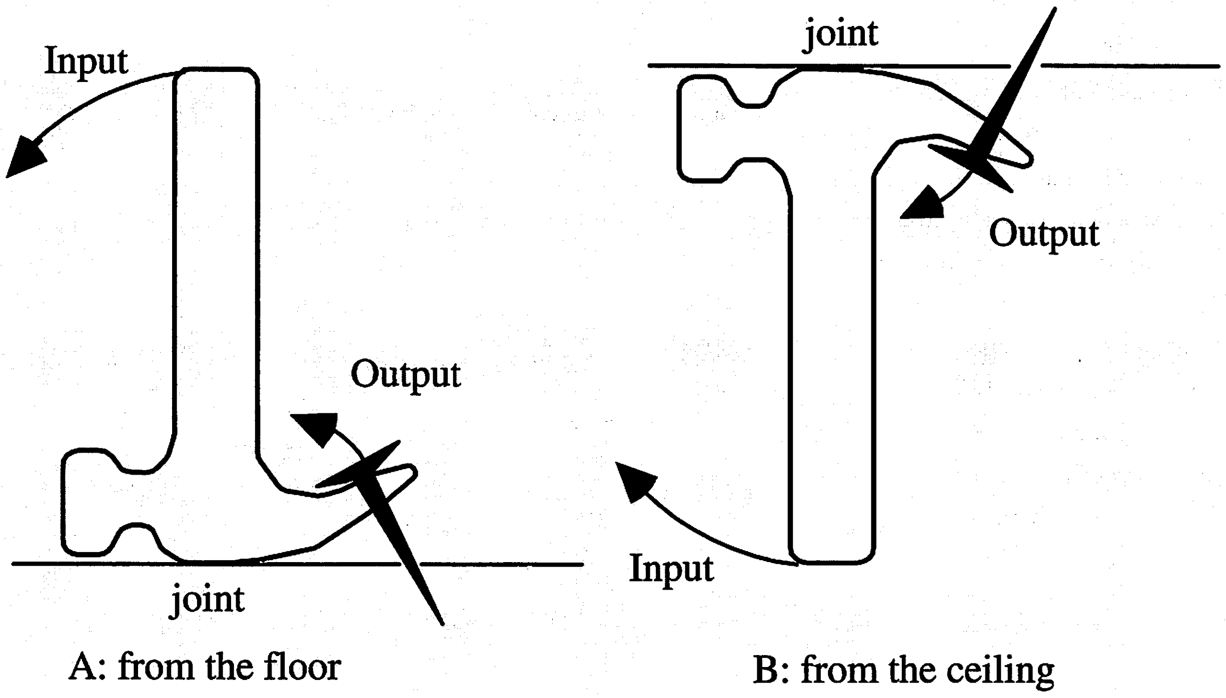
Some joints are not as permanent as door hinges or the pin joints in folding chairs, which stay together because of the way they are made. They are temporary joints that work only as long as there is a force pushing the links together. An example occurs when you use a hammer to remove a nail (Figure 2-6). The hammer rotates against the fixed surface, but only because it is held there by a force. The force is gravity if it is resting on the floor (Figure 2-6A) or the force of your hand if the hammer is against the ceiling (Figure 2-6B).

The "Make a Model of a Mechanism" activity in Chapter 3 is designed to explore links and joints.

2-5: Detail of a folding umbrella in closed and open positions



2-6: Temporary joints formed by a hammer held by force against a fixed surface



How Levers Work

Suppose you have to lift a heavy desk momentarily to get something out from under it. One way is to use a long wooden board to pry it up. Near the desk end, rest the board on a solid support that allows it to rotate. Then a small amount of force on the other end of the board will be sufficient to lift the desk. (See Figure 2-7A.) The board itself is a *lever,* and the pivot it rests on is called a *fulcrum.* The point where you apply the force is called the *effort,* which is just another word for input. The effect of applying this force, lifting the desk, is called the *load,* which is the output in this case.

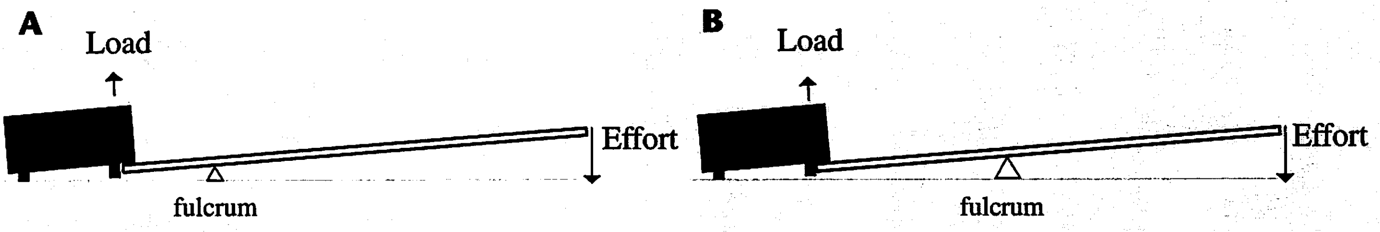
This lever works because the effort moves a lot further than the load. Because the effort end moves a longer distance, it doesn't take as much force as the actual weight of the desk. The load end, on the other hand, moves a very short distance, but with a much greater force. If you moved the fulcrum towards the middle, as in Figure 2-7B, you would lose this advantage. Now the effort end and the load end move about the same amount, and the force is also about the same at both ends.

A lever can make it easier to lift something, or overcome a force of any kind, by multiplying the effect of the force at the effort end. How much does the force get multiplied? This depends on the location of the fulcrum. The closer the fulcrum is to the load end compared with the effort end, the more the effort force is multiplied. These distances from the fulcrum have special names, which are shown in Figure 2-8. The distance from the load to the fulcrum is called the *load arm,* and the length of space between the effort and the fulcrum is the *effort arm.* Their ratio, which tells you how much the effort force is multiplied, is called the *mechanical advantage.* This connection between the ratio of the distances and the ratio of the forces also has a special name. It is called the *Law of the Lever,* and was discovered by Archimedes more than 2000 years ago!

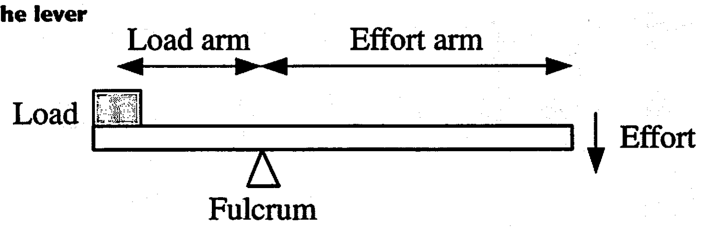
"How Do Levers Make Work Easier?" in Chapter 3 is designed to explore levers and mechanical advantage.

Most people would recognize the desk-lifting board as a lever, but many levers are less obvious. A common idea is that a lever must be straight, but the hammer in Figure 2-9 is also a lever, although it is bent. The handle of the nail clipper in Figure 2-4 is another example of a bent lever. Another common misconception is that the lever must always sit above the fulcrum, but the fulcrum can equally well be on top, as in Figure 2-6B. Figure 2-9 shows the effort, effort arm, load, load arm, and fulcrum for the example of the hammer.

2-7: Using a level to lift a desk



2-8: The law of the lever

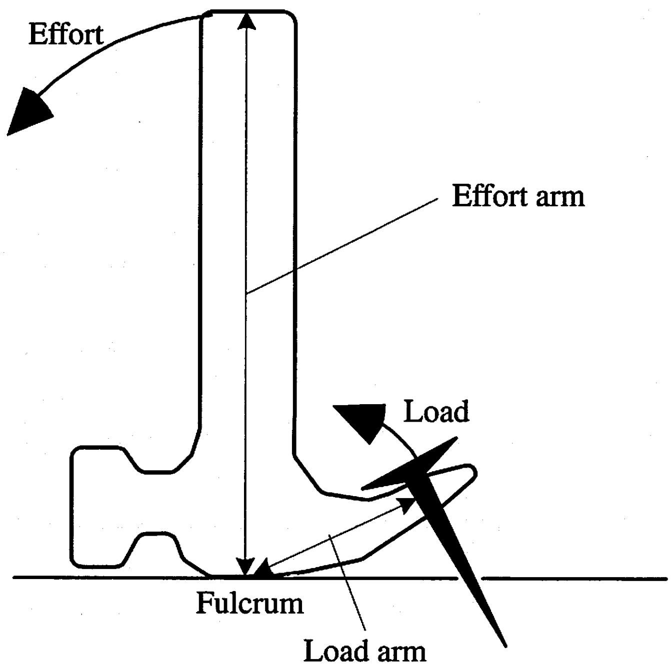


$$\text{Load arm} \times \text{Load weight} = \text{Effort arm} \times \text{Effort force}$$

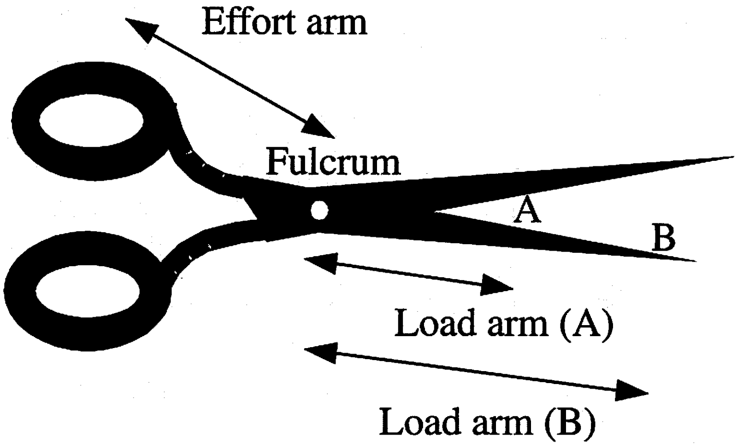
or

$$\frac{\text{Load}}{\text{Effort}} = \frac{\text{Effort arm}}{\text{Load arm}} = \text{"Mechanical Advantage"}$$

2-9: **A hammer as a lever**



2-10: **Why is it easier to cut something at A than at B?**



To see the Law of the Lever in practice, you can try the following experiment. Hammer a nail part way into a block of wood, as shown in Figure 2-9. Grab the handle near the end, and pull it towards you. The nail should begin to come out easily. Now try the same experiment with your hand about halfway down the handle. The effort arm is reduced, while the load arm stays the same, meaning that the mechanical advantage is reduced. Sure enough, it is harder to pull the nail out when you move your hand away from the end of the handle and closer to the nail.

An interesting twist with the hammer is that the fulcrum does not stay in one place. As you pull it towards you, you will find the hammer resting on the head. In a way, this works for you, because the mechanical advantage is greatest at the beginning, when you need it the most.

Another example of mechanical advantage has to do with an ordinary pair of scissors. (See Figure 2-10.) When something is hard to cut, you move it instinctively closer to the pivot, e.g., from B to A in the diagram. Why? Most people claim that the blades are sharper there. Perhaps they are, but there is an even better reason to cut closer to the pivot: you are increasing the mechanical advantage. The effort arm is the same in both cases, but the load arm is much shorter when you cut at A than when you do so at B. Therefore the mechanical advantage is greater, which means that the same amount of effort can cut a harder object at A than at B.

Rearranging Levers

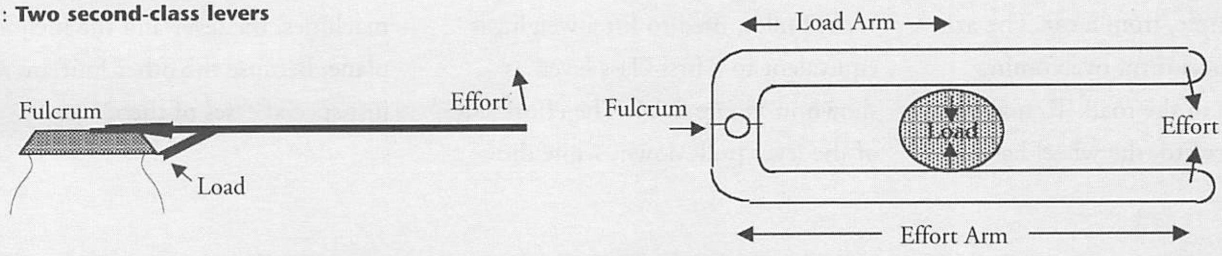
The levers discussed so far have all been arranged with the fulcrum between the effort and the load. This scheme of "Effort-Fulcrum-Load" is the most familiar one, and many people contend that the fulcrum is always in the middle. However, two other arrangements are equally possible, namely "Fulcrum-Load-Effort" and "Fulcrum-Effort-Load." Both are very common, and the Law of the Lever applies equally well to them. For example, both a nutcracker and a bottle opener are of the "Fulcrum-Load-Effort" type, or as they're better known, second-class levers. (See Figure 2-11.) The term *second-class lever* implies no value judgment, but is merely a convenient way of distinguishing between this and the more familiar "Effort-Fulcrum-Load" type, which is called a *first-class lever*. Note that a second-class lever always has a mechanical advantage greater than 1, because the load is closer to the fulcrum than the effort is, making the effort arm greater than the load arm (see Figure 2-11B).

If you assumed that the remaining type of lever, "Fulcrum-Effort-Load" should be called a *third-class lever*, you were right! Staple removers and tweezers are both examples of third-class levers. (See Figure 2-12.) As in the second-class lever, the fulcrum is at the end, but in these cases, the effort is closer to the fulcrum than the load. Because the effort arm is shorter than the load arm, the mechanical advantage is less than one, and it takes more force to operate the device than is delivered to the load.

If this is true, why would third-class levers be used at all? Recall that in the example of lifting a desk, there was a price paid for the reduction of effort. Although the effort end didn't need as much force, it had to travel a longer distance. A third-class lever uses this principle in reverse. The effort may require more force, but it doesn't have to go very far. A small movement at the center of the tweezers or staple remover results in a larger movement at the load end, which is why these devices are designed as third-class levers.

Your forearm is another example of a third-class lever. The fulcrum is your elbow joint, the load is your hand and whatever it happens to be lifting,

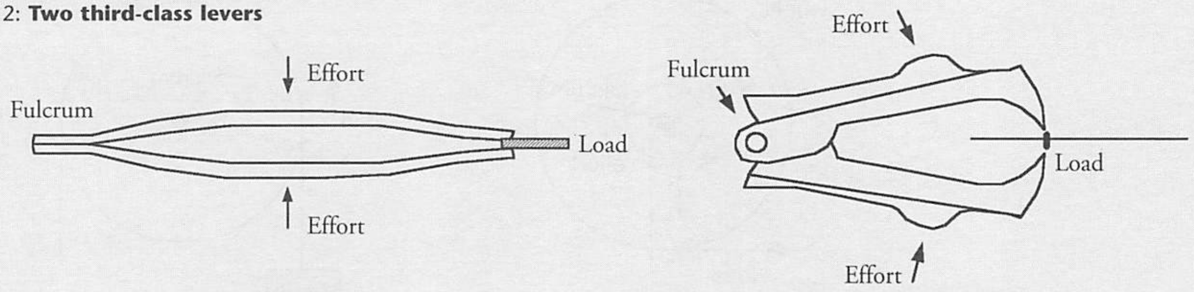
2-11: **Two second-class levers**



A: Bottle Opener

B. Nut Cracker

2-12: **Two third-class levers**

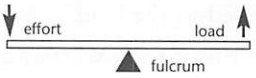
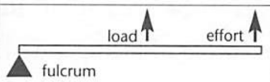
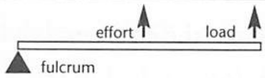


A: Tweezers

B. Staple Remover

Table 2-2

THREE CLASSES OF LEVERS

Type	Description	Mechanical Advantage	Examples
1st Class		less, greater or equal to one	scissors, pliers, oars, hammers (as nail extractors), can opener, hand truck
2nd Class		greater than one	wheelbarrow, nutcracker, garlic press, bottle opener, handlebars
3rd Class		less than one	forearm, tweezers, staple remover, fishing rod, shovel

and the effort is supplied by a muscle which connects the upper arm to the lower arm just inside the joint. The arms of cranes and bulldozers work the same way. Table 2-2 summarizes the three classes of levers.

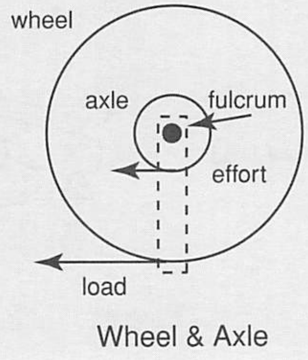
Science books usually identify six *simple machines: the lever, wheel-and-axle, pulley, inclined plane, wedge,* and *screw.* Two of these—the wheel-and-axle and the pulley—are really examples of the lever.

Figure 2-13 shows a wheel-and-axle, for example, from a car. The axle makes the wheel turn, overcoming the resistance of the road. To make the vehicle go forward, the wheel has to push back against the road, which is the load in this case. The effort is supplied by the axle, which is much closer to the fulcrum (at the center) than the road is. Therefore, a wheel-and-axle is a third-class lever. The dashed line shows what an ordinary straight lever would look like if it were doing the same job as the wheel-and-axle. Of course, the lever would only work for an instant, because as soon as it rotated, it would no longer be in contact with the road.

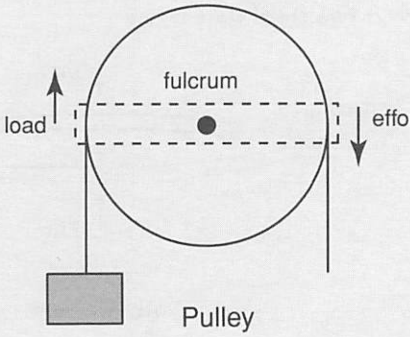
A pulley, used to lift a weight, is equivalent to a first-class lever, as shown in Figure 2-14. The effort side of the lever pulls down, while the load side lifts the weight up, and the fulcrum is at the middle. The dashed line shows how the pulley could be replaced momentarily by a straight first-class lever, which would do the same job.

Two of the other three simple machines—the wedge and the screw—are examples of a third kind of simple machine—the inclined plane. The lever and the inclined plane are basic to all mechanisms. It would be more accurate to say there are only two simple machines, the lever and the inclined plane, because the other four are really just special cases of these!

2-13: **The wheel-and-axle as a third-class lever**



2-14: **The pulley as a first-class lever**

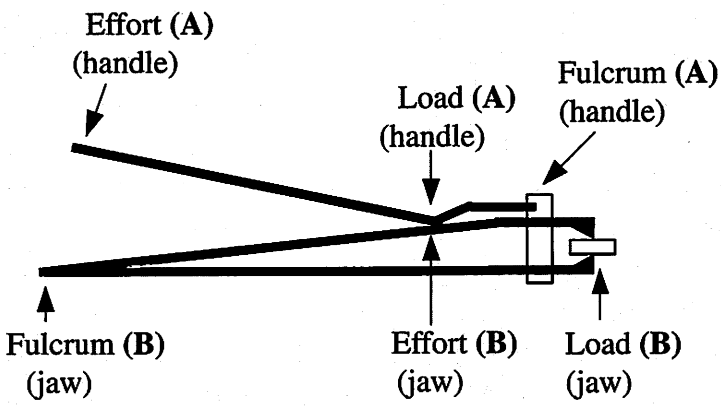


Compound Levers and Linkages

Most of the examples so far show individual levers operated by hand, as in the cases of the hammer and the bottle opener. In some cases, like the tweezers, the scissors, and the staple remover, two identical levers use a common fulcrum and are hand-operated in tandem. Each of these devices could be described as a double lever. In the case of the nail clipper, shown again in Figure 2-15, we see a system of two levers arranged so that one lever operates another. The handle is a second-class lever (A), whose load (output) is the effort (input) to the upper jaw, which is a third-class lever (B).

A device like the nail clipper, in which one lever acts on another, is called a *compound lever* or *linkage.* Other examples of linkages include folding chairs and baby carriages, vise-grip pliers, umbrellas, lawn sprinklers, windshield wiper mechanisms, adjustable-arm desk lamps, clothes drying racks, "lazy tongs" lamps and mirrors, "pop-out" tool boxes and sewing boxes, bicycle handbrake mechanisms, manual typewriter mechanisms, and most automotive hood and tail-gate opening hinges.

2-15: **The nail clipper as a compound lever or linkage**

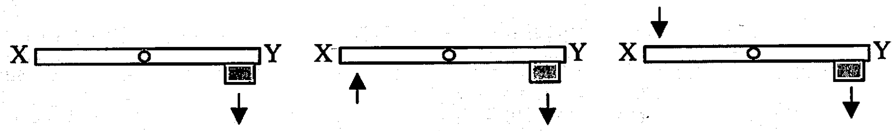


How Children Understand Mechanisms

Although little research has been done about children's conceptions of mechanisms, Piaget did look at this issue. In *Success and Understanding,* he reports on research regarding levers. Figure 2-16 shows one example.

A child of nearly five years was presented with a hotizontal first-class lever. The fulcrum was in the center of the bar. The problem was: How can you lower a block of sugar at Y using your finger at X? At first, the child simply lowered the block by

2-16: **A five-year old's view of a first-class lever**



A. How do you lower the object at Y by operating the lever at X?

B. Child's correct solution (after several tries)

C. Child's account of what he did

hand, without using the bar. Then he claimed there was no way to do it with the bar, because the bar wouldn't budge when he pulled it down at the pivot. Then, with a little coaching, he managed to lower the block at Y by raising the bar at X. When asked how he had done it, he insisted that he had pushed the bar down at X, rather than up. Apparently, he could not imagine that the bar could actually go up at one end and down at the other!

Piaget explains that this sequence reflects a lag between the child's intuitive hands-on knowledge and his ability to conceptualize it abstractly. In other words, a young child can perform the task without being able to explain it correctly. According to Piaget, as children mature, conceptualization gradually becomes more important. By early adolescence, children actually form a concept of the situation before taking any action.

Piaget's research occurred in the context-free setting of a pegboard lever on a pegboard base. Presumably, the children he studied had no prior experience with this type of apparatus, which was not part of any mechanism they had ever used. Lehrer & Schauble (1998) did a study called "Children's Conceptions of Gears" which looked at how second- and fifth-grade children understand the transmission of motion from one gear to another. Lehrer and Schauble asked questions like:

1. If one gear is driven, what makes the other one turn?
2. Do the two gears rotate in the same or different directions?
3. What determines the relative speeds of the two gears?

Some of this research was done using gears on a pegboard isolated from the rest of the world. The same questions were later asked of children examining an eggbeater and a ten-speed bike. Not surprisingly, the younger children were able to answer the first question more accurately when it was presented in the context of familiar devices. In describing why the both pegboard gears turn at the same time, one child said, "It's kind of like a copycat." In other words, one of the gears is just imitating the other. He had no concept of the causal mechanism linking the two gears. In looking at the eggbeater, the second-graders were much more likely to recognize the role of the gear teeth in transmitting the motion from one gear to the next. Lehrer & Schauble's work underscores the importance of teaching mechanisms using artifacts that are already familiar to children.

In his book, *The Child's Conception of Causality*, Piaget also reports on a study of how children understand the gear transmissions of bicycles. Children younger than about eight couldn't offer a reasonable explanation of what makes a bicycle go. Children of about four and five gave accounts that did not involve the feet or the pedals at all. Their explanations included "it must go," "the lamp," "the street," "the air in the tires," etc. At about six or seven, children identified the parts involved in making a bicycle go, but did not understand their cause-and-effect relationships. One child, for example, saw that the pedal operates the front sprocket, but thought that the rear wheel drove the chain! Starting at about eight years, Piaget's subjects could identify the causal sequence pedal –> front sprocket –> chain –> rear sprocket –> rear wheel. Perhaps the most striking aspect of these studies is how different children's ideas are from what adults assume.

An important idea that is developed through work on mechanisms is modeling. A model is an imitation of something that captures some fundamental features, but is also different from the real thing. Chapter 1 discusses how to make and troubleshoot models of mechanisms. Penner, et al, (1997) describes how first- and second-graders grappled with the task of making functional models of the human elbow. In the course of this work, they gradually came to distinguish between models that look like the real thing and those that work like the real thing. Based on this work, the children became much more knowledgeable both about simple mechanisms and also about the nature of models.

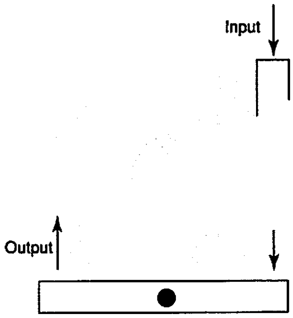
Mystery Mechanisms: The Design Puzzles Solved!

We will conclude our discussion of the concepts underlying the study of mechanisms by solving the mechanism design problems posed at the end of Chapter 1, shown in Figures 1-42, 1-43, and 1-44.

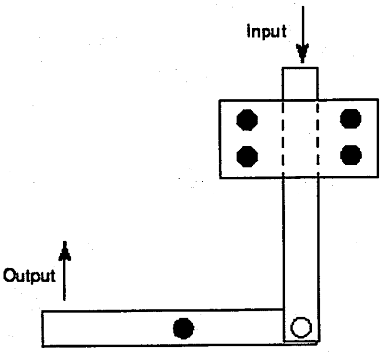
Design Puzzle #1: The Arms Flap Up When the Head Goes Down!

2-17: **Design Puzzle #1**

2-18: **Using a first-class lever**



2-19: **Solution to Design Puzzle #1 showing slider**



The problem is shown in Figure 2-17. To solve this problem, think about what needs to happen at the output. It will need to swing upward, as a result of an input that pushes downward. What sort of lever has opposite directions of motion at the input and output? Looking at the scissors in Figure 2-10 or the desk-lifter in Figure 2-7, it is clear that a first-class lever will do this job. Figure 2-17 is redrawn as Figure 2-18, showing the output link as a first-class lever. The solid circle indicates that the fulcrum is a *fixed pivot* attached to the base of the mechanism.

Now what could be behind the remaining cloud? Something is needed to transmit the vertical translation from the input to the right-hand side of the first-class lever. Clearly, a slider will accomplish this task, and the complete design is shown in Figure 2-19. The connection to the first class lever is made by a *floating pivot* represented by the open circle. A floating pivot connects two links, but does not attach them to the base. Note that the sliding link is constrained by a guide (see Figure 1-40). The circles represent paper fasteners.

The width and location of the guide are important. If it is too tight or too far from the floating pivot, the link may not be able to rotate slightly, allowing it to turn the output link. If, on the other hand, the guide is too loose, it may have too much side-to-side movement. Another thing you can play with is the location of the fixed pivot on the output link. If it is moved to the right, the output motion will be greater, but more force will be required at the input. The opposite will be true if it is moved to the left. As with any design problem, a great deal can be learned from trying to rework the design once you have a first working model.

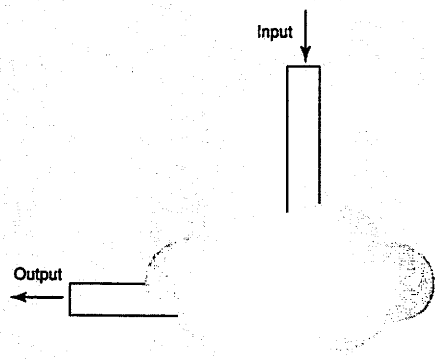
Design Puzzle #2: The Arms Shoot Out When the Head Goes Down!

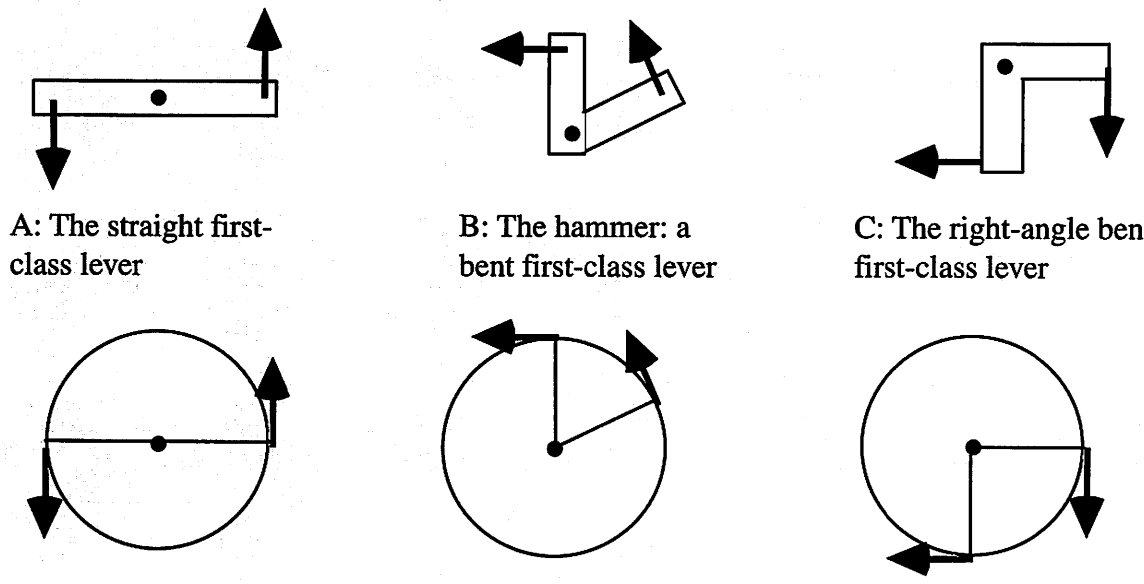
In this problem, the arms shoot out instead of up when the head is pushed down. As in the first problem, we start with one side only. The input and output are shown in Fig. 2-20.

Although apparently similar to Design Puzzle #1, this challenge is actually quite different. In Puzzle #1, the direction of motion had to change by 180°. Here, a 90° change of direction is needed between input and output. None of the three classes of levers shown in Table 2-2 will accomplish this result, but the hammer in Figure 2-9 offers a clue. Although the hammer is a first-class lever, the effort and load are different by much less than 180°. The reason is that the hammer is a bent lever—the bar itself changes direction.

Another way to see how to make the change of direction is to make an analogy between the lever and the wheel. We have already seen, in Figure 2-14, how the opposite sides of a pulley behave like a first-class lever. Figure 2-21 extends this analogy by showing two other ways to make a wheel act like a lever. Figure 2-21(A) restates the idea of Figure 2-14, showing a wheel as a straight first-class lever, with the effort and load at opposite ends and moving in opposite directions. Figure 2-21(B) is a simplified view of the hammer in Figure 2-9, and an equivalent circle. This time, the input and output are not taken from opposite sides, but only about 60° apart. Figure 2-21(C), finally, offers a solution to the

2-20: **Design Puzzle #2**




A: The straight first-class lever

B: The hammer: a bent first-class lever

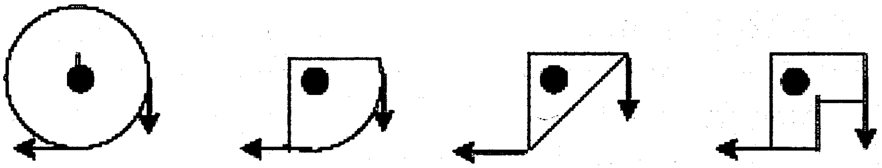
C: The right-angle bent first-class lever

2-21: **Three analogies between wheels and levers** right angle problem of Design Puzzle #2. It shows how both a wheel and a bent lever can change the direction between the effort and the load by 90°.

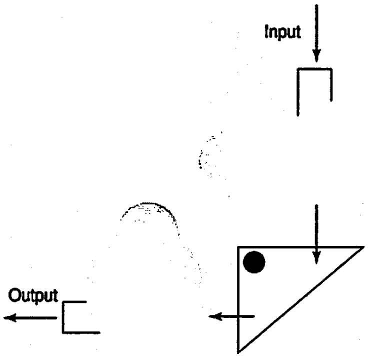
An important thing to note in all three sets of diagrams is that you don't need the entire wheel to do the job. In Figure 2-21(A), a straight bar replaces the wheel. In terms of input and output, they both do the same thing. In Figure 2-21(B) and (C), the wheels are also replaced by bars, but in these cases the bars are bent. The bent bars work the same way as the wheels except that they are not as strong. To make the L-shaped lever stronger, all you have to do is fill it in; a triangle is much stronger than an L. You could also use a quarter circle, which is similar in shape to a triangle. The rest of the circle is simply not needed. These shapes are compared in Figure 2-22.

Using the ideas from Figure 2-21(C) and Figure 2-22, it is easy to design the basic mechanism for Design Puzzle #2. Figure 2-23 shows how to use a triangle to change the direction of motion by 90°. The rest of the problem consists of transmitting the forces from the input to the bent lever, and from the bent lever to the output. This is accomplished, as in the previous problem, by adding sliders. A complete solution is shown in Figure 2-24. Note that the sliders are attached to the triangle by floating pivots, while an off-center fixed pivot attaches the triangle to the base.

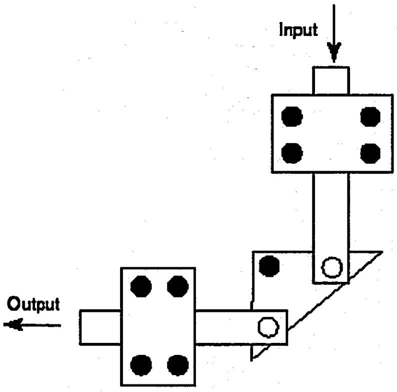
2-22: **From circle to bent lever**



2-23: **Using a triangle to make a bent lever**

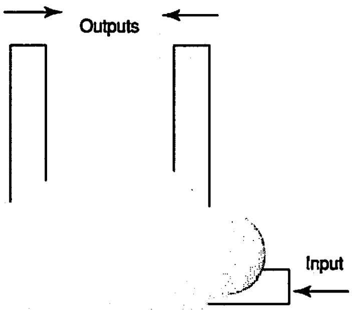


2-24: **Solution to Design Puzzle #2**



Design Puzzle #3: The "Kissing Couple" Problem

2-25: **Design Puzzle #3**



The problem in Design Puzzle #3, shown in Figure 2-25, was to make a little toy that has an input on the side which is pushed in, and two outputs on the top which come together.

The first thing to notice about this problem is that it really consists of two problems, each having one input and one output. The input is the same for both problems. These are shown in Figure 2-26. Breaking the problem up into two little problems is an example of the "divide-and-conquer" strategy for solving problems.

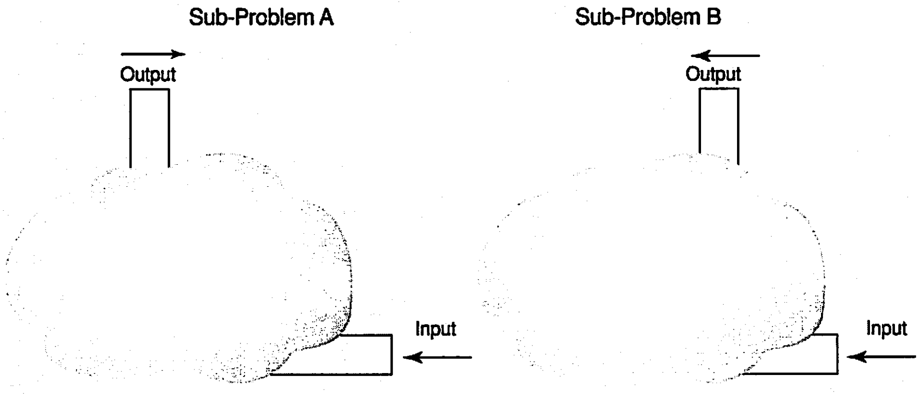
Sub-problem A is actually the same problem as Design Puzzle #1 (arms wave up when the head goes down) except that it has been turned on its side. The equivalence between these problems is shown in Figure 2-27.

If you turn the book 90° counter clockwise, sub-problem A will look just like Design Puzzle #1.

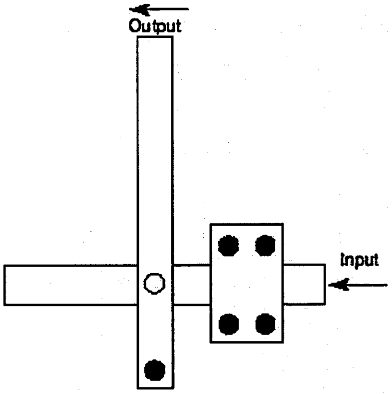
Since we already know how to solve this part, we can go on to sub-problem B. This problem is very similar to Design Puzzle #1, but with one very important difference: the output and the input go in the same direction rather than opposite directions. So, we ask what sort of lever has both input and output going in the same direction, with the output at one end. A look at Figure 2-12 or Table 2 reveals the answer: a third-class lever will work. Figure 2-28 shows a solution to sub-problem B with a third-class lever.

The only remaining step is to combine the solutions of the two sub-problems into the solution for the entire problem. This is done by using the same input for both outputs, shown in Figure 2-29.

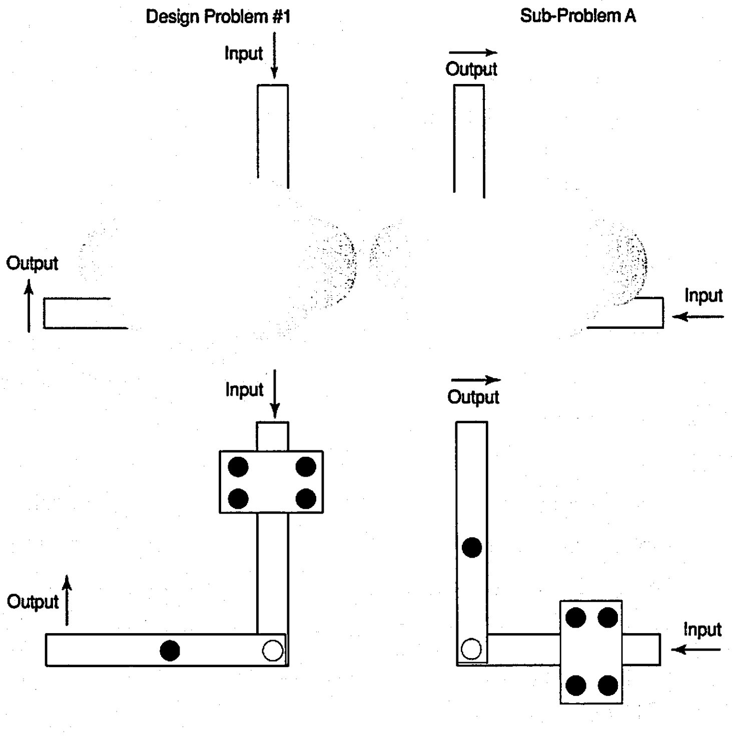
2-26: **Design Puzzle #3 broken into two sub-problems**



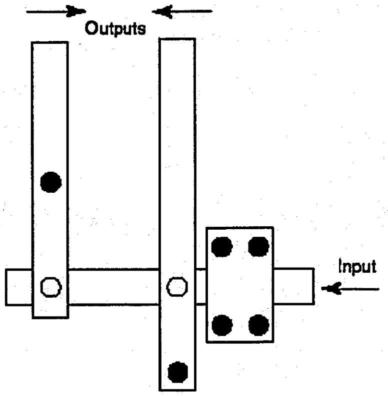
2-28: **Sub-problem B of Design Puzzle 3 is solved.**



2-27: **Comparing sub-problem A of Design Puzzle #3 with Design Puzzle #1**



2-29: **Solution to Design Puzzle #3**



How Circuits Work

The Flashlight, Revisited

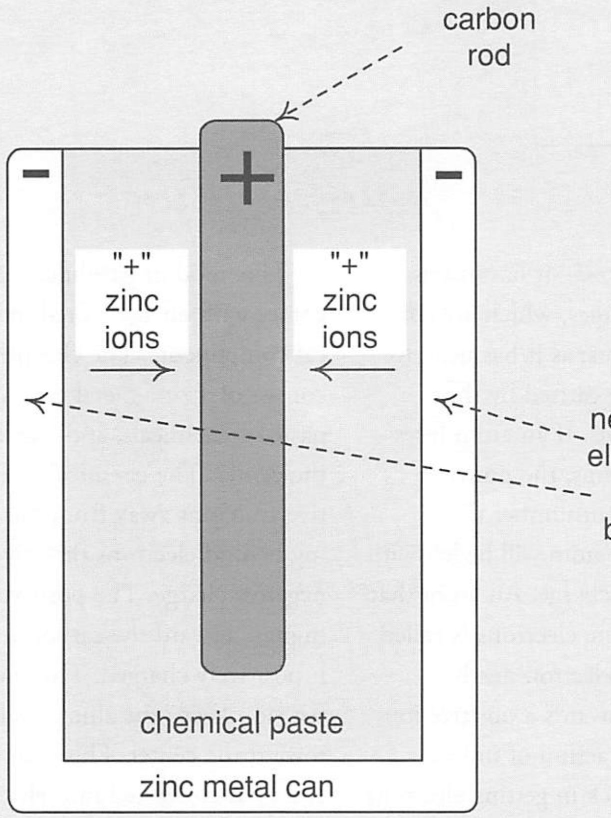
In Chapter 1, "Appetizers," we raised the question of how a flashlight works. We saw how the switch completes a circuit consisting of the two batteries, bulb, switch, metal strip, and metal spring. When the circuit is complete, the bulb should come on. In a way, this discussion raised a lot more questions than it answered:

- Why doesn't the bulb light when the switch is OFF, considering that the batteries are still in contact with the tip of the bulb?
- Why doesn't the current flow through the air? Why does it seem to flow only through the metal parts?
- What do the batteries do?
- How come the bulb lights up when a current passes through it?
- Which part actually produces the light?
- Why is there a glass bulb around the whole thing?
- What happens when a bulb "blows"?

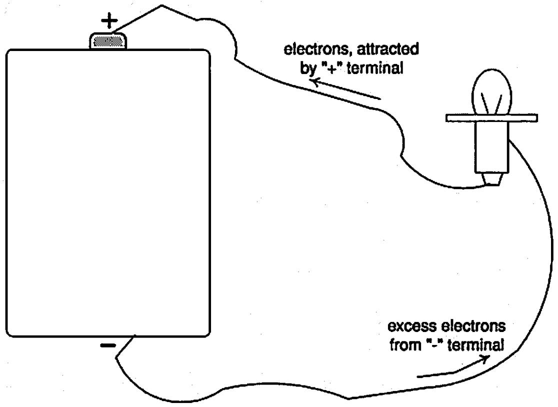
Let's start with some basic concepts of electricity. All electrical phenomena are explained by the existence of *charges.* These are invisible but very real properties that come in two varieties, which the early discoverers, such as Benjamin Franklin, arbitrarily called "positive" and "negative." It later turned out that electricity is mostly carried by *electrons,* which carry the negative charges. The important thing is that the flow of electricity requires that these little particles move from one place to another. This idea is suggested by words like *flow* and *current,* which make the analogy between electricity and the movement of fluids such as water.

Now, here is a little problem: What incentive is there to make these little negatively-charged electrons move? The answer is contained in the observation that like charges repel while opposite charges attract. This implies that if you have a bunch of electrons in one place, because they all have negative charges, they will try to get as far apart from one another as possible. On the other hand, if you can create a positive charge somewhere, electrons will be attracted there. How can you do this?

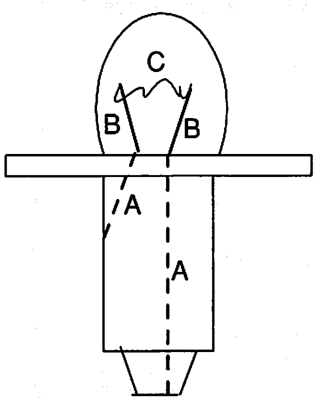
2-30: **Typical dry cell battery**



2-31: **Battery in a simple circuit**



2-32: **The parts of a small lightbulb**



Every *atom* is *neutral*—it has just as many positive charges, which are contained in its nucleus, as it has negative charges, which are carried by the circulating electrons. If an atom loses one of these electrons, the positive charges will now outnumber the negatives, and the atom will be left with an overall positive charge. An atom that has lost one or more electrons is called a positive *ion*. An electron nearby will be attracted towards a positive ion, because of the attraction of unlike charges. So, the trick in getting electrons to flow is to somehow remove electrons from a whole bunch of atoms.

So, to make a current flow, there has to be some special way of pulling electrons off of atoms and overcome the tendency of these atoms to hold on to the electrons. This situation is somewhat like rolling a rock up a hill. Obviously, the rock would "rather" stay at the bottom, but if you exert enough energy, you can roll it all the way to the top. In an electric circuit, the thing that "gets the rock up the hill"—i.e., pulls the electrons off the atoms—is the battery.

Like food or gasoline, the battery comes with energy stored in its chemical components. The cheapest batteries consist of a zinc metal can, a gooey paste of chemicals, and a carbon rod in the center. The chemicals attract positive zinc ions away from the can, leaving behind electrons that give the can a negative charge. The positive zinc ions migrate toward the carbon rod, making it positively charged. The chemical reaction keeps the zinc ions flowing toward the center. This is how chemical energy is converted into electrical energy, as shown in Figure 2-30.

Now, suppose we attach a light bulb to the battery, via two metal wires, as shown in Figure 2-31. Now, the excess electrons on the negative terminal of the battery, left behind by the departing zinc ions, have somewhere to go. Attracted by the battery's positive terminal, they flow through the bulb and back to the battery.

Why did we say that the wires had to be made of metal? Electrons can travel much more easily in some materials than in others. In a metal, there are a lot of electrons that are free to move fairly easily. These free-floating electrons account for all of the major characteristics of metals: they conduct heat, reflect light, and conduct electricity.

Next, let's see what happens in the bulb. A little bulb works the same way as an ordinary domestic light bulb. The only part that actually lights up is a thin wire filament made of tungsten, a relatively rare metal. (See Figure 2-32.) This filament (C) is supported by the two visible wires (B), which attach to the tip and the side of the base by some hidden wires (A).

Why does the filament light up, but not the other wires? The filament is a wire too, but it is so thin that it simply doesn't have enough room to carry all of the electrons easily. As a result, there are many more collisions within the filament than within a normal wire. These collisions heat the filament up until it glows, which accounts for the light. The glass bulb serves to keep oxygen out. If oxygen were present while the filament was white hot, the filament would simply burn up. You can see this happen occasionally with a domestic light bulb that hasn't been used for a while. Over time, air has leaked into the bulb, and the next time you turn it on, POOF!!! It glows very bright for an instant, and then blows.

Something else that can go wrong with this circuit is that the battery can go "dead." This happens when the chemical paste loses its power to push zinc ions away from the can and towards the carbon rod. Then there is no longer a mechanism for making the electrons flow in the circuit.

Now, suppose we add a switch to this circuit. You can make a crude switch just by disconnecting one of the wires and alternately touching it and removing it from the metal case of the bulb. (See Figure 2-33.) Why does the light go off when the wire is no longer touching? When the wire is removed, the electrons would have to flow through the air in order to complete the circuit. To make electrons flow through air requires a lot more energy than is available, because nearly all the electrons in air are tightly bound to atoms. The same is true of all the other materials known as *insulators.*

The makeshift switch that is made by disconnecting and reconnecting the wire does exactly the same thing as a manufactured switch, except that manufactured ones are more reliable. All they do is disconnect and reconnect the wires when you move the lever, push the button, turn the knob, or slide the button. The configurations in Figures 2-31 and 2-33 work the same way as the flashlight in its ON and OFF positions, respectively. In both cases, you have a battery, bulb, and metal pieces connecting them. The major differences are:

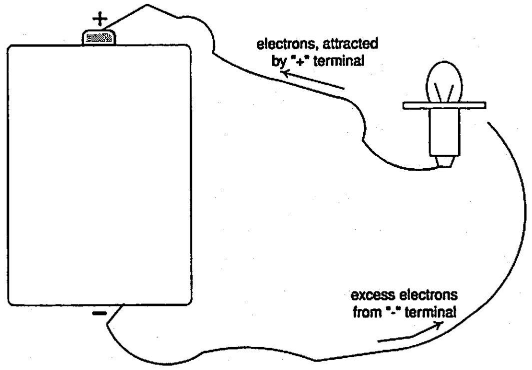
1. The flashlight has two batteries instead of one, and a more reliable switch.
2. In the flashlight, one of the batteries is directly in contact with the bulb, with no wire in between.
3. In the flashlight, there is a metal spring and metal strip connecting the battery to the other side of the bulb, instead of a wire.

From the point of view of the electrons, which do all the work in this circuit, none of these differences matters very much, except that two batteries give them twice as much energy as one. The circuit in the diagram is otherwise equivalent electrically to the flashlight circuit, although they look very different.

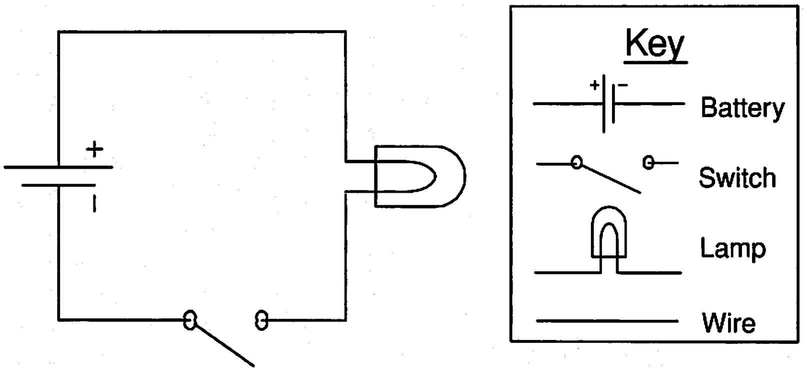
One way to show the equivalence between the circuits is to use a special kind of map called a *schematic diagram* to represent them both. A schematic uses a standard set of agreed-upon symbols to represent all of the components. Schematic diagrams are a bit like musical scores, in that all of the people who use them have learned to interpret the symbols.

Schematic circuit symbols save a lot of time and effort, because they leave out all of the details that are unimportant to the functioning of the circuit, such as the colors of the wires or how long they are. A schematic diagram of the flashlight circuit is shown in Figure 2-34. The standard circuit symbols are explained in the key.

2-33: **Simulating a switch by disconnecting a wire**



2-34: **Schematic diagram of flashlight circuit**



Circuit Concepts and Popular Beliefs

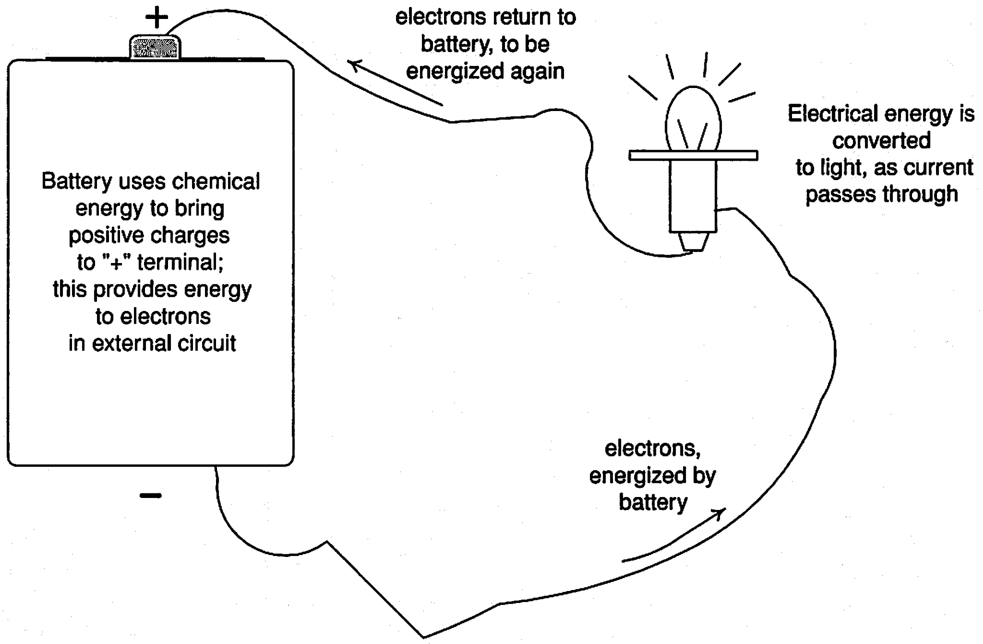
The picture we have presented so far of a basic circuit says that when the bulb lights, the following things happen:

1. Current, in the form of moving electrons, flows from one side of the battery, through the bulb, and back to the battery;
2. The battery supplies energy to the electrons, which the bulb converts to light and heat energy; and
3. The same amount of current flows all the way around the circuit, because the electrons eventually return to the battery to be energized again, as illustrated in Figure 2-35.

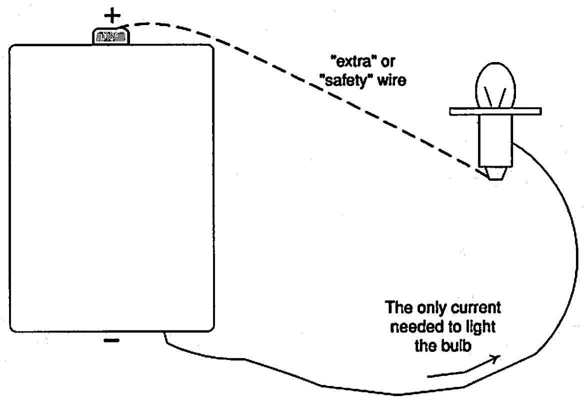
Although these are the basic ideas accepted by scientists, popular beliefs about circuits are quite different. These alternative ideas begin in childhood, as Tasker and Osborne (1985) show, and are still held by students who have passed college physics, as McDermott & Schaffer (1992) demonstrate. Few adults seem to develop the concepts accepted by modern science. According to this research, there are three basic "folk theories" of electric circuits:

1. The "single-wire" theory says that you really only need one wire to light the bulb. When confronted with the evidence that the bulb won't light, until the second wire is attached, children have claimed that the other wire is "just an extra" or "a safety wire." They see the battery as a thing that "gives" electricity, much as a faucet provides water. This theory may be a by-product of the analogy between water and electricity. (See next section.) This theory is shown in diagram form in Figure 2-36.
2. The "clash-of-currents" theory accepts that both wires are needed. It claims, however, that the current flow in each wire is toward the bulb. When the two currents reach the bulb from

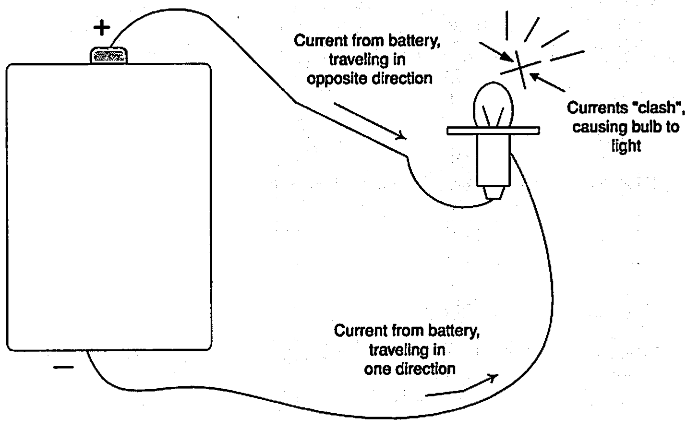
2-35: **Circuit operation, summarized**



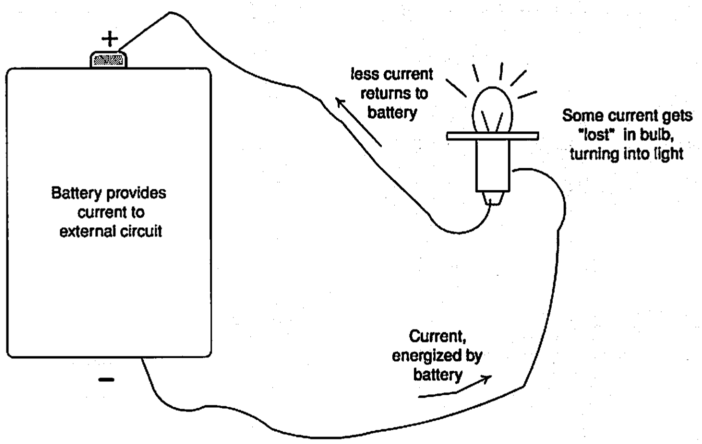
2-36: **The "single-wire" theory**



2-37: **The "clash of currents" theory**



2-38: **The "destroyed-current" theory**



opposite directions, they "clash," producing light. This idea is depicted in Figure 2-37.

3. The "destroyed current" theory says that the current leaves the bulb in the same direction that it came in, but says that some of this current gets "lost" or "destroyed" in the bulb. As a result, there is less current leaving the bulb than there was coming in. This theory identifies current, rather than energy, as the property of electricity that is converted into light. Therefore, some of the current gets "used up" in the bulb, and the current leaving is much less than that entering. A diagram is shown in Figure 2-38.

The research on popular concepts of electricity was designed to find out how people understand science concepts such as current and voltage. It involved circuits with batteries and bulbs only. Nearly everyone's daily experience with circuits involves turning them on and off with switches, but switches are not part of this research. Here is an example of the difference between a science orientation and a technology approach. Science education tries to teach the underlying principles of circuit operation, while technology education focuses on the uses of circuits in everyday life.

In our own work with electric circuits, we have found that prior knowledge of science concepts does not necessarily translate into an understanding of technology, and vice versa. Some teachers who were proficient with science units on "Batteries and Bulbs" had difficulty adding switches to their circuits or seeing the relationship between circuits in the laboratory and those in their homes. At the same time, other teachers with little or no experience in science could figure out quickly how to make simple circuits with switches and see how these related to their own experiences. Science and technology look at the same artifacts in different ways, and the kinds of knowledge they emphasize are different.

Circuits, Mechanisms, and Analogies

In some ways, circuits are a lot like mechanisms. Both circuits and mechanisms have inputs and outputs and both are examples of systems. In the circuits we have considered so far, the inputs were switches and the outputs were light bulbs. In both circuits and mechanisms, there is a direct cause-and-effect relationship leading from the inputs to the outputs: throwing the switch makes the bulb light and operating the handle of a pair of nail clippers makes the jaws come together.

Unfortunately, circuits are not nearly as easy to explain as mechanisms. In a simple mechanism, you can usually figure out how the input leads to the output just by looking closely at all of the moving parts. The inner secrets of an electric circuit are much harder to fathom, because you can neither see nor touch the tiny electrons that are doing all the work. A simple mechanism is more-or-less transparent; you can take it apart and see for yourself how it works.

Because you can't see inside circuits, some analogies have been developed to make them easier to understand. These analogies are statements that "a circuit really works a whole lot like such-and-such," where "such-and-such" is something that you *can* see and/or touch.

The most commonly used analogy relates the flow of electricity to the flow of water. The wires are like pipes, a switch is like a valve or faucet, and a battery is like a pump. The energy of flowing water could be converted to a useful form—for example, into turning a water wheel or turbine. This device would be analogous to a light bulb.

However, there is a major difficulty with this water analogy. The most familiar water flow systems involve plumbing fixtures such as sinks, toilets, bathtubs, and washing machines. All of these are *open systems,* which do not recirculate the water once it has been used. It simply goes down the drain and is replaced by new tap water. In an electric circuit, on the other hand, there must be a complete, closed path or the electrons will not flow anywhere in the circuit. After they have lost their energy, for example in a light bulb, they must be returned to the battery to make their journey again. Most circuits are *closed systems* where the "electrical fluid" is recirculated.

In order to make a better analogy, we need to think of a closed system that keeps the same fluid flowing continuously in a circuit. Here are two examples of closed fluid flow systems:

- A building that uses steam heat has a closed system of pipes. These lead from the boiler, which turns water to steam. The steam passes through all of the radiators in the building, where it heats the indoor spaces. Eventually it turns back to water and returns to the boiler, where the cycle starts over.
- A car radiator cools the water/antifreeze mixture that carries heat away from the engine. This fluid is forced through the engine by the water pump, and then back to the radiator where it gets cooled again.

In both systems, a fluid is forced through the system by a boiler or pump that gives it energy, playing the same role as a battery in a circuit. As it flows, it heats or cools the environment, which is analogous to the electrons making the bulb light up. Finally it returns to the original heater or pump, and begins the cycle again. Each of these systems is a closed circuit, like an electric circuit, in that the same stuff flows around and around. The problem is that these systems are also closed in the sense that you can't see what's going on inside them!

To visualize an electric circuit, we need to make an analogy with some kind of circuit that is open to view. One possible analogy is with a roller coaster. At the bottom of a hill, the cars are attached to a tractor, which pulls the cars up a big hill. At the top of the hill, the cars are released, and they coast down to the bottom. The energy they have gained sends them up another small hill. Eventually, they return to the foot of the big hill, and the tractor does its work again. The tracks of the roller coaster are similar to the wires in a circuit, and the cars are like the electrons. The tractor is like the battery. When they go up a little hill, from the energy gained by going down the big one, that is analogous to lighting a bulb. There is, however, a problem with this analogy too. On a roller coaster, there are cars in only a few places, while in an electric circuit, the flow is continuous, like the flow of water.

Circuit Situations Revealed!

In Chapter 1, we presented some electric circuit "situations" and asked you to think about how they might work. The three situations were:

1. The Lamp, which will light when both its own switch and the switch on the power strip are ON;
2. The Yard Light, which will come on when either or both of the two switches are ON; and
3. The Stair Light, which can be turned either ON or OFF by either of two switches, located at the head and foot of the stairs, respectively.

In Chapter 1, we described these situations in Tables 1-2, 1-3, and 1-4, respectively, which show the condition of each light for every possible condition of the switches. In each case, there are two switches, which we can call "A" and "B". Using this shorthand, we have combined the data for all three cases into Table 2-3.

Table 2-3

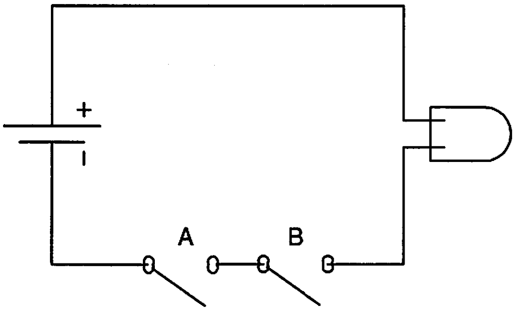
THREE ELECTRIC CIRCUIT SITUATIONS

Switches		Lights		
A	B	Lamp	Yard Light	Stair Light
OFF	OFF	OFF	OFF	OFF
OFF	ON	OFF	ON	ON
ON	OFF	OFF	ON	ON
ON	ON	ON	ON	OFF

The Lamp Situation

In the Lamp Situation, both switches need to be ON for the lamp to work. Another way of saying this is that either of the switches, if OFF, could prevent the lamp from working. Suppose we have a complete circuit with no switches, such as the one shown in Figure 2-31. Now suppose that one of the wires is broken in two places. This would prevent the current from making a complete circuit, and keep the light off. Repairing only one of the breaks will not help, because the current will still be blocked by the other break. Only when both breaks are fixed will the lamp come on again. Now imagine that we use switches to replace the breaks in the wires. Using the language of schematic diagrams, this circuit would be shown as in Figure 2-39.

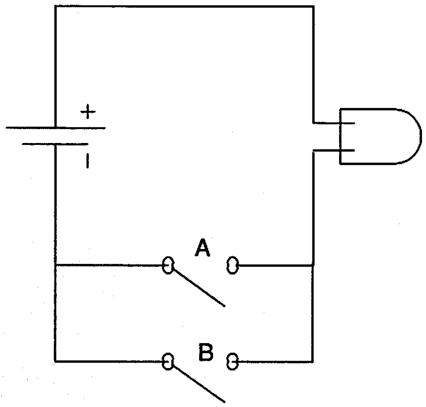
2-39: **The Lamp Situation**



Let's see whether this circuit solves the lamp problem. Mentally put both switches in the ON (UP) position. There is now a direct path from the battery to the bulb, as in Figure 2-31. Move either switch (or both) to the OFF (DOWN) position, and the circuit is broken, just as in Figure 2-33, and no current flows to the bulb. This is the circuit we were looking for. In this case, the switches are said to be arranged *in series,* because all the current through one must go through the other.

The Yard Light Situation

2-40: **The Yard Light Situation**

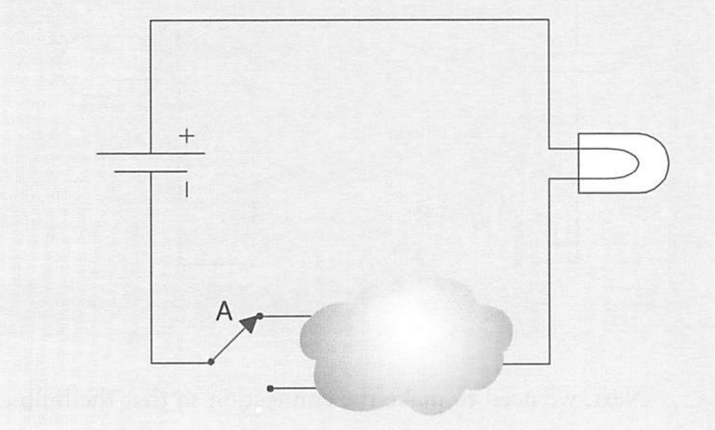


In the Yard Light Situation, either switch can make the bulb light. In other words, neither switch, by itself, can keep the light off. It's only when both switches are OFF that the bulb is shut down. How do you make a circuit that works this way? Suppose you were connecting a battery to a bulb with a long wire, but you were afraid that someone might accidentally break the wire. One strategy would be to run another wire along a different path, connecting the same battery and bulb. In case one of the wires got broken, the other would still be available to carry the current. For the bulb to turn off, both wires would have to be broken. Now replace the breaks in the two wires with switches. This would give you the circuit is shown in Figure 2-40.

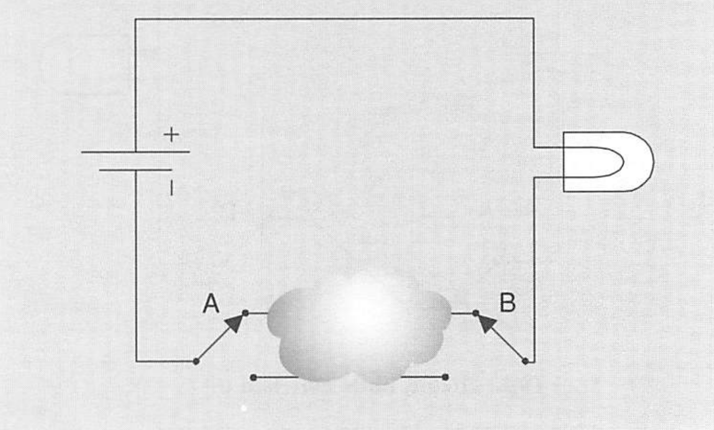
Each of the two paths from the battery to the bulb will work as long as its switch is UP, i.e., ON. Because the two switches are connected end-to-end at both ends, they are said to be *in parallel.*

The Stair Light Situation

2-41: **Two-way switch installed**



2-42: **Another two-way switch**



The Stair Light Situation is the most subtle of the three. There is no simple series or parallel connection that solves this one. In the Yard Light Situation, there were two ways to turn on the light: switch A or switch B. Each of these alternatives involves only one switch. If either one of the switches is ON, it doesn't matter what the other switch is doing.

In the Stair Light Situation, there are also two ways to turn on the light. But with the Stair Light Situation, each method depends on both switches. The two ways are:

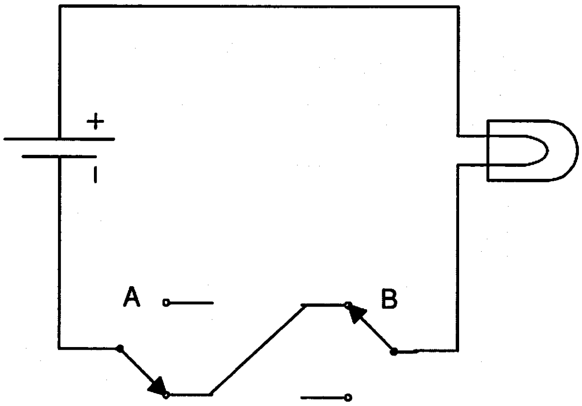
- Switch A is OFF (DOWN) and switch B is ON (UP); or
- Switch A is ON (UP) and switch B is OFF (DOWN).

From this description, we can see that turning the lamp ON could involve either the UP or the DOWN position of each switch. This was not the case in the Lamp and Yard Light Situations, where only the UP positions were used to make the current flow. As a result, the Stair Light requires a different kind of switch, one that could carry current when either up or down. This "two-way" switch is shown in Figure 2-41. Note that the movable part of the switch, represented by an arrow, can attach to either of two terminals (UP or DOWN), each of which has a wire leading from it. We have put a "cloud" over these wires, because we haven't decided yet what to connect them to.

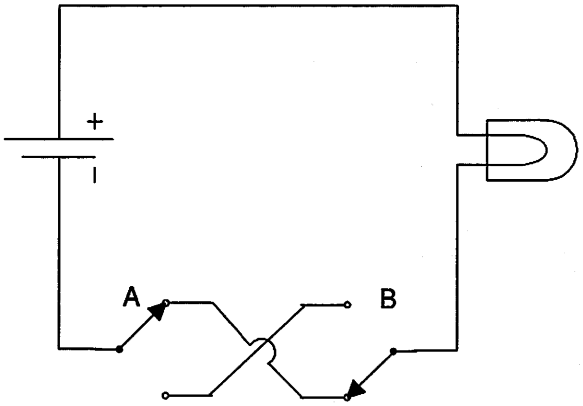
So far, we have installed one of the two switches, "A." Since both switches work exactly the same way, we will need another of these two-way switches for "B." As we have seen, current will need to go through both switches in order to light the bulb. So, our next step is to put a second two-way switch, "B," in series with "A." This additional switch is shown in Figure 2-42. There is still a "cloud" between the two switches, because we haven't decided yet how to connect them.

Now, let's take just one of the ways the bulb could light: Switch A is DOWN, and switch B is UP. If we connect a wire from the DOWN terminal of switch A to the UP terminal of switch B, and put the switches in those positions, we should get a complete circuit, as shown in Figure 2-43. This is one of the two possible ways of making the bulb light.

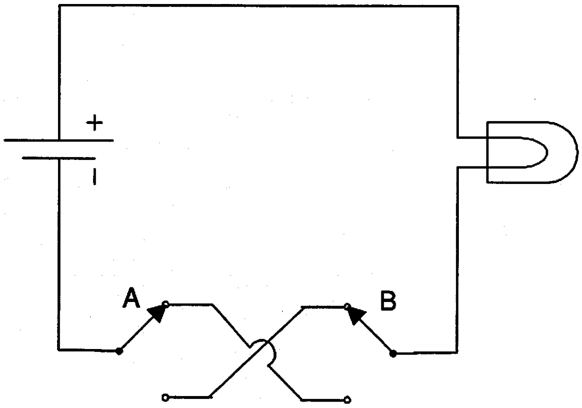
2-43: **One way to turn on the Stair Light**



2-44: **Adding the other way to light the Stair Light**



2-45: **Stair Light circuit, both switched UP**



Next, we need to make the connection so that the bulb can light the other way: Switch A is UP and switch B is DOWN. This connection, which is simply the opposite of the one we just made, is shown in Figure 2-44. The little hook where the wires cross is a symbol that indicates "the wires are not touching each other."

Now let's check to see that this circuit works in all of its configurations. Figure 2-45 shows the case where both switches are UP. The bulb should not light, and it doesn't, because there is no complete circuit. The same would be true if both switches were DOWN. We have solved the mystery!

Beyond Electricity: Controlling Fluids and Mechanisms

Control and *control system* are two of the "big ideas" of technology. One way around the conceptual difficulties with circuits is to approach them using these broader concepts. From the point of view of controls, an electrical switch is just one of many devices that controls the flow of energy. A circuit is just one kind of control system, which processes energy based on information from its control device. We turn next to a discussion of controls, including both electrical and mechanical types.

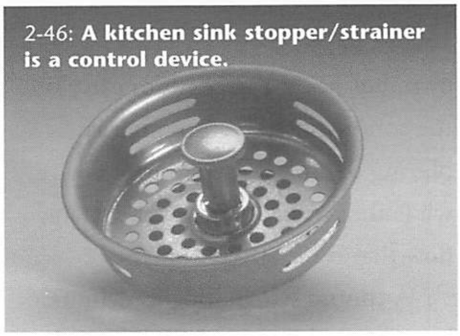
In previous sections, we have looked at devices that control the flow of electricity. Many if not most of the controls we encounter daily are electrical, because electricity is very easy to move from one place to another and to transform into different forms of energy. However, even in our highly electrified world, there are other kinds of flows and motions that can be controlled. In this section we will consider other kinds of controls.

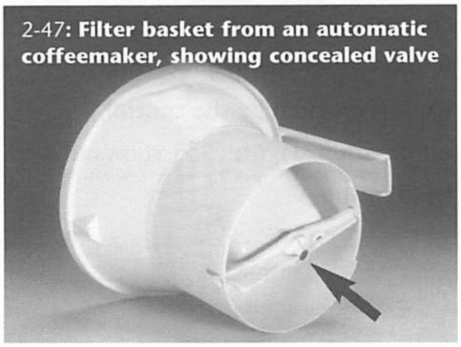
As we have seen, there are strong analogies between the flow of electricity and the flow of fluids, although there are also important differences. Although we normally think of fluids as liquids, gases are also fluids that flow in much the same way as liquids. If you have a gas stove, a gas furnace, a gas dryer, or a gas hot water heater, you can notice plumbing connections to these devices that look quite a bit like plumbing for water. The fluid in this case is natural gas. Compressed air is another gas that is frequently transported through pipes and hoses. Most service stations have compressed air hoses for filling tires.

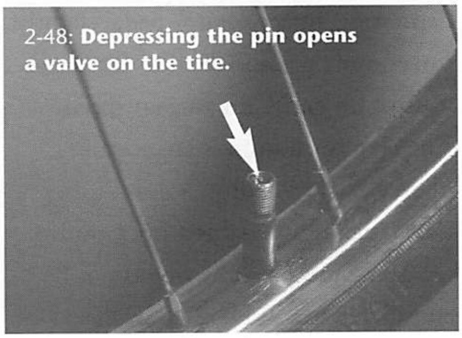
Electrical switches are sometimes compared with shut-off valves, which are used in plumbing to start or stop the flow of gas or water. Faucets are a little different from shut-off valves because they have many positions between completely ON and completely OFF. With these devices, the user can adjust the flow from a trickle to a strong, steady flow, or anywhere in between. By analogy, with electronic devices, a shut-off valve is a *digital* device, like a switch, with only two positions, ON and OFF. A faucet is an *analog* device, which is continuously variable from ON to OFF. Other control devices for fluids include:

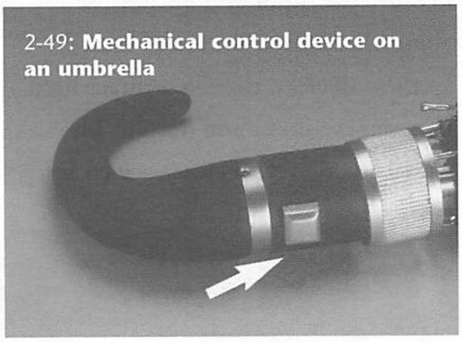
- a handle used to flush a toilet;
- a valve that permits air flow into an inflatable toy, raft, or air mattress;
- a burner control knob on a gas range or oven;
- an adjustable nozzle on a hose or shower head;
- a kitchen sink stopper/strainer (see Figure 2-46); and
- a nozzle that adjusts the spray from a hose or shower head.

Can you tell which of these are analog and which are digital?


2-46: **A kitchen sink stopper/strainer is a control device.**


2-47: **Filter basket from an automatic coffeemaker, showing concealed valve**


2-48: **Depressing the pin opens a valve on the tire.**


2-49: **Mechanical control device on an umbrella**

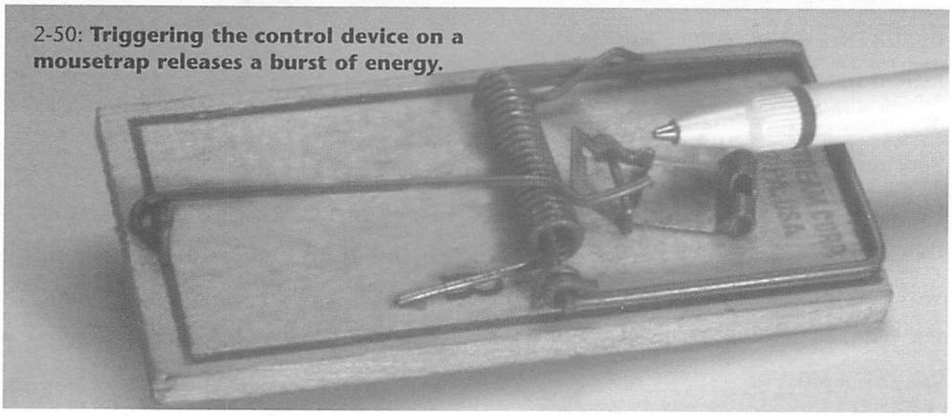
Some controls for fluids are of the hidden type. For example, Figure 2-47 shows a filter basket from an automatic coffee maker. The user puts the coffee grounds and filter into this basket and inserts it into a slot in the coffeemaker. Inserting the basket fully into the slot activates a little valve at the bottom center. The valve allows the water through the basket only when the basket has been properly positioned. Except that it operates on water, not electricity, this valve is very similar to the hidden pencil sharpener switch shown in Figure 1-55. A valve on a bicycle or automobile tire (Figure 2-48) is another example of a concealed control device for fluids. This type of valve has a little pin in it, which opens the valve when depressed by a matching pin at the end of the air hose.

We have also seen some controls in our discussion of mechanisms. A door lock (Figure 1-11) can be seen as a control that regulates the flow of people into and out of a room or house, much as a valve controls the flow of water or gas. An umbrella has a push-button (Figure 2-49) that releases a large spring, causing the entire umbrella to open. A bicycle handbrake (Figure 1-10) is part of a control system, operated by a lever on the handlebars, which causes the entire bicycle and rider to come to a stop.

The umbrella release button, cylinder lock, and bicycle handbrake are all examples of mechanical control devices. In each case, a small amount of energy at the input (the control) unleashes a much greater flow of energy elsewhere. A graphic example of a mechanical control device is the mousetrap, shown in Figure 2-50. If the trap is set properly, the unwitting "user" (a mouse) exerts ever so little energy to release the trap, and WHAM!!! A much larger burst of energy is released by the spring!

A similar description applies to electrical switches and fluid controls. A tiny bit of energy at the input—the flick of a switch or turning of a valve—can control a large flow of electrical or mechanical energy elsewhere. Pushing an elevator button, which is nearly effortless, can cause a huge motor to lift thousands of pounds. Similarly, depressing an accelerator pedal slightly forces more gas and air into the engine, causing an entire car to gain speed. The elevator button is an example of an electrical control, while the accelerator pedal is a fluid control.

Some mechanisms would not be considered examples of controls because the input and output use about the same amounts of energy. In these devices, there is a direct link between the input and output. The wastebasket, eyelash curler, ice cream scoop, egg topper, pizza tray holder, etc., are not really control devices for this reason. In these cases, the control is not really separate from the thing controlled. A control system has to have some way of storing energy, so that the control device can release it on demand. In a mousetrap or umbrella, mechanical energy is stored in a spring. A battery performs the same function in an electric circuit, and a tank stores gravitational energy for a toilet by holding water above the level of the bowl.


2-50: **Triggering the control device on a mousetrap releases a burst of energy.**

Controls Defined

We have given some examples of what we call controls, but we have not explained what the term really means. Because the word *control* has so many meanings in everyday life, it can be difficult to pin down what is and is not a control. In technology, *control* has a precise meaning. It involves two activities: the flow of information and the flow of energy.

Imagine a professional wrestler who has never learned the script for the bout. A prompter, standing by the side of the ring, whispers each instruction: "Grab him by the waist... Lift him up... Twirl him around your head...." The prompter is sending information, in the form of commands, but is himself expending very little energy. The wrestler, on the other hand, is processing a great deal of energy, but only on the basis of information received from the prompter. One member of the team, the prompter, has plenty of information, and decides what should be done at any moment, but lacks the power to do it. The other member, the wrestler, lacks any information of his own, but has the strength to carry out the commands. The prompter is playing the role of the control device, while the wrestler handles the energy flow that is being controlled.

A control system, by this definition, has a control input, which uses little energy to communicate information. It also has an energy processor, whose work is dictated by the control information. Figure 2-51 shows this relationship.

In any control system, we should be able to identify three basic elements:

- The control input;
- The energy processor that is controlled; and
- The form of the energy that is processed.

Table 2-4 gives some examples of common control systems, with each of these elements identified.

In all but one of the control systems we have examined so far, a human user supplies the information to the control input. (The one exception is the mousetrap, where the unfortunate "user" is a rodent.) Consequently, these are sometimes described as *manual control systems.* There are many important control systems that do not depend on human inputs, because they generate their own information. These are known as *automatic control systems.*

2-51: **Control system block diagram**

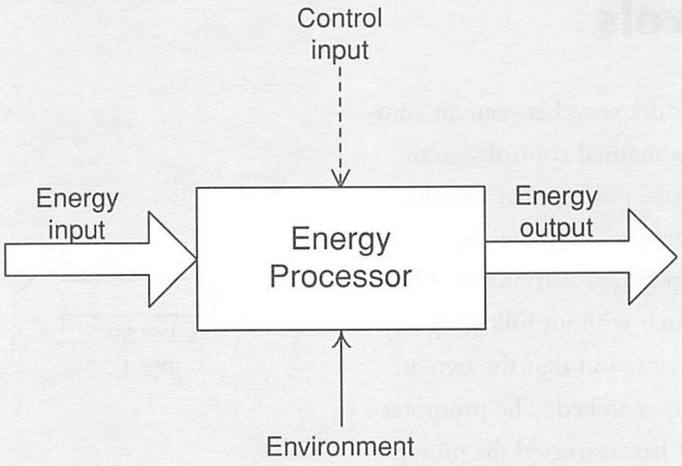


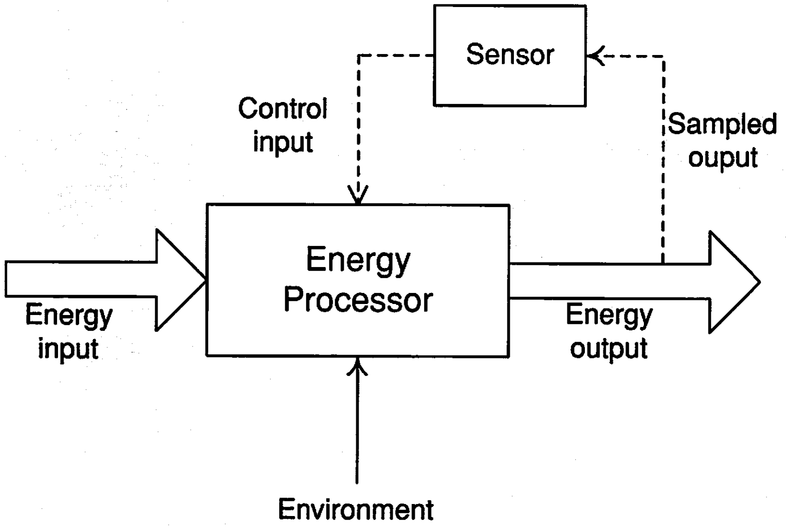
Table 2-4

SOME CONTROL SYSTEMS

System	Control input	What is controlled?	Nature of energy flow
Mousetrap	Release lever (activated by mouse)	Trap arm	Release of energy stored in spring
Stovetop	Burner control knob	Gas burner	Flow and combustion of gas, releasing heat energy
Car	Accelerator pedal	Engine	Flow and combustion of fuel; energy of motion of the car
Door lock	Key	Door	Energy of motion of people passing through
Electric circuit	Switch	Light bulb	Electric energy supplied by battery; light energy radiated by bulb
Hose	Nozzle	Water spray	Energy of flowing water

Automatic Controls

2-52: **Automatic control system**



To see the difference between an automatic and a manual control system, let's revisit our professional wrestler and his prompter. Suppose the wrestler's opponent is trying his best to win the match without following any prepared script, and that the two are about evenly matched. The promoter of the event has instructed the prompter of the first wrestler to prolong the match as long as possible, for commercial reasons. What strategy should the prompter follow in order to prevent his man from either winning or losing?

Recall that in the original example, the prompter made his wrestler follow a predetermined script. In this new case, the opponent adds an unpredictable element to the situation. If the prompter's man is winning, the prompter should not let him continue beating up his competitor and risk ending the bout prematurely. On the other hand, if the same wrestler is losing, the prompter should give him the moves he needs to get back in the match.

In this situation, where an adversary provides a varying context, the prompter sizes up the situation before issuing instructions. He always tries to reverse whatever is happening at the moment in order to keep the bout on a neutral course. If his man is winning, he tells him to slow it down, and vice versa. Translating this example to the realm of devices, imagine a system where the human prompter is replaced by a circuit and/or a mechanism. Such a device would use information about the state of things to turn energy flows on or off. This type of setup is called an automatic control system, because it operates on its own, basing its actions on its own data about each current situation.

The best known example of an automatic control system involves the thermostat system used to control heating and air conditioning in a house. Thermostats are also used to maintain the desired temperature in refrigerators and in some ovens, irons, and electric blankets. After the user sets the desired temperature, the thermostat monitors the actual temperature continuously. The monitoring device, in this case a thermometer, is called a *sensor.* Once the temperature reaches the desired level, the thermostat turns the heating or cooling device off.

Every automatic control system relies on some sort of sensor to provide information about the outcome. This information feeds back to the control device, which in turn modifies the energy flow accordingly. For this reason, automatic control systems are sometimes called feedback systems. A block diagram of an automatic control system is shown in Figure 2-52. The dashed line from "Sampled output" to "Control input" is sometimes called the *feedback loop.* It transfers information only. Because of the presence of this loop, which returns back from the output to the input, a feedback system is sometimes called a *closed loop system.* The manual control system, which lacks feedback, is called an *open loop system.*

Let's look at how the information from the thermometer is used in a thermostat-controlled home heating/cooling system. If the air is too warm, the thermostat senses this and tells the air conditioner to come on; conversely, if it the temperature is too low, it activates the furnace. In either case, the actual conditions are the basis for deciding what to do next. The purpose is always to restore the temperature to a comfortable setting. The thermostat plays the role of the prompter—it controls the energy sources that bring the temperature back to the desired value. The energy sources are the furnace and the air conditioner, and these are analogous to the wrestler who obeys the instructions of the prompter.

Who plays the role of the adversary in the home heating/cooling system? Automatic control systems are designed to provide shelter from unpredictable changes in the natural and artificial environments. In the case of a thermostat system, the "adversary" includes both natural events, such as changes in outdoor temperature and sunlight; and human activities, such as opening and closing windows and doors, and turning lamps and appliances on or off. All of these affect the indoor temperature. These factors that make the control system necessary can be collected under the heading *environment.*

Manual and the automatic control systems both respond to changes in the environment, but they do so differently. A manual control system depends on a human user to recognize that the environment has changed and to compensate using the control input. For example, if a car is slowing down because it is going uphill, the driver recognizes this fact and operates the accelerator pedal. An automatic system senses changes in the environment and operates the control input automatically, eliminating the need for a human operator in the feedback loop. For example, a car with cruise control does not depend on the driver to use the accelerator. Instead, it uses its own data about the speed of the car to speed the engine up or slow it down.

Table 2-5 gives some examples of automatic control systems found in everyday life.

Table 2-5

EXAMPLES OF AUTOMATIC CONTROL SYSTEMS

System	Control input	Sensor	Energy flow that is controlled	Environment against which system operates	Goal of system
Home temperature control (thermostat)	ON/OFF switches of furnace and air conditioner	Thermometer	Furnace and air conditioner	Natural and artificial variations in temperature	Maintain indoor temperature at desired value
Automotive cruise control	Throttle opening	Speedometer	Car engine	Friction, variations in road surface, hills	Maintain desired speed
Tank toilet	Valve, which allows water to fill in tank	Float and arm, attached to valve	Flow of water into tank	Flushing of toilet, evaporation, leakage	Maintain water level in tank
Automatic sprinkler for fire protection	Glass bulb, blocking water supply	Liquid in bulb expands when hot, breaking bulb	Flow of water into room	Possibility of fire	Extinguish fire from room
Steam iron with "automatic shutoff"	Automatic shutoff switch	Motion sensor, detects that iron has not been moved for 10 minutes	Heat flow through iron	User forgets to turn it off	Prevent iron from starting fire by heating one place too long
Exposure control of automatic camera	Lens opening (f-stop)	Light sensor	Amount of light allowed through aperture and lens	Amount of ambient light varies in time and space	Prevent film from being over- or under-exposed

Feedback Control in Nature and Society

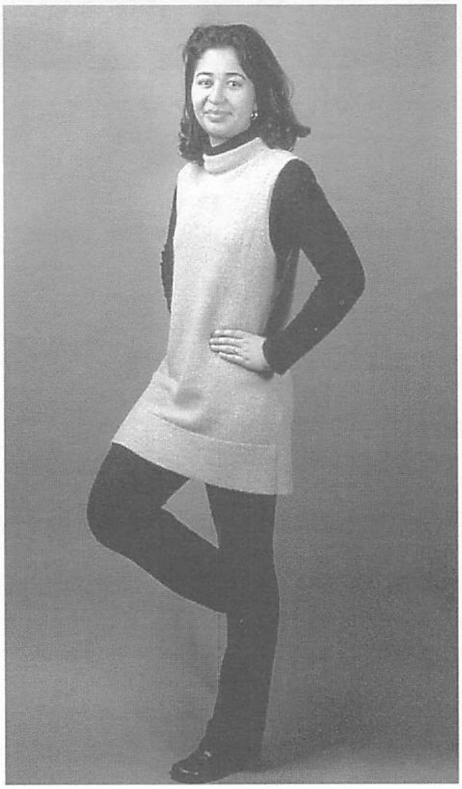
All of the examples in Table 2-5 are from the world of technology. Nature, too, abounds in feedback systems. Here are some simple experiments you can do to explore how feedback works in your body:

1. **Try to touch your toes, standing with your back to a wall.** You can't do it! Why not? To answer this, watch from the side while someone whose back is not against a wall touches his or her toes. Notice how the rear end moves back as the person leans down. This movement is necessary to keep one's balance. Otherwise, too much of the weight is leaning forward, and it is impossible to avoid falling forward, which is what happened when your back was against the wall. When you touch your toes normally, feedback tells your muscles to move your buttocks back, so you won't fall over.
2. **Stand on one foot.** With a little effort, you can probably keep your balance with one foot off of the floor. (See Figure 2-53.) However, you may notice a series of jerky movements, as you lean too far in one direction, then another, and your feedback system compensates by telling your muscles to move in the opposite direction. Now, close your eyes. It is now much harder to remain standing on one foot, and you will probably have to use your arms to keep your balance. (See Figure 2-54.) That's because your major source of feedback information—vision—is no longer active.
3. **Trace a drawing using a mirror.** On a piece of paper, draw a simple figure such as a square or star. Then place the drawing in front of a mirror. Looking only in the mirror, and not at the drawing directly, try to trace the figure you have drawn, as shown in Figure 2-55. It is much harder than normal tracing because the mirror image has disrupted the normal feedback from eye to hand.

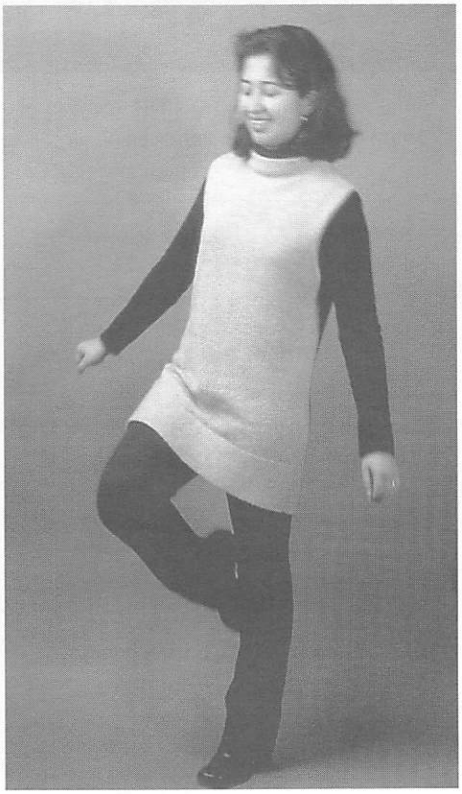
Here are some more examples of feedback in the human body:

- Body temperature is regulated by a complex system that tries to maintain it at 98.6 degrees, regardless of outside temperature or level of physical activity. This system causes sweating to occur when the body temperature starts to rise. It also causes shivering when the temperature drops too low.
- The pulse and breathing (respiration) rates are controlled by another complex feedback system whose goal is to supply sufficient nutrients and oxygen to all parts of the body. The system does this by increasing the

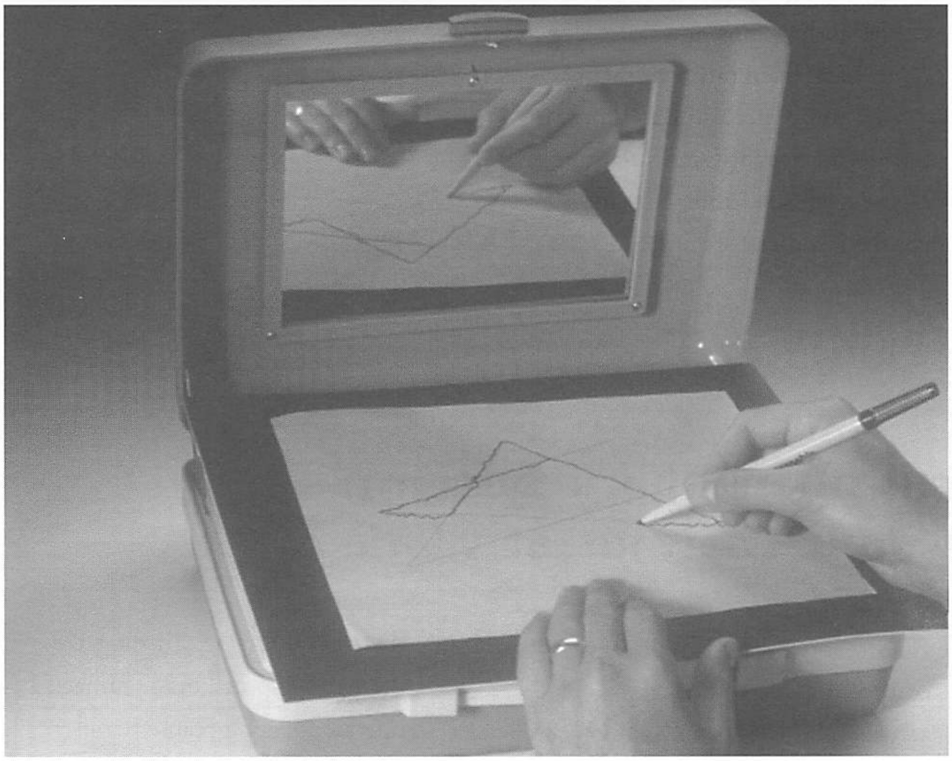
2-53: **Keeping one's balance on one foot**



2-54: **Keeping one's balance on one foot is harder with eyes closed.**



2-55: **Trying to trace a drawing reflected in a mirror**



pulse and respiration rates during periods of intense activity and decreasing them when the body is at rest.

- The light input to the eye is controlled by the pupil. It plays exactly the same role as the aperture (or "F Stop") in a camera. In broad sunlight, the pupils close, so that little of the light will enter. In a darkened room the pupils open up to let in as much light as possible. The adjustment can take some time, and the system can be overwhelmed by rapid changes in the environment. For example, the light suddenly bothers you when you emerge from a tunnel or building on a bright, sunny day.

The human body is only one example of a natural system. Every biological organism utilizes many different forms of feedback control to maintain its internal environment against changes and challenges from outside. A plant that grows towards the light is regulated by a complex feedback system that senses light and uses this information to control growth.

Feedback is also an essential element in longer-term and larger-scale natural systems such as biological evolution, plant and animal populations, ecosystems and the global climate system. Let's look briefly at this last system.

The earth's atmosphere contains a delicate balance of gases, the most important of which are oxygen and carbon dioxide. Green plants have produced nearly all of the oxygen, while most of the carbon dioxide is released by the ocean or by animal life. For millions of years, the amounts of these gases have been prevented from changing rapidly by complex feedback mechanisms. As carbon dioxide concentrations increase, more plant growth is stimulated, which in turn removes some of the carbon dioxide from the atmosphere. On the other hand, increases in oxygen benefit animals, which replace the excess oxygen with carbon dioxide. Recently, however, the destruction of forests and burning of fossil fuels threaten to overwhelm this natural feedback, leading to sharp increases in carbon dioxide and global warming.

Feedback is also a major factor in nearly every social enterprise, from the very smallest to the very largest. A teacher routinely uses feedback in the design of lessons, of student groups, of classroom arrangements, etc. She tailors each of these to her students' needs by continuously monitoring what works and what doesn't, and making corrections based on this information. What can make lectures so stultifying is the lack of feedback from the students back to the teacher. The same is true of instruction driven by standardized tests, because it takes so little account of students' needs and interests. Larger social systems, such as cities and nations, must also depend on feedback from ordinary people in order to be successful in addressing their needs. Social systems that do not use feedback can legitimately be described as dictatorships.

Popular Conceptions of Feedback Systems: Do You Know How Your Thermostat Works?

Although feedback and automatic control are key concepts in modern science and technology, they are probably not well understood by most people. Although words like feedback and loop have crept into everyday language, their technical meaning is often lost. "Can I have your *feedback?"* (Translation: "Are there any comments?") "These days, I am completely out of the *loop!"* (Translation:" I am not in the inner circle.")

So, what do people really know about feedback and control? Kempton (1987) did a study on "folk theories" of home heating control. Based on interviews and actual recordings from homeowners thermostats, he describes two different theories people have about these devices:

1. The "valve theory" assumes that a thermostat works like a faucet or accelerator pedal. The higher you set it, the more rapidly the heat gets pushed into the room.
2. The "on-off theory" says that the thermostat turns the furnace on whenever the temperature in the room is below the thermostat setting. Turning the setting up makes the furnace operate longer, because it will take more time to reach the desired temperature, but not faster, because the furnace can only operate at one speed.

The "on-off" theory gives the most accurate description of how a thermostat really works, but the valve theory is the most widely held. Most people think that they can make the room warm up faster by turning the temperature setting way up.