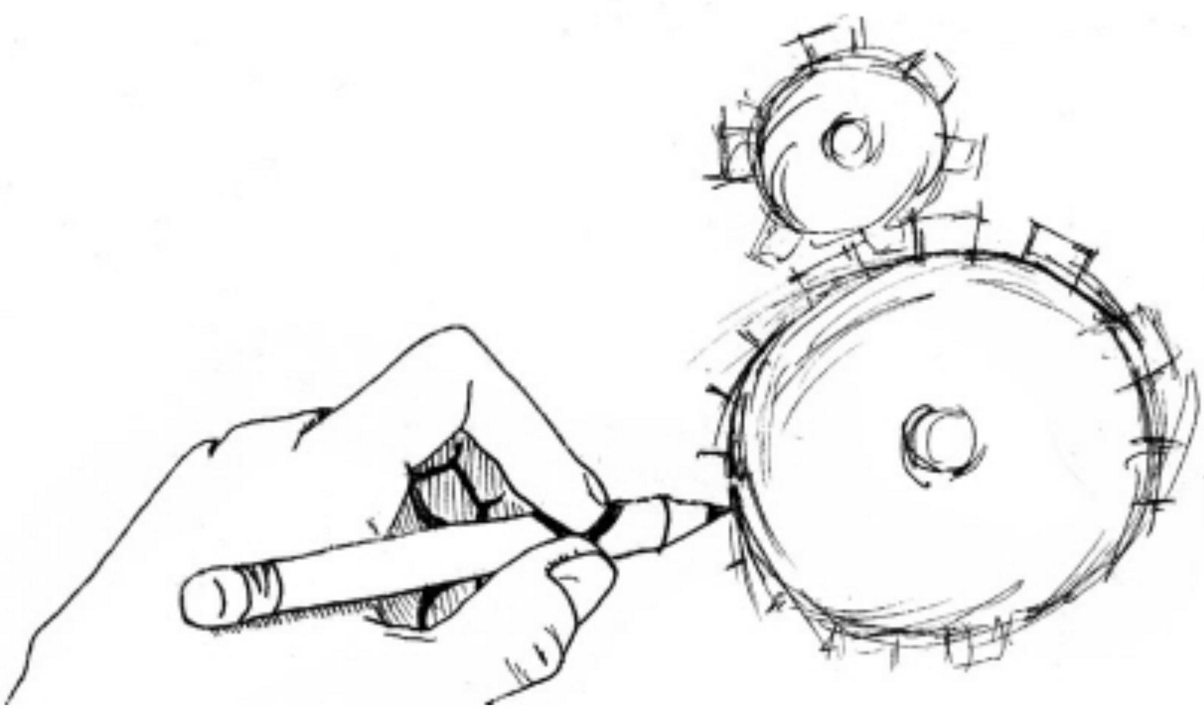
8

Combining Simple Machines for Work and Fun



For hundreds of years, engineers and designers have been coming up with ways to convert rotary motion into useful work. You already know how to choose a motor and attach something to it, but maybe the output you're looking for isn't a simple rotary motion.

In this chapter, we'll explore how to convert rotary motion into more complicated motions by combining simple machines. First, we'll go over some general mechanisms you can use, and then we'll cover the basic types of motion and ways to convert between them. Finally, we'll look at some examples of combining simple machines to create kinetic sculpture and mechanical toys. Whether you combine simple machines for work or for fun, the applications are limited only by your imagination and, I suppose, some pesky laws of physics.

Mechanisms for Converting Motion

Rotary motion—the most common input motion—can be converted into more complicated motions through systems of cams and followers, cranks, linkages, and ratchets. All complicated machines, mechanisms, and robots are made up of combinations of simple machines like these. They help us convert rotary motion into linear, up and down, oscillating, or intermittent output motion. Cornell University keeps a library of examples that can be accessed online as the Kinematic Models for Design Digital Library (http://kmoddl.library.cornell.edu). The work of Cabaret Mechanical Theatre (www.cabaret.co.uk) and Flying Pig (www.flying-pig.co.uk) highlight more whimsical examples.

This is a great time to start taking things apart, if you haven't already. Many toys, appliances, and other everyday devices have built-in mechanisms that you can use—either directly in your projects or as inspiration for their design.

Do you have an old printer that doesn't work? Then you probably have two stepper motors that turn rotary motion into the linear motion of the print head with a system of timing belts, pulleys, steel shafts, and bushings. Do you have an old Hokey Pokey Elmo? You will find many treasures inside, including motors and linkages. Scavenging parts from consumer products that benefit from economies of scale to keep prices down is a great alternative to buying components piece by piece, which is always more expensive. You can also use these parts to do some 3D sketching of your ideas before committing to more permanent designs and materials.

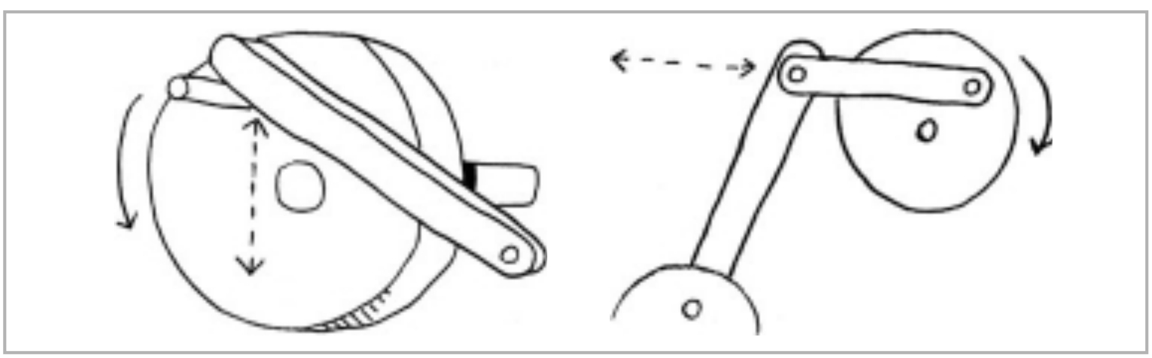
NOTE **3D sketching** ***is the practice of using cheap materials and components you have around to build simple, temporary, and not necessarily functional models to wrap your brain around an idea. It's a good idea to keep some cardboard, duct tape, LEGOs, and spare parts around for such sketches. If you need more flexibility, you can try your hand at the 3D modeling programs we'll cover in Chapter 9.***

Cranks

A crank is basically a lever attached to a rotating shaft. You can use a crank as a handle to turn a shaft, as in the old bucket-raising cranks on top of a well (see the crank on the party sheep project shown later in Figure 8-17). In this case, you're using the crank as a simple wheel-and-axle machine, similar to the steering wheel in a car, as discussed in Chapter 1. If you flip this configuration, the rotating shaft can drive the crank itself. In this case, the crank can be used to convert rotary motion to *reciprocating*, or back-and-forth, motion. The *throw* of the crank is the diameter of the path it travels.

You can make cranks easily by sticking a wooden dowel into a hole in a piece of wood, or with a pair of pliers and a coat hanger or other thick wire. The crank on the left in Figure 8-1 is friction drive, since it just relies on friction and gravity to return to the original state. The crank on the right in Figure 8-1 is connected to the output shaft or lever so is not just relying on gravity.

FIGURE 8-1 Friction-drive crank that relies on gravity (left) and positive-drive oscillating crank (right)



Cams and Followers

Cams are useful any time you have one or more objects you want to move in a periodic or irregular motion. In the most basic terms, a cam is any eccentric or noncircular shape that can convert rotary motion into linear motion. Cams open and close the valves on modern internal combustion engines. They are used extensively in the mechanical toys we'll talk about later in the chapter.

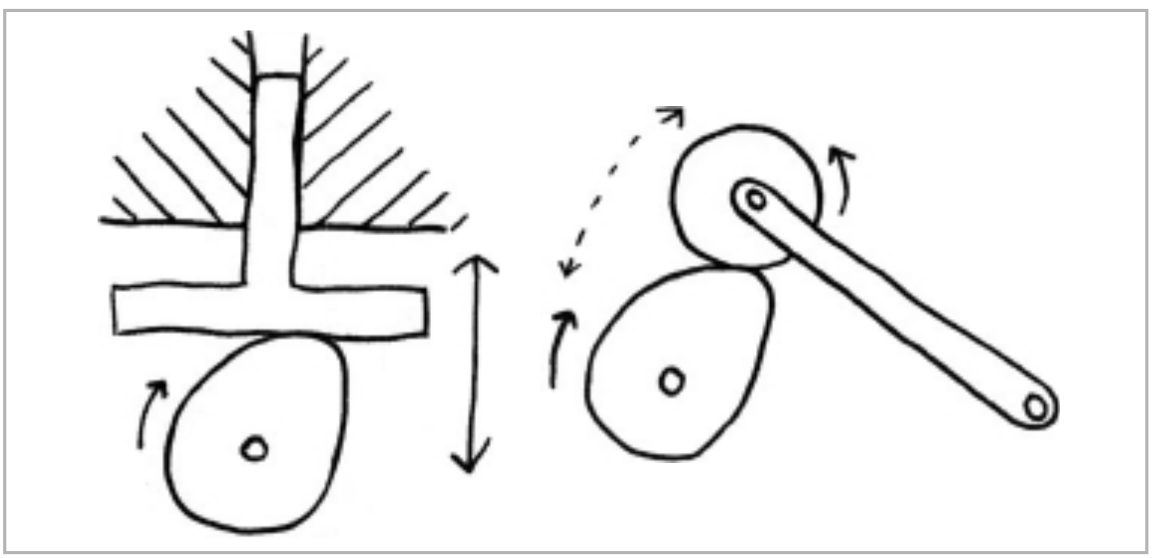
You can make cams yourself from wood if you have some basic tools, or find them off the shelf from WM Berg (www.wmberg.com) and other suppliers. The party sheep shown later in Figure 8-17 uses a cam attached to the rotating shaft inside to make its head nod.

Edge Cams

The most basic type of cam is called an *edge* (also *disk* or *peripheral*) cam (see Figure 8-2). The part that the cam moves is called a *follower*. The edge cam transfers motion to a follower moving against its edge. This is a friction-drive system because there is nothing locking the cam and follower together. Edge cams can be used to create linear (translating) motion or oscillating rotary motion.

The difference between the highest point on the lobe and the minimum radius on the cam is called the *throw*, and is the maximum amount of linear motion the cam can

FIGURE 8-2 Edge cam with translating follower (left) and with oscillating follower (right)



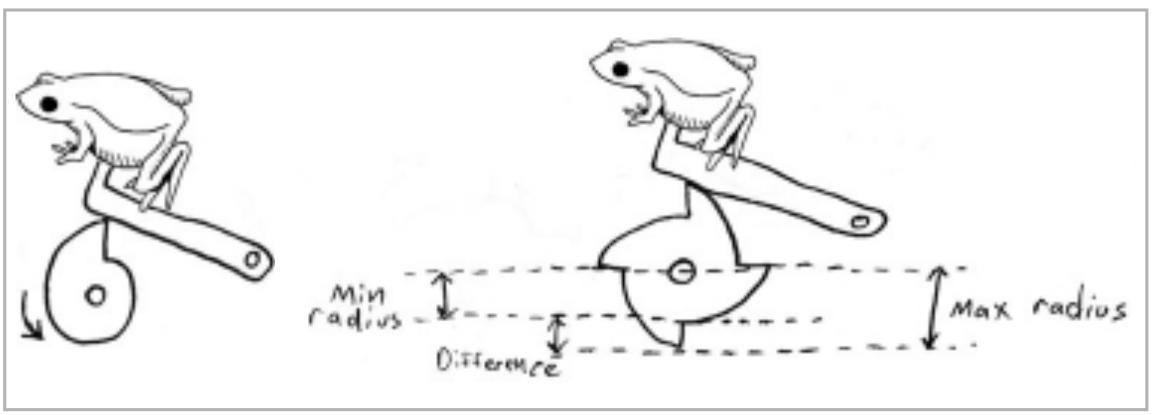
transfer to the follower. The cam can also be a disk mounted off center (eccentric cam), in which case the throw is just the difference between the maximum and minimum distances to the axis of rotation. The follower can be flat, like the translating cam in Figure 8-2 (left); it can end in a roller, like the oscillating cam in Figure 8-2 (right); or it can take the shape of a curved surface or hemisphere.

The *cam shaft* is the rotating input shaft that makes the cam spin. When the follower creates linear motion, there is usually a shaft or *stem guide* to channel this motion. The followers in Figure 8-2 rely on gravity to hold them against the cam, but could also be spring-loaded.

The cams in Figure 8-2 can rotate in both directions, but sometimes you need to make a cam that can rotate in only one direction and lock in the other. The snail cam in Figure 8-3 (left) will produce a steady rise then sudden fall when rotated counterclockwise, but will eventually lock against a follower if rotated clockwise. The ratchet-shaped cam in Figure 8-3 (right) has four of these lobes, so it will produce four such motions with just one rotation of the cam shaft. We call these motions *events*, and one complete revolution of the cam is a *cycle*. The number of events per cycle will be limited by the size of your cam. The timing of these events will also depend on the speed of rotation of the cam shaft.

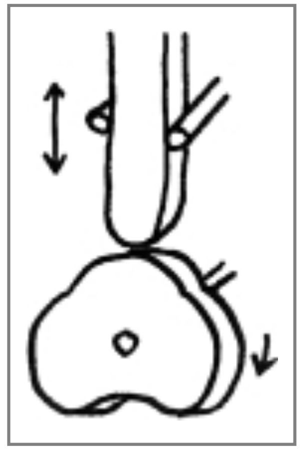
Cams can also produce complex and irregular motion. The edge cam in Figure 8-4 has a *dip*, or *recess*, in addition to a lobe. The profile between the lobe and the dip with a

FIGURE 8-3 Snail cam with one lobe (left) and with four lobes (right)



constant radius is called the *dwell*, because the follower just dwells there and doesn't create motion. The shape of the follower is important. A finer point on the follower will be more able to track intricate variations on the cam, but will need to be strong enough to survive the stress of riding in and out of all those bumps (see www.flying-pig.co.uk/mechanisms/pages/cam.html). Using a bearing or roller on the end of the follower is a good way to decrease this stress by decreasing friction. A bigger cam will give you more leverage to push on a follower and be easier to turn than a small one trying to do the same job, so don't try to do too much with a small cam.

FIGURE 8-4 Edge cam with lobe and dip



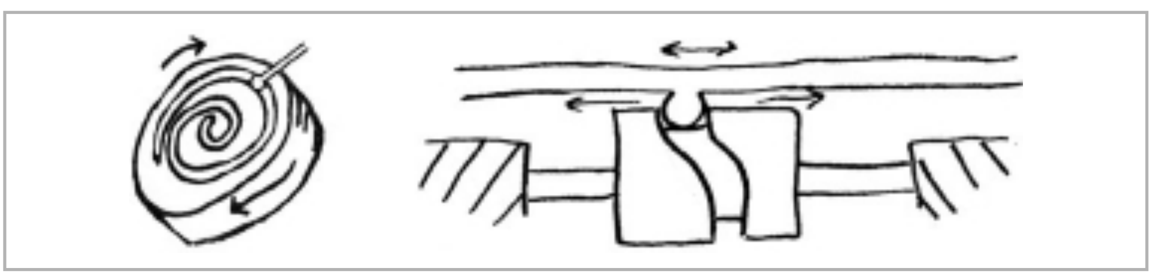
Face and Drum Cams

A *face cam* (also called a *radial* or *plate cam*) transfers motion to a pin or roller free to move in a groove on its face. These are usually designed to operate in both directions, and create a positive-drive situation in both directions because the follower is contained in the groove of the face cam.

A *drum cam* (also called a *barrel* or *cylindrical cam*) has a path cut around its outside edge in which the roller or follower sits.[1] It creates a back-and-forth motion on the follower in a plane parallel to the axis of the cam.

Figure 8-5 shows both of these cam profiles. Face and drum cams are less popular and harder to make at a hobbyist level, but are included here to show you the possibilities.

FIGURE 8-5 Face cam (left) and drum cam (right)



Linkages

A *linkage* is a connection that transfers motion from one mechanical component to another. Linkages are often the simplest, least expensive, and most efficient mechanism to perform complicated motions. They come in many shapes and configurations, and can do many jobs, such as the following:

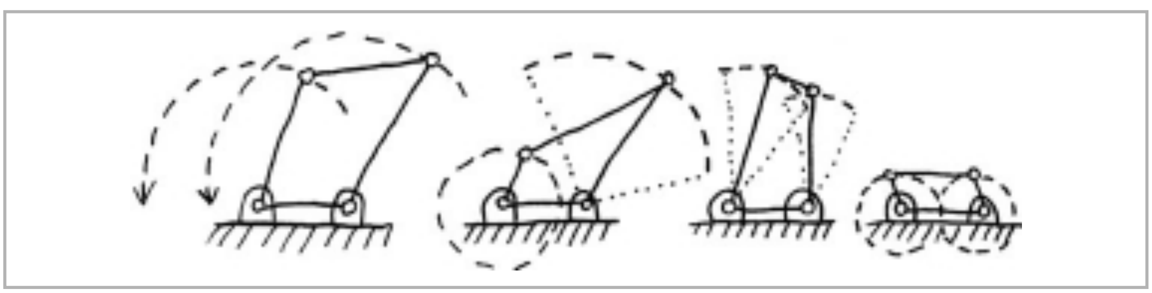
- Change direction or otherwise alter path of motion
- Alter speed and/or acceleration
- Change timing of moving parts
- Apply a mechanical advantage
- Create elegant and efficient motion

Most linkages are *planar*, which means all the motion takes place in the same plane. Linkages usually have only one job, regardless of the number of links: create a specific output motion from a specific input motion.

Four-bar linkages are the simplest closed-loop linkage. They can create many different output motions by varying the lengths and relationships of the four segments (see Figure 8-6):

- **Ground/frame** The link that is kept stationary.
- **Coupler/lever** The link opposite the ground.

FIGURE 8-6 Types of four-bar linkages



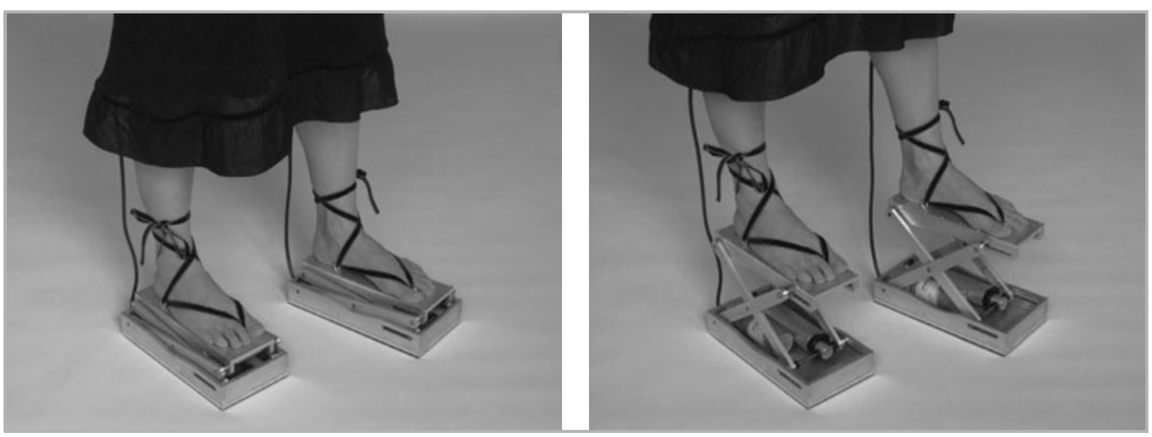
- **Crank/rocker** The driven link that joins the ground and the coupler. If it rotates through 360°, it's a crank. If it's limited to back-and-forth motion, it's a rocker.
- **Follower** The link opposite the crank/rocker. Confusingly, this is also sometimes called the *crank* or *rocker*, depending on its motion.

Within the four-bar linkage family, there are more than a dozen well-known variations. The linkage that drives windshield wipers is probably the most popular example. A close second is the four-bar linkage that opens up inside your umbrella.

In order for a linkage to have continuous motion (at least one link can rotate a full 360°), the sum of the shortest and longest links must be less than the sum of the remaining two links. This is called Grashof's law, so four-bar linkages that follow the law are called *Grashof linkages*.

Pantographs are linkages designed so that if a drawing is traced at one point, an enlarged (or miniaturized) copy will be drawn by a pen fixed to another. These were used to copy and scale line drawings hundreds of years ago. *Scissor linkages* are used in large scissor lifts and small lab jacks to raise and lower platforms (see Figure 8-7).

FIGURE 8-7 Adi Marom's short++ shoes use a scissor linkage and linear actuator to raise and lower a platform you can stand on (credit: Adi Marom).



Project 8-1: I Heart Pantographs

In this project, we'll make the cardboard pantograph shown in Figure 8-8 and experiment with drawing patterns with it.

Shopping List:

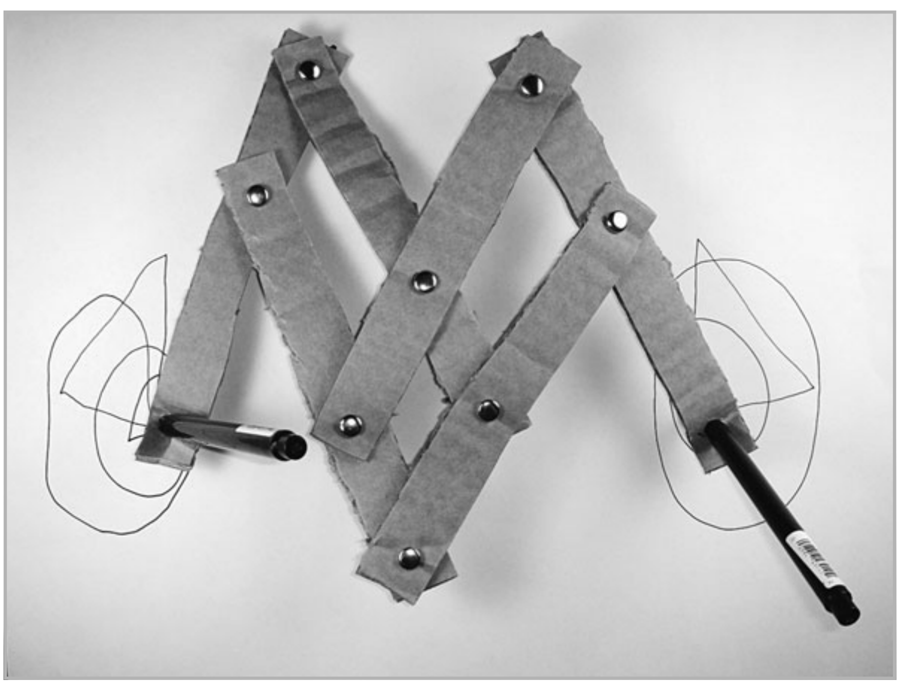
- Paper fasteners
- Cardboard
- Pens or markers

Recipe:

1. Cut out six strips of cardboard in equal lengths. The ones shown in Figure 8-8 are about 6 in long by 1 in wide.

2. Attach the cardboard strips to each other with the paper fasteners (see Figure 8-8).

FIGURE 8-8 A cardboard pantograph (drawing machine)

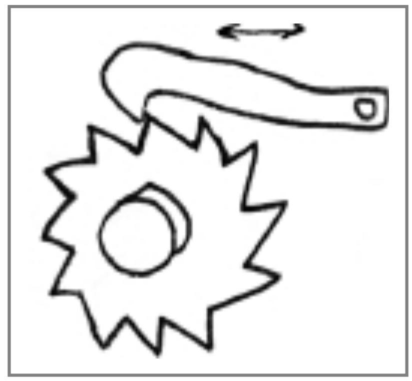


3. Make a hole in the bottom of each of the cardboard pieces on the sides and put a pen or marker in each hole.
4. Hold the center paper fastener and see how you can draw symmetrical (but mirrored!) patterns by moving the cardboard pantograph around.
5. Try replacing some of the paper fasteners with pens to draw more lines, or changing the length of some of the strips to make the patterns asymmetrical.

Ratchet and Pawl

A ratchet-and-pawl system creates a stepped motion and can be used as a locking mechanism (see Figure 8-9). A *ratchet* is a wheel with notches cut into it, similar in shape to a gear.[2] A *pawl* pushes against the notches and allows the ratchet to be driven in steps. A second pawl (*detent*) can stop the wheel from slipping backward. A ratchet-and-pawl system can also be used as a clutch to allow a shaft to rotate in only one direction.

FIGURE 8-9 Ratchet and pawl



Motion Conversion Options

Most of the time, the easiest motion to create as an input for a mechanism is rotary motion, either from an electric motor or a hand crank. There are many ways to change this rotary motion to linear, intermittent, reciprocating, oscillating, or irregular motion. Sometimes you can convert between these motions as well—for example, between oscillating and linear. You can also use the simple mechanisms described in this chapter to transform a motion without changing its type. For example, you can change a slow to a fast rotary motion, magnify linear movement, or change the axis of motion.

Table 8-1 shows some ways to convert between the following different types of motion:

- **Rotary** Motion in a circle (the most common input motion).
- **Oscillating** Back-and-forth motion around a pivot point, like a pendulum in an old clock (this type of input is easy to achieve with a standard hobby servo motor).
- **Linear** Straight-line movement.

- **Reciprocating** Back-and-forth motion in a straight line.
- **Intermittent** Motion that starts and stops in a regular, predictable pattern.
- **Irregular** Motion with no obvious pattern or that doesn't fit into the other categories.

To use the table, locate the input motion you want on the top and the output motion you want on the left side. The box where they intersect shows your options for doing the conversion. (Much of the material in this table is from www.flying-pig.co.uk/mechanisms.)

We've already talked about the more general methods: gears, pulleys and belts, sprockets and chains, levers, cranks, linkages, and so on. The following are some of the trickier conversions shown in Table 8-1:

- **Scotch yoke** Used to create linear and reciprocating motion from an oscillating input (see Figure 8-10). Using a scotch yoke is an excellent way to convert the oscillating motion of a servo arm to linear motion.

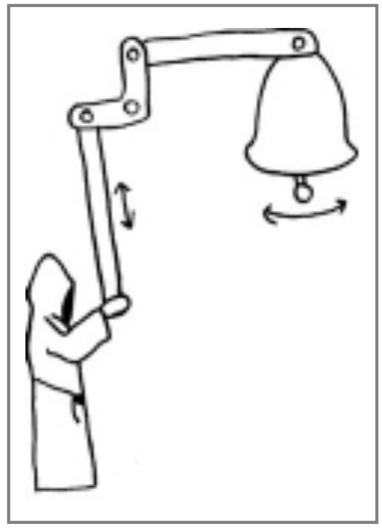
FIGURE 8-10 Scotch yoke in running of the bulls (CC-BY-NC-SA image used with permission from Greg Borenstein and Scott Wayne Indiana)

TABLE 8-1 Converting Between Types of Motion

			INPUT				
			ROTARY	**OSCILLATING**	**LINEAR**	**RECIPROCATING**	**INTERMITTENT**
OUTPUT	**CONVERSIONS**	**ROTARY**	Gears, pulleys and belt, sprockets and chain, crank slider	Crank	Rack and pinion, linkage	Piston, bell crank	
		OSCILLATING	Crank, quick return			Linkage	
		LINEAR	Wheels, rack and pinion, scotch yoke	Scotch yoke	Scissor linkage		
		RECIPROCATING	Cam, crank, piston	Crank, cam, bell crank			
		INTERMITTENT	Geneva stop	Ratchet		Ratchet	
		IRREGULAR	Cam	Cam			
	TRANSFORMATIONS	**INCREASE/ DECREASE**	Gears, pulleys and belt, sprockets and chain	Gears		Lever	Lever, gears
		REFLECT	Gears	Gears	Pulley, lever	Pulley, lever	Pulley, lever
		ROTATE	Bevel gear, worm gear	Bell crank	Bell crank	Bell crank	Bell crank

- **Bell crank** Can be used to create different motion conversions and transformations depending on which part is driven and which part is doing the driving (see Figure 8-11). This is why you see it in many of the boxes in Table 8-1.

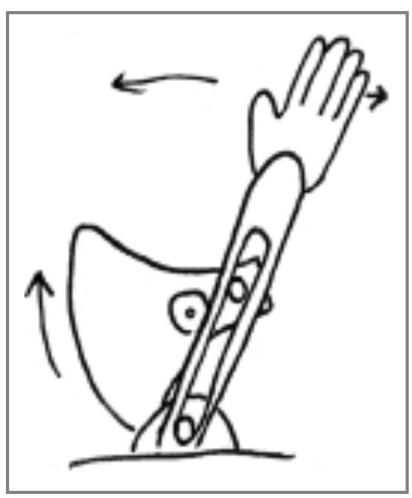
FIGURE 8-11 A bell crank



- **Geneva stop** Used to create intermittent output from a constant rotary input. In the version shown in Figure 8-12, it takes four turns of the lower circular shape to turn the star-shaped piece once. It's difficult to get the geometry just right, but you can get off-the-shelf versions from WMBerg or make your own with downloaded plans from Thingiverse (a 2D version for laser cutters from www.thingiverse.com/thing:1616 or a version for 3D printers at www.thingiverse.com/thing:1642).
- **Quick return** Used to create oscillating motion from a continuous rotary input. In the example in Figure 8-13, since the peg that drives the arm back and forth is closer to the bottom pivot point during part of the waving motion, the wave in one direction will be faster than in the other.

FIGURE 8-12 A Geneva stop mechanism

FIGURE 8-13 A quick return



Automatons and Mechanical Toys

Automatons and mechanical toys provide some of the earliest examples of kinetic design. Early automatons were sometimes incredibly complex combinations of cams, linkages, springs, and components, often in the form of dolls or mannequins. These dolls could write poems or play the flute, based only on the interactions of mechanical parts, without any electronics, sensors, or feedback. They were powered by hand, steam, or water.

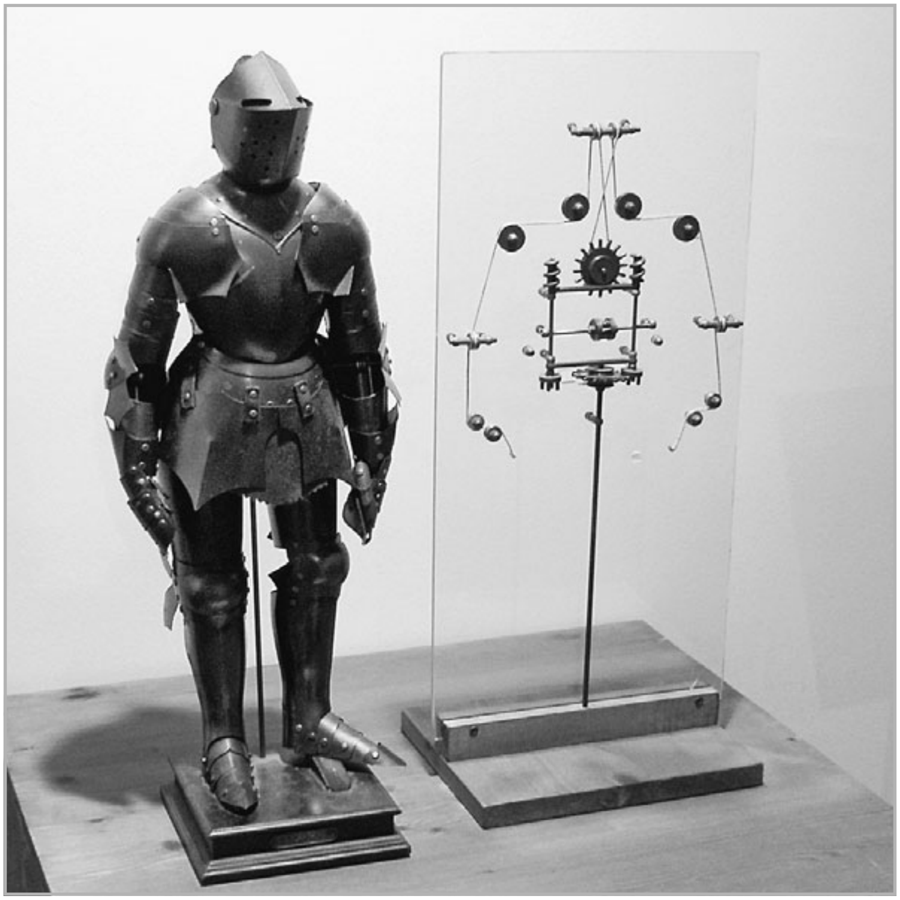
The earliest recorded automatons appeared in Egypt around the second or third century BC and were used as teaching tools to explore physical laws through movement.[3] The Greeks and Arabs were next to pick up the craft, followed by a dead period during the Middle Ages when most mechanical devices were condemned as pagan magic. Fortunately, this period ended, and by the fourteenth century, automatons began to appear in the huge cathedral clocks all across Europe.

One early example of a humanoid automaton is a robot that Leonardo DaVinci designed around 1495 (see Figure 8-14). We don't know if he actually built it while he was alive, but a few people have used his plans to create models that confirm that it works as intended. The French would-be priest Jacques de Vaucanson dropped out of his training when the Jesuit priests destroyed the angel automatons he designed for their apparent heresy. He went on to create the Digesting Duck in 1739, which looked, quacked, and crapped like a real duck through an elaborate system of cams and followers. Pierre Jacquet-Droz, a Swiss clockmaker, was another master of elaborate automatons. He created a little mechanical family with a writer, a draftsman, and an organ player around 1772. Henri Maillardet created a similar drawing automaton in 1810, which is on permanent exhibit at The Franklin Institute in Philadelphia and has been restored to create some of its original drawings.

Once making a living from selling and exhibiting elaborate automatons became impractical in the late 1800s, similar mechanisms gave way to mechanical toys, music boxes, and clocks that could be mass-produced. In many of the toys, you could crank a handle, which wound a spring, which then stored energy that would go about powering the toy. Simple string-pull jumping jack toys and other mechanical figures were manufactured by the thousands and sold all across Europe.

When some of these makers immigrated to the United States, the traditions of different countries merged into American folk art and toy design. Alexander Calder, a mechanical

FIGURE 8-14 Leonardo DaVinci's robot



engineer turned artist, was probably the first American to popularize this kinetic art form through his mobiles and his circus, which he created in the 1920s. Calder's circus of miniature moving wire figures grew from a few characters in 1920 to eventually fill five suitcases, which he carried around to give performances. A video of his circus was created in 1961 and was most recently on exhibit at the Whitney Museum of American Art in New York City, along with a collection of his circus characters. Sam Smith, a British artist, created kinetic art and toys throughout the 1960s and 1970s that heavily influenced many modern mechanical toy makers.

More modern examples of kinetic sculpture and mechanical toys include Arthur Ganson's machines and the work of the artists of Cabaret Mechanical Theatre. Figure 8-15 shows Eun Jung (EJ) Park's Mechanical Storytelling: The Story of Grouchy the Clown automaton (see www.ejpark.com). Figure 8-16 shows an example from Andrew Jordan's Sound Creatures project (see www.andyjordan.us/).

FIGURE 8-15 Mechanical Storytelling (image used with permission from Eun Jung Park)

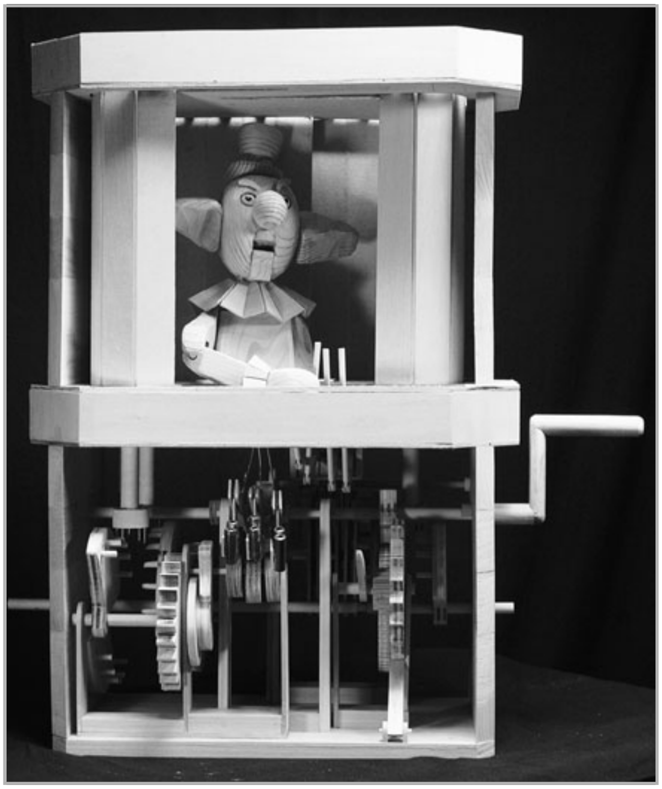


FIGURE 8-16 In this example from Andrew Jordan's Sound Creatures project, the spiral painted cam in the center throws its housing back and forth, creating irregular reciprocating motion from continuous rotary input.

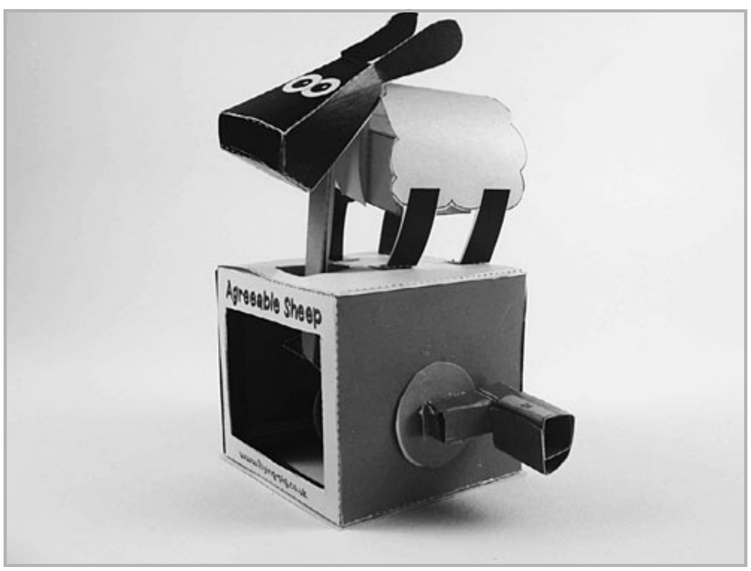
Project 8-2: DIY Automaton—The Agreeable Sheep

Flying Pig provides a few sets of free plans to make animated creations in paper. My favorite is the Agreeable Sheep by Rob Ives. We called our version, shown in Figure 8-17, the Party Sheep due to the fluorescent card stock we used.

Shopping List:

- Size A4 or 8.5 × 11 in card stock
- Hobby knife and scissors
- Metal ruler
- Cutting mat or old magazine
- Glue stick or white glue
- Penny

FIGURE 8-17 The Agreeable (Party) Sheep (credit: Jade Highleyman, Eyebeam student resident, for putting this together and photographing it)



Recipe:

1. Download the model and the making instructions from www.flying-pig.co.uk/pdf/sheep.pdf.
2. Print the templates. The first three pages of the nine-page PDF are instructions. The last six are front and back versions of three templates for the sheep. If you can't print double-sided, you'll need to manually feed these into your printer in the correct orientation. Don't worry about perfect alignment.
3. Use scissors or a hobby knife to cut out all the drawings.
4. Score all the lines you will fold on by gently running the knife over the dashed lines. A metal ruler helps here to keep your scores straight.
5. Fold along all the dashed lines.
6. Follow the instructions on where to glue what. Have some patience between the gluing steps to make sure your sheep stays together.
7. Tape the penny inside where indicated.
8. Ask the sheep a yes or no question. Crank the handle and wait for an answer.

References

1. U.S. Bureau of Naval Personnel, *Basic Machines and How They Work* (New York: Dover Publications, 1971).
2. Aidan Lawrence Onn and Gary Alexander, *Cabaret Mechanical Movement: Understanding Movement and Making Automata* (London: G&B Litho Limited, 1998).
3. Rodney Peppé, *Automata and Mechanical Toys* (Marlborough, Wiltshire: Crowood Press, 2002).