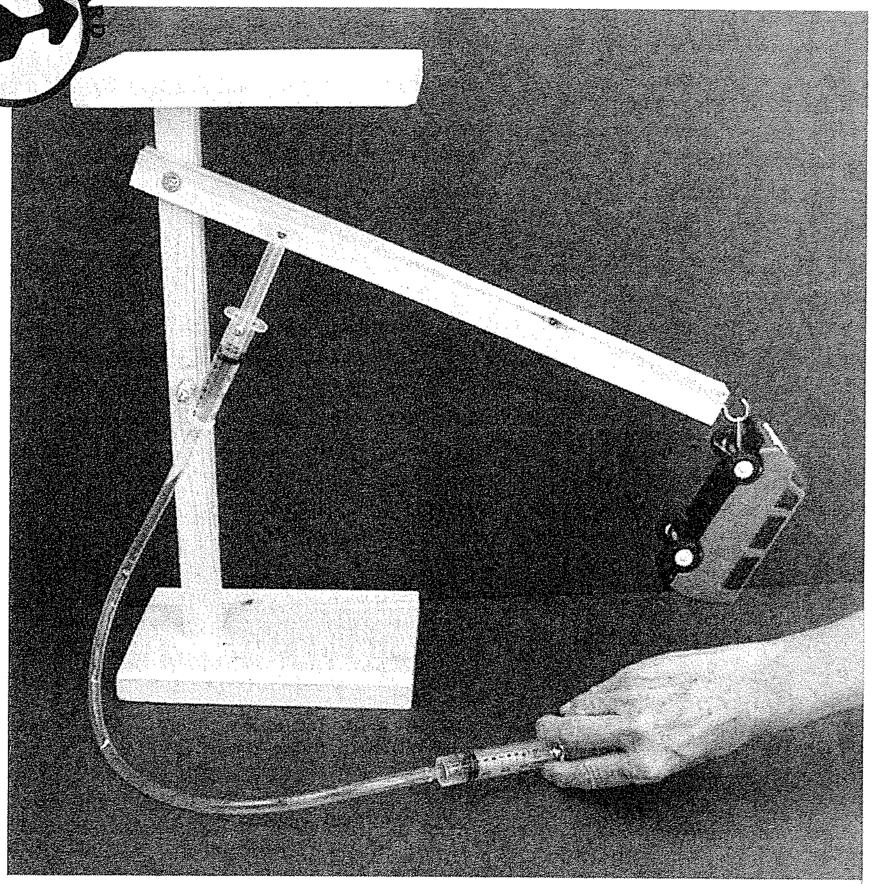
Hydraulic Arm

You'll feel the pressure to do some heavy lifting.

When you push the plunger on a syringe, water is forced into a second syringe, extending its plunger and lifting a mechanical arm. The process illustrates aspects of fluid pressure, force, mechanical work, and biomechanics.

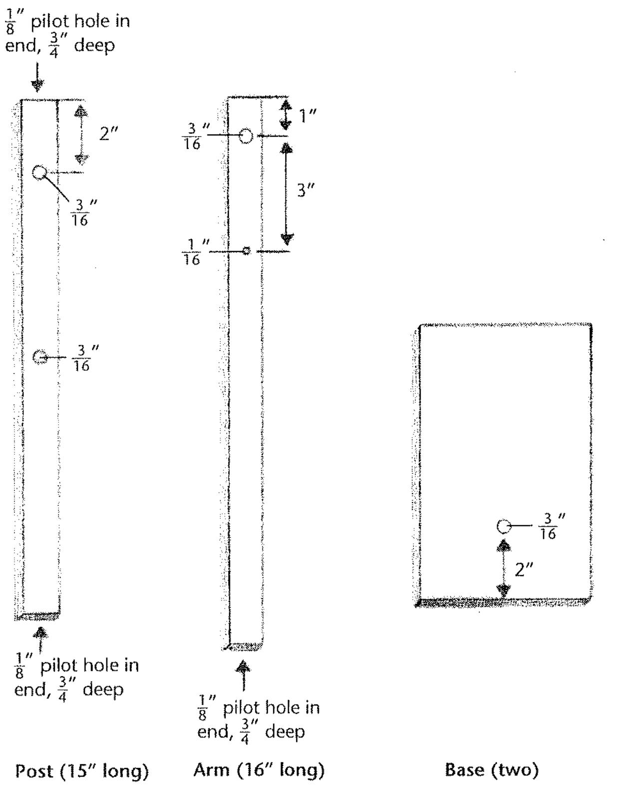
Materials



- electric drill
- drill bits, $\frac{3}{16}$ in, $\frac{1}{8}$ in, $\frac{1}{16}$ in
- 2 wooden bases, about 5 in × 8 in × $\frac{3}{4}$ in (12.5 cm × 20 cm × 2 cm) thick (ordinary 1 in × 6 in pine shelving works well)
- 1 wooden post, about 15 in × 1 in × $\frac{3}{4}$ in (38 cm × 2.5 cm × 2 cm) thick
- 1 wooden arm, about 16 in × 1 in × $\frac{3}{4}$ in (40 cm × 2.5 cm × 2 cm) thick
- 2 flat-head wood screws, #8 × $1\frac{1}{2}$ in
- 2 machine screws, 10-24 × 2 in
- screwdrivers to fit screws
- 5 washers to fit the machine screws (e.g., SAE 10 flat washers)
- 2 wing nuts, 10-24
- cup hook, $\frac{7}{8}$ in or 1 in
- 2 plastic oral syringes, 10 mL (Oral syringes are used by pharmacists and veterinarians to accompany prescriptions and may sometimes be obtained for no charge or purchased inexpensively. You can also obtain syringes, tubing, connectors, etc., for hydraulic and pneumatic projects from Kelvin, 800-535-8469, www.kelvin.com, or from The Science Source, 800-299-5469, www.thesciencesource.com; see Alternative Construction for use of 5-mL syringes if you can't get the 10-mL size.)
- 1 oral syringe, plastic, 1 mL
- 2 sheet-metal screws, short (e.g., #6 × $\frac{3}{8}$ in)
- 1 nail, bright box, $1\frac{1}{2}$ in
- 1 cable tie with mounting head, 7.5 in (usually available at home improvement stores and some hardware stores; see Alternative Construction using an eyebolt if you have trouble obtaining the cable tie with mounting head)
- pliers
- scissors
- 4 hex nuts, 10-24
- 2 ft (60 cm) of clear plastic tubing to fit the syringes you use (available at hardware and aquarium supply stores; the tubing that fit the syringes we used had an outside diameter of $\frac{5}{16}$ in, an inside diameter of $\frac{3}{16}$ in, and a wall thickness of $\frac{1}{16}$ in)
- water source
- assorted small objects that can be hooked or tied onto the cup hook of the arm (e.g., toys, set of keys)

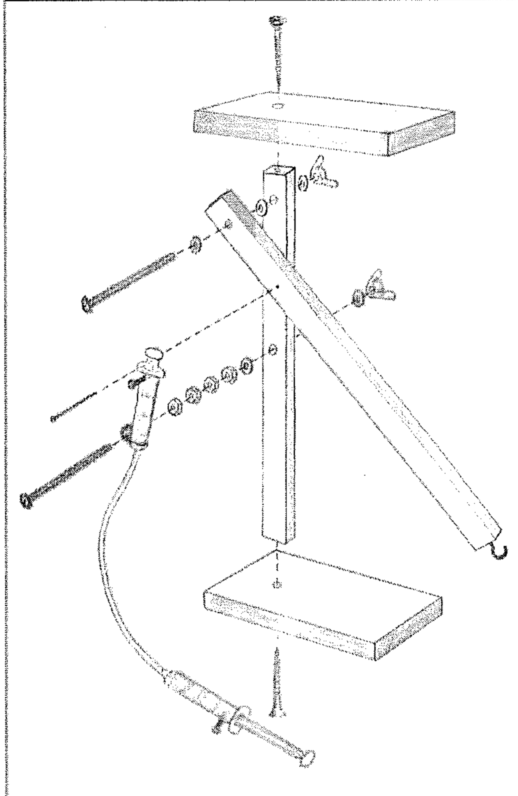
ASSEMBLY

Figure 1



Drill holes in the post, arm, and base, as shown.

Figure 2



Exploded view of the whole assembly

1 Drill holes in the four pieces of wood as shown in figure 1. (There are two bases to allow you to use the hydraulic arm in the "upside down" position.)

2 Figure 2 shows an exploded drawing of the assembly of the Hydraulic Arm. Refer to this drawing as necessary as you proceed through the assembly steps that follow. (See figures 3 and 4 for details regarding the cable tie and stop screw.)

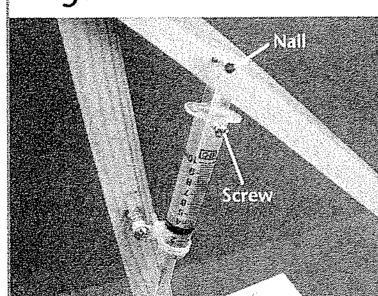
3 Assemble the two bases and the post, using the two wood screws. Be sure the heads of the wood screws do not stick out from the bases.

4 Attach the arm to the post, using a machine screw, three washers, and a wing nut.

5 Screw the cup hook into the end of the arm.

6 Drill a small hole (smaller than the sheet metal screws) in the body of each of the two 10-mL syringes, just below the top flange. Screw a small sheet-metal screw into each of these holes, and rotate the syringe plungers so that the screws can go in as far as possible without hitting the plungers (see figure 3). The screws should now act as stops to keep the plungers from being pulled completely out of the syringes by accident.

Figure 3

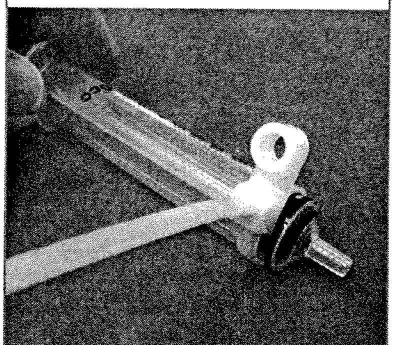


Syringe assembly with pivots

7 Select one of the syringes, and drill a $\frac{1}{8}$-inch hole through the shaft of its plunger approximately $\frac{1}{4}$ inch (0.5 cm) from the end of the plunger. A nail will later be placed through this hole (see the "Nail" label on figure 3). This syringe is the "fixed syringe."

8 Place the cable tie on this syringe as shown in figure 4. Pull it as tight as possible so the syringe does not slip easily. (If necessary, use pliers to pull the cable tie tighter after you have tightened it initially by hand.) Cut off all but about $\frac{1}{4}$ inch (0.5 cm) of the excess tie as shown in figure 5.

Figure 4



Cable tie on syringe

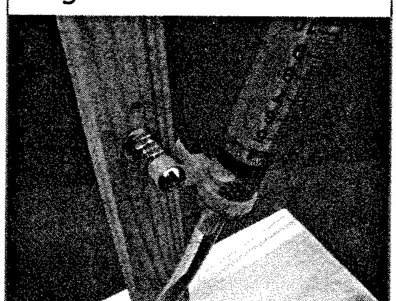
9 Attach the syringe to the post by placing a machine screw through the hole in the cable tie. Then thread onto the machine screw four hex nuts and a washer before attaching the syringe to the post (see figure 5) and adding another washer and a wing nut (see figure 2). Adjust the hex nuts to allow enough space between the last hex nut and the head of the machine screw so that the mounting head of the cable tie will allow the syringe to pivot freely but not slide sideways excessively. When this adjustment has been made, make sure that the four hex nuts are tight against each other, and tighten the wing nut.

10 Put the nail through the hole in the syringe plunger, and force it into the hole in the arm until the head of the nail is almost up against the plunger (see figure 3), but not so far that the point of the nail protrudes significantly from the other side of the arm. If necessary, use pliers to push the nail into the hole.

11 Attach the plastic tubing firmly to the tip of the second 10-mL syringe. Fill the syringe and tube completely with water. Eliminate air bubbles by flicking the syringe or tube with your finger to get them to rise, and then topping off with more water as necessary. If you have difficulty, you might try filling the tube separately and then attaching it to the full syringe.

12 Push the plunger all the way into the fixed syringe (the one attached to the post and arm) so that there is no air in the syringe. Attach the open end of the water-filled tube firmly to the tip of this syringe. Be sure there are no large air bubbles anywhere in the system.

Figure 5

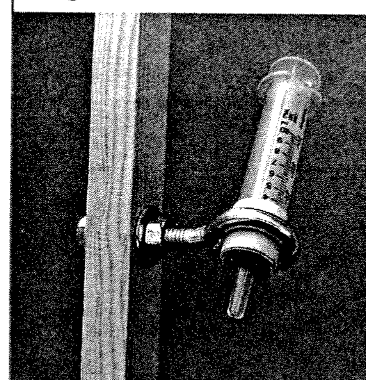


Pivot assembly close-up

Alternative Construction

- An eyebolt (plus two washers, and two hex nuts or two Teflon-insert stop nuts) can be used as an alternative to the cable tie for holding the syringe (see figure 6). Masking tape can be used to build up the syringe diameter to fit the eyebolt hole. The eyebolt shown here is $\frac{5}{16}$ inch by $3\frac{1}{4}$ inches, but hole sizes on eyebolts from different manufacturers are not uniform; be sure the hole on the eyebolt is large enough for your syringe to fit into.

Figure 6



Eyebolt holding syringe

- If necessary, you can substitute 5-mL plastic oral syringes for the 10-mL ones. These are commonly sold in drug stores. They are slightly smaller, and the plungers do not extend quite so far. Depending on the size of the syringe you use, you may need to modify the locations of the holes used to fix the syringe to the arm and post.

To Do and Notice

Push on the plunger of the movable syringe. What happens? Pull on the plunger. What happens now?

Use the arm to lift a small object. (If the arm tips, either put a book or other heavy weight on the base to steady it, or find a lighter object to lift.) How does the force of your push on the plunger compare to the force that the other plunger exerts on the arm? How do the distances that the two plungers move compare with each other?

Notice carefully how hard you have to push on the plunger to lift a particular object, and notice how far the arm can move the object.

Remove the object, then push water into the fixed syringe so that the arm is elevated as much as possible. Support the elevated arm so that it can't fall. (You could have a friend hold the arm, or you could support it with a stack of books.) Then raise the movable syringe until the end of the tube attached to it is well above the fixed syringe. Keeping the end of the tube raised (to prevent water from coming out when the syringe is removed), remove the 10-mL syringe and replace it with the 1-mL syringe.

Remove the support from the arm. Pull the plunger on the 1-mL syringe until the syringe is full. Replace the object on the hook, and then push the plunger on the 1-mL syringe to lift the object.

Notice the difference in how hard you have to push on the plunger to lift the object this time, and notice how far the object is lifted.

Put the 10-mL syringe back in place at the end of the tube, using the same technique you used to replace it with the 1-mL syringe. Turn the whole device upside down and use the syringe to raise and lower the arm. Compared to the right-side up position, what's different about the process of elevating the arm?

Blaise Pascal

1623–1662

The pascal unit of pressure is named for Blaise Pascal, a French mathematician, scientist, and philosopher. His chief contribution to physics was in the field of *hydraulics,* which applies the properties of water and other liquids, such as how they transmit pressure, to engineering problems. In about 1650, Pascal authored a treatise, *On the Equilibrium of Liquids,* in which he states that an external pressure applied to a liquid in a container is transmitted equally throughout the container. This idea, which has come to be known as Pascal's principle, is the underlying physics of this snack.

What's Going On?

When you push on the plunger of the movable syringe, the arm rises; when you pull on the plunger, the arm descends.

Pushing on the plunger applies pressure on the water in the movable syringe. Since the water is confined and incompressible, Pascal's principle comes into play, telling us that the pressure is transmitted undiminished to all parts of the water and to the walls of its container. Since the plunger of the fixed syringe at the other end of the tube forms part of the container for the water and is the only part of the container that can expand, the pressure causes the plunger in the fixed syringe to move.

Pascal's principle and a little mathematics can be used to show that—if the syringes are identical—the force you apply to one plunger is transmitted in full to the other plunger (see Box o' Math). Additionally, as you can observe, each plunger moves the same distance.

With the 1-mL syringe, the force that you push with is noticeably less than that with the 10-mL syringe, but the arm is not lifted nearly as far. In accordance with Pascal's principle, the pressure on the plunger of the 10-mL syringe is the same as the pressure on the plunger of the 1-mL syringe. But since the area of the 10-mL plunger is far larger than the area of the 1-mL plunger, the force exerted on the 10-mL plunger is far larger than the force you push with (remember, $F = pA$).

Box o' Math

Pressure is defined as force per unit area

$$p = \frac{F}{A}$$

If you divide the force you push with by the area of the plunger that is in contact with the water, you can find the pressure exerted on the water. You can mathematically rearrange the equation above to become $F = pA$. This tells you that if you multiply pressure (expressed in pounds per square inch) by area (expressed in square inches) the square inches cancel out, and you are left with force, expressed in pounds.

$$\text{pressure} \times \text{area} = \frac{\text{pounds}}{\cancel{\text{square inch}}} \times \cancel{\text{square inch}} = \text{pounds}$$

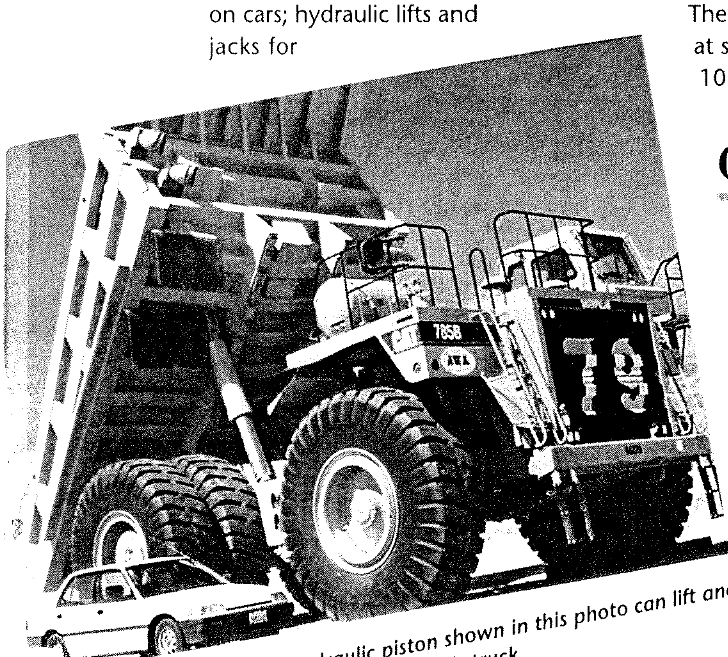
Because the pressure on both plungers is the same, and the areas of both plungers are identical, then the force on both plungers is the same. (In the SI system, force is expressed in newtons—see Did You Know?)

The good news is that you have obtained a force advantage, but the bad news is that you're paying for it with a distance penalty. Mechanical work is the product of force times the distance the force moves through ($W = Fd$), and this product remains constant.

In the right-side up position, the plunger pushes on the arm to raise it. But when you turn the whole assembly upside down, the syringe *pulls* on the arm to raise it, just like your muscles do with your own arms. The muscle that allows your forearm to lift things, called the *biceps*, is attached near your shoulder and just below your elbow. When the biceps contracts, it has the same effect on your arm as the syringe has on the hydraulic arm when the assembly is upside down. In both cases, a large force is exerted so that a small weight can be lifted, but the weight can be lifted a large distance compared to the distance the force moves (the distance the syringe plunger moves, or the distance your muscles contract).

So What?

Hydraulic systems are used in countless applications: brakes and steering on cars; hydraulic lifts and jacks for servicing cars; airplane wing flaps, stabilizer controls, and landing gear; mechanical arms on garbage trucks; blades on bulldozers; and so on.



The small hydraulic piston shown in this photo can lift and dump tons of earth from this truck.

Did You Know?

Under Pressure

Automobile and bicycle tire pressures in the United States are commonly expressed in pounds per square inch (abbreviated psi), a unit from the English system of measurement. In the modern metric system (Système International d'Unités, or SI), the unit of pressure is the pascal (symbol Pa). One pascal is equal to one newton per square meter (n/m^2). Because 1 psi is approximately 6900 Pa, you can see that the pascal is a very small unit. For this reason, pressures are often expressed in kilopascals (symbol kPa; 1 kPa = 1000 Pa).

A Load on Your Shoulders

The average atmospheric pressure at sea level is equal to 14.7 psi, or 101 kPa.

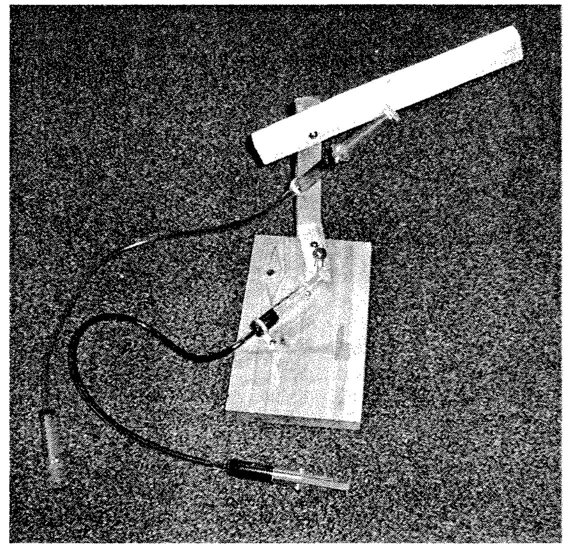


Figure 7 *Dual-action arm*

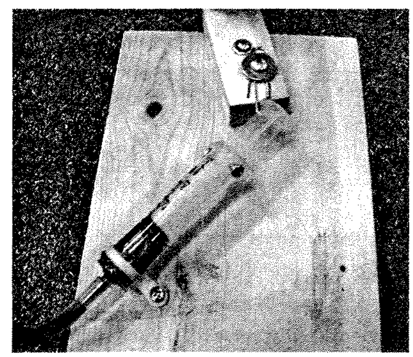


Figure 8 *Close-up of syringe and linkage for dual-action arm*

Going Further

Robot Arm

Design and build a hydraulic arm that has more than one motion. Figure 7 shows an example of an arm that turns on its base in addition to lifting things, and figure 8 shows a close-up of the linkage used on the base. Can you design and build an arm that also has a "wrist" and "hand" at the end?

Credits & References

Modesto Tamez, Crans Squire, and Pablo Dela Cruz contributed to the development of this snack.

Bloomfield, Louis. *How Things Work: The Physics of Everyday Life.* New York: John Wiley & Sons, 1997. There is an excellent discussion of hydraulic elevators on pages 236–237.

Cameron, John, James Skofronick, and Roderick Grant. *Physics of the Body,* 2d ed. Madison, Wis.: Medical Physics Publishing, 1999. Pages 41–50 have a good discussion of the biomechanics of the arm.