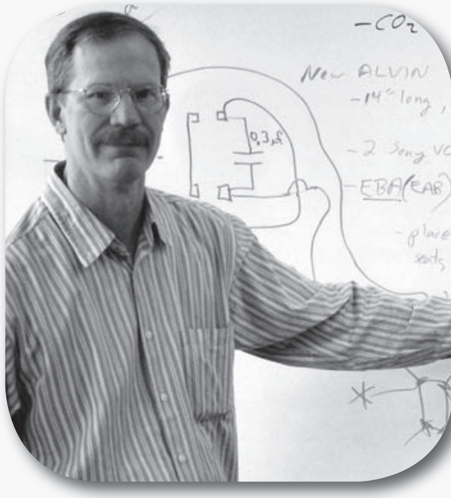
In Deep

Bob Brown



Courtesy of John Ost

Scientists rely on technologies to help them investigate the natural world, whether they are exploring the vastness of outer space or the microscopic contents of a single cell. Engineers create these technologies by relying on principles and natural laws developed by scientists.

I understand the relationship between scientists and engineers well. My name is Bob Brown, and I am a design engineer at Woods Hole Oceanographic Institution (WHOI), an ocean research organization based in Massachusetts. For years, I was also a pilot on the Alvin, the United States' only deep-sea diving submersible vehicle that carries passengers. The Alvin can dive to depths of 4,500 meters—that's 14,764 feet!—and has made over 4,000 dives in its long, illustrious career.

Key Concepts from Previous Chapters

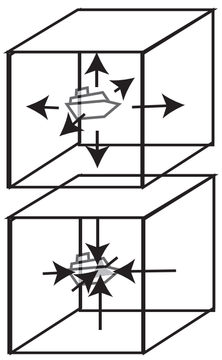
- 14 Stress(σ) = F/A
- 14 Strain(ε) = $\Delta L/L$
- 15 Differences drive change
- 15 Energy travels from areas of high concentration to areas of lower concentration

Fluids
are substances that flow easily, such as liquids and gases.

Pressure
is a force per unit area.

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

It is often used to describe
- force exerted by a contained liquid on the walls of its container
- force exerted by a contained liquid on the surface of an object submerged in it



The Alvin has surveyed the sunken ship *Titanic,* explored the first hydrothermal vents ever discovered in the Pacific Ocean, and even located a hydrogen bomb accidentally dropped in the Mediterranean Sea.

As its pilot, I've seen some amazing sights on the ocean floor and have watched as scientists discovered new life forms, such as bacteria that feed on sulfur produced by deep thermal vents. Discoveries like these have led space scientists to rethink what kinds of life may be possible on other planets.

The Alvin has given marine scientists an invaluable tool. But like any technology, it's not perfect. I'm now working to redesign Alvin so it can go deeper and explore some of the most remote regions on Earth—places humans have never seen.

A High-Pressure Environment

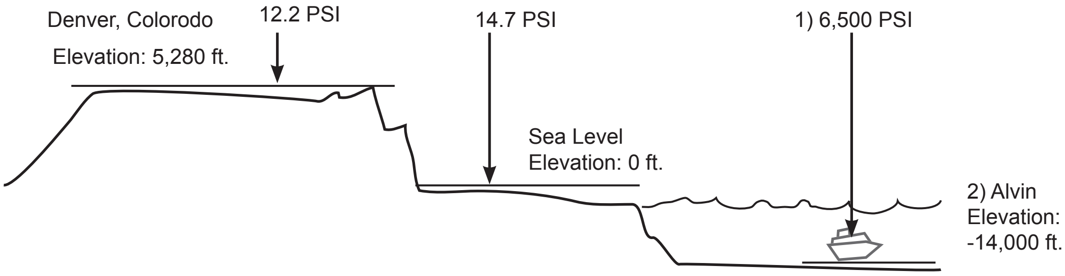
Designing a submersible vehicle requires an understanding of the conditions it is likely to experience at the bottom of the ocean. The redesigned Alvin must be able to withstand very, very high pressure.

Pressure is defined as force per unit area. Pressure and stress have a similar definition and meaning, and the terms are used interchangeably. However, scientists and engineers tend to use the term *pressure* when describing the force exerted by a contained fluid. A ***fluid*** is a substance that flows easily, such as a liquid or a gas. The pressure from a fluid might be exerted on the walls of a container or on an object submerged in it. For example, the water in a fish tank exerts an outward pressure on the aquarium walls. Similarly, the walls of a toy submarine submerged in an aquarium are also subjected to water pressure, because the force exerted by the fluid is perpendicular to every surface it contacts.

To get a feeling for differences in pressure, imagine two soccer balls filled with air. One ball is filled with a small amount of air, so it is easy to squeeze. The second ball is packed with so much air that it is very firm. The air inside of each soccer ball is pushing against the inner wall. However, the air in the second ball is pushing with greater force per unit area. If you were to measure the air pressure inside each ball, you would find that the firmer one would have the higher pressure.

1st ball: small amount of air 2nd ball: packed with air

Air in our atmosphere and water in the ocean, or any other body of water contained in our atmosphere, also have a measurable pressure. Air pressure is due largely to the weight of all the air molecules above us in the atmosphere pushing down against the Earth's surface. At sea level, you experience the force of all this air at a pressure of 14.7 PSI (pounds per square inch). If you went to Denver, Colorado, which is at higher altitude, you would find that the air pressure is only 12.2 PSI. That's because there is less air above Denver pushing down.



If, instead of going to Denver, you were to dive into the sea, you would experience increasing pressure due to the weight of the seawater above you—plus the weight of all the air in the atmosphere above the sea! The deeper you dive, the more water you have above you, and, in turn, the greater the pressure. A general rule of thumb is that fluid pressure in the ocean increases about fifteen PSI for every thirty feet you dive.

We want the new Alvin to reach even deeper depths, more than 21,000 feet below sea level. As we redesign Alvin, we are assuming that the submersible will be operating at a maximum water pressure of about 9,700 PSI. That's a fluid pressure over 600 times greater than the pressure the submersible will experience on the surface! To fortify the Alvin's replacement against the massive pressure it will experience, we must make the structure very strong; otherwise it could suffer a catastrophic failure, resulting in the loss of the craft and the crew.

The Alvin's replacement must be made out of material that has enough strength to endure the demanding pressure at its depth limit. After researching the available materials, we chose a titanium alloy, which is extremely lightweight and strong—so strong that the walls of the Alvin's replacement will need to be only about three inches thick. The oxygen content of the material is quite low—another advantage from our point of view. The low oxygen content will help prevent the material from reacting with seawater to form corrosion.

When there is a ***fluid pressure difference,*** fluid will flow from the area of higher fluid pressure to the area of lower fluid pressure until there is no difference, unless something gets in the way.

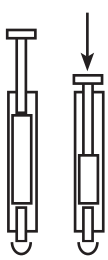
Designing the structure would be fairly straightforward if Alvin's replacement did not have windows or a door. These hull openings must be designed so they seal very tight to prevent leakage. We test the seals around the windows and doors extensively. Even a small leak would flood the submersible quickly, due to the enormous pressure difference between the water outside the Alvin (seawater) and the air pressure inside. This ***fluid pressure difference*** will force the fluid to move from the higher-pressure area to the lower-pressure area until there is no difference or unless something gets in the way.

What would happen to the air already inside the Alvin if a leak did occur? The water flooding into the submersible would begin to exert pressure on the trapped air. As more water entered, the increasing pressure would compress the air into a smaller and smaller volume. Gases, like air, are ***compressible*** fluids. The empty space between gas molecules is quite large, which allows the pressure to squeeze the molecules together. Under increased pressure, the gas occupies a smaller volume, but its mass stays the same. Liquids, on the other hand, are essentially ***incompressible,*** because applying pressure to a liquid will not significantly change its volume. So even though the air would not be escaping, the Alvin would still fill up with water.

To Sink or Swim

One of the systems aboard the Alvin's replacement uses the compressibility of gases to make the submersible descend to the ocean floor and ascend back to the surface. The Alvin weighs just over eighteen tons, and its replacement will weigh nearly as much. You might think that these submersibles would sink like stones to the ocean floor, but they don't. In fact, the Alvin would never reach the ocean floor if we didn't help it.

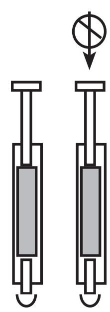
Fluids in a Syringe



Compressible

If you push the piston of a capped syringe filled with **air,** you can compress the air inside the syringe to a smaller volume.

This is because air is a compressible fluid.



Incompressible

If you try to push the piston of a capped syringe filled with **water,** you can't compress the water inside the syringe into a smaller volume.

This is because liquids are an incompressible fluid.

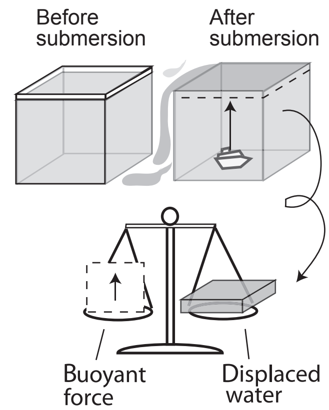
Any object immersed in fluid experiences a ***buoyant force*** that pushes it upward. Because pressure increases with depth, the pressure on Alvin's lower surface (bottom) will always be higher than its upper surface (top), pushing it upward. The buoyant force on an object in a fluid is equal to weight of the volume of fluid that is displaced.

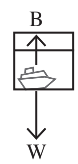
So how does *anything* sink? While the buoyant force pushes up on a submerged object, the weight of the object pulls it down. If the volume of an object weighs more than the volume of water it displaces, it sinks. If the buoyant force and the weight of the object are equal, the object will be ***neutrally buoyant.*** A neutrally buoyant object won't move up or down unless another force acts on it.

Engineers make submersibles descend or ascend by adjusting either the weight or the displacement volume of a submersible. To dive to the sea floor, the "original" Alvin carries steel weights. With the steel weights, the Alvin's total weight is greater than the buoyant force, so it submerges. When the Alvin arrives at its destination depth, the pilot drops some of the weights onto the sea floor, making the Alvin neutrally buoyant. The pilot can then use the Alvin's thrusters to maneuver near the ocean floor, allowing scientists on board to make observations and collect samples. By dropping the remaining weights, the Alvin becomes more buoyant, allowing it to return to the surface.

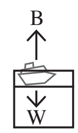
Back when the original Alvin was being designed, in the 1950s, people were not so concerned about leaving steel weights on the sea floor. That attitude has changed. We now know that the steel weights can actually alter the communities of living organisms on which they fall by changing the chemistry of the water surrounding them.

The ***buoyant force,*** the upward push on the object, equals the weight of the volume of water displaced by an object.

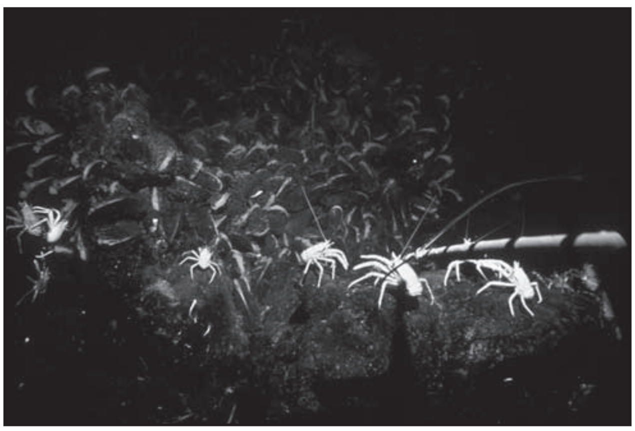




If the object weighs more than the buoyant force, it will sink.

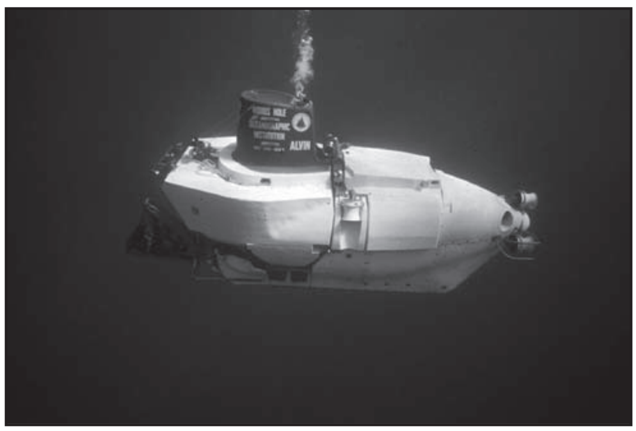


If the object weighs less than the buoyant force, it will float.



Courtesy of Robert Hessler, Woods Hole Oceanographic Institution

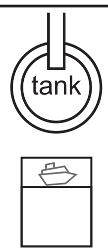
Underwater images taken by Alvin



Courtesy of Rod Catanach, Woods Hole Oceanographic Institution

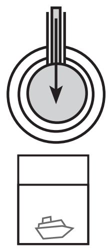
The Alvin, operated by Woods Hole Oceanographic Institute engineers, is the nation's only deep-diving sub that carries passengers.

Vehicle Depth Control with VBS



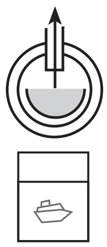
Tank is filled with air and **no water.**

Vehicle is on the **surface.**



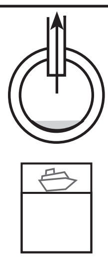
Water is pumped into tank; **air** in tank **compresses.**

Vehicle **sinks.**



Some water is pumped out of the tanks; **air** inside tank **expands.**

Vehicle acquires **neutral buoyancy.**



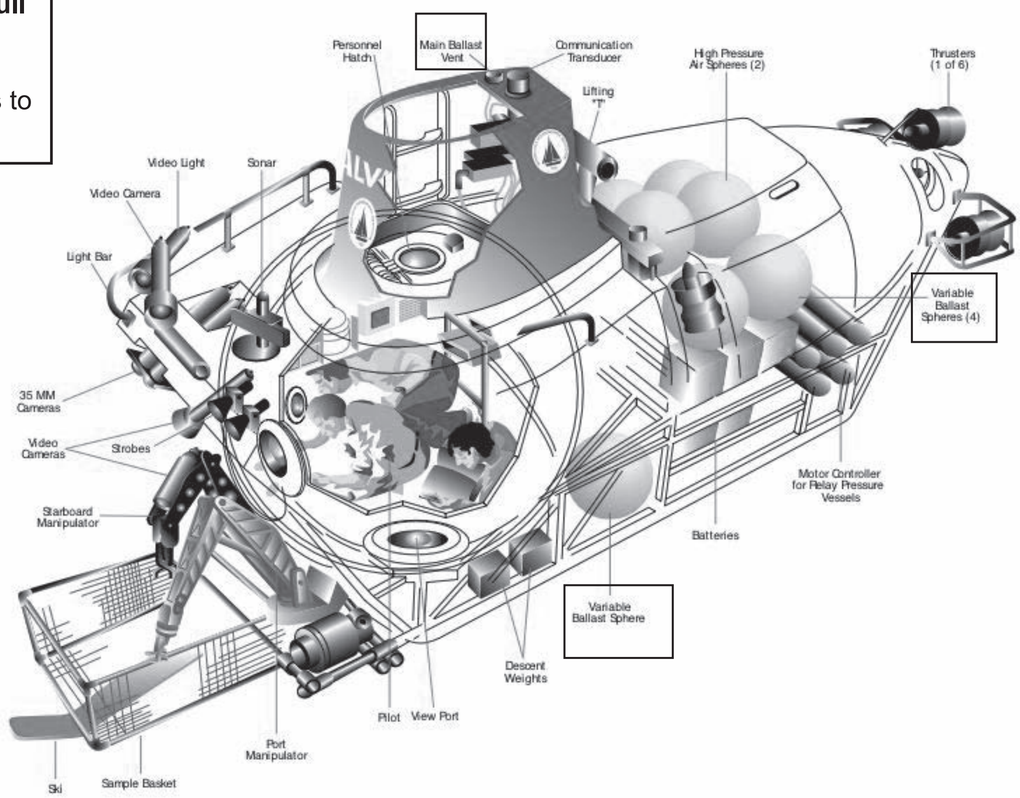
Water is pumped out of the tank; the **air expands** to the **full volume** of tank.

The vehicle **rises** to the surface.

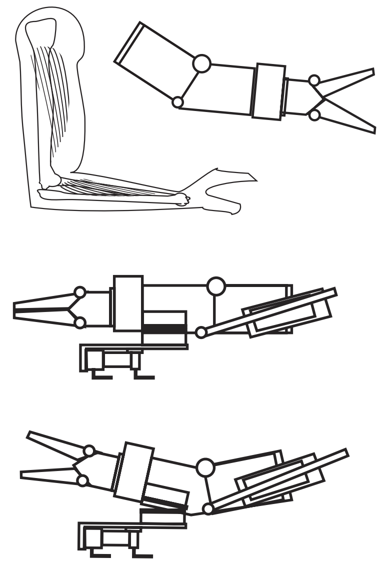
As we design a replacement for the Alvin, we're developing a system for diving that does not use weights at all. It's called the Variable Ballast System (VBS). The system will be a larger-scale version of a system already used on the Alvin to fine-tune its buoyancy as soon as the vehicle has arrived at its destination depth. In Alvin's replacement, the VBS will be used for ascent and descent as well. No more steel weights!

Take a look at the steps used by the Variable Ballast System on the left. Seawater is pumped into and out of spherical tanks located at the front and rear of the submersible. The spherical tanks are hollow, and their volume is fixed. When we're floating at the surface, the spheres contain air. To dive, we pump water into the spheres, without removing any of the air. As the spheres fill with water, the air in the spheres compresses, taking up less volume. Pumping water into the spheres increases the weight of the submersible without increasing its displacement volume.

After we have reached our destination on the sea floor, we pump some water out of the tanks to achieve neutral buoyancy. As we pump water out, the air inside the tanks expands, taking up the volume of the tank not filled by water. When it's time to ascend back to the surface, we make the submersible lighter by pumping more water out of the tanks, and the submersible returns to the surface.



A Strong Arm



Much like the Alvin, the replacement submersible will be equipped with an arm that can reach out and pick up specimens of rock, sediment, or marine life. The arm will then place the specimen in a storage basket on the side or front of the submersible, where it will be stored until the submersible surfaces and scientists can collect it.

The arm is modeled after a human arm with a shoulder joint, an elbow joint, and a wrist joint. And like a human arm, the Alvin's arm has seven degrees of freedom—meaning the arm can move in seven different ways.

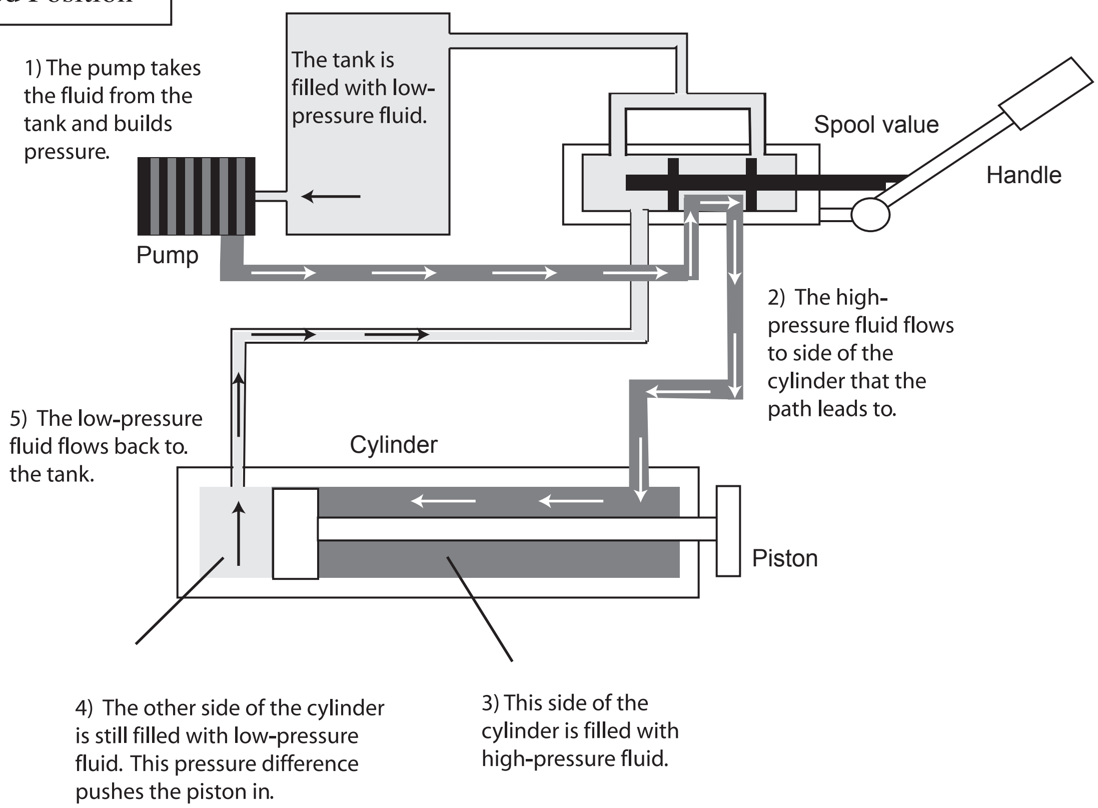
Use your own arm to get an idea of what is meant by degrees of freedom. First, extend your arm straight out so it is parallel to the ground with your palm facing the floor. Keep your arm straight, and then move it from the shoulder. You'll notice that you can move it three ways: vertically, horizontally, and rotationally, as if you were turning a knob. Your shoulder joint has three degrees of freedom.

Now move your arm from the elbow only, holding your shoulder joint fixed. Your elbow joint moves vertically, but not horizontally and not rotationally. Your elbow has only one degree of freedom. Now move only your wrist. You'll see that, like your shoulder, your wrist has three degrees of freedom, even though horizontal and rotational movement of the wrist is limited. (In fact, most of the rotational movement takes place along your arm below the elbow.)

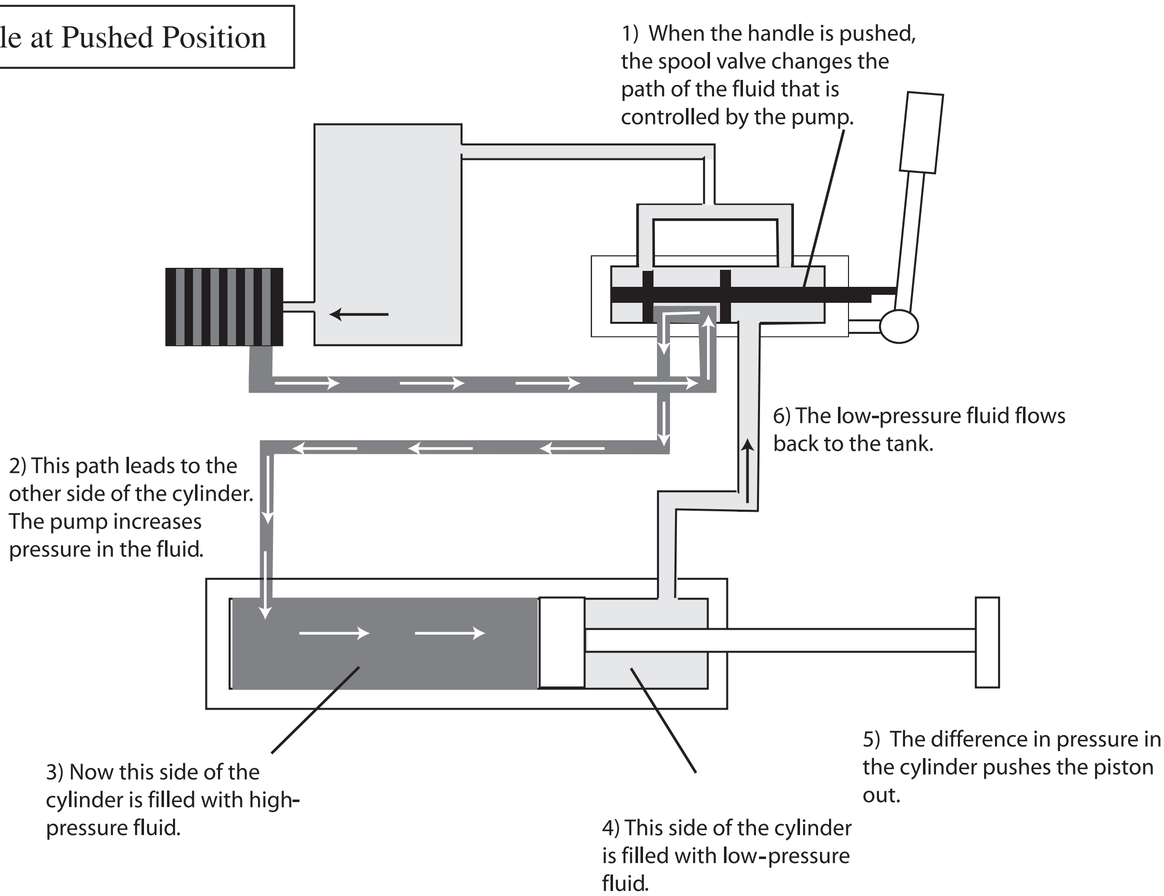
The arm on the Alvin also has seven degrees of freedom, and for that reason, it can move much like a human arm moves. But, of course, muscles don't move Alvin's arm. Instead, a hydraulic power system serves as the "muscles." ***Hydraulic systems*** use liquid to transmit power by taking advantage of fluid characteristics and pressure changes.

Several kinds of hydraulic systems exist, but the diagram on the following page illustrates a hydraulic system similar to the one used to move Alvin's arm. The hydraulic system is filled with a liquid, usually oil or water. This liquid is often called the ***working fluid.*** A pump increases the pressure of the working fluid in one part of the system, by pushing on it. This force creates a difference in pressure between the fluid on one side of the piston and a fluid on the other side of the piston. Remember that a fluid flows from the region of higher pressure to the region of lower pressure until there is no difference, or unless something gets in the way. In this system, the piston is "in the way," but because it is not fixed, it is pushed by the flowing fluid. As shown in the diagram, the handle controls which way the piston moves by changing which side of the piston is higher pressure and which side is lower pressure.

Handle at Pulled Position



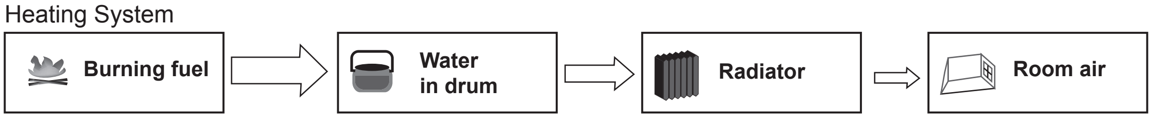
Handle at Pushed Position



In Unit 2, you learned about thermal systems—or systems that make objects get hotter or colder by transferring energy. In this unit, you'll learn about systems that make things move—such as hydraulic systems. When energy is transferred through a system so that an object moves, the system is doing ***work*** on the object. Now, you can understand why the fluid in a hydraulic system is called a "working" fluid; it is transferring energy from the input of a system to the output of a system.

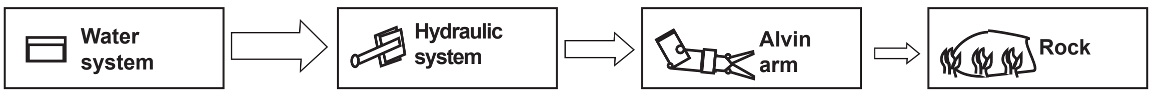
Consider these energy diagrams.

Heating System



The diagram above illustrates a heating system, while the diagram below depicts the Alvin's hydraulic system. When the Alvin's hydraulic arm picks up a rock on the sea floor, it is transferring energy to move the rock. The motion of the rock tells you the arm is doing work on the rock.

Hydraulic System



With hydraulic "muscles," the arm can lift objects that weigh as much as 200 pounds. How much energy is being transferred from the Alvin's arm to the rock? The amount of energy transferred can be calculated using the following equation:

$W = Fd$	W = Energy transferred F = Force on the object d = distance traveled

Where W (for work) is the energy transferred, F is the force on the object, and d is the distance traveled by the object.

If Alvin's arm were to pick up a twenty-pound rock and lift it five feet off the sea floor, how much energy would be transferred?

$$W = Fd$$
$$W = 20 \text{ lb.} \times 5 \text{ ft.}$$
$$W = 100 \text{ ft. lb.}$$

F = 20 lb.
d = 5 ft.

Foot-Pounds (ft.lb.) is the English unit for work.

Engineers have designed many systems that do work: elevators, car lifts, cars, airplanes, ski lifts, to name only a few examples. Any technology that applies a force to move something is doing work! You'll explore several of these systems in this unit.

As we design a replacement for the Alvin, we're working to make the hydraulic arm easier to use. In the original Alvin, an operator would have to manually flip switches controlling the hydraulic system for each piston. This manual work made operating the arm very time-consuming. (To see why, try picking up an object by moving only one joint in your arm in one direction at a time!) The Alvin's replacement will use a different system to control the arm. Inside the cockpit of the Alvin, there will be a small-scale version of the arm. The operator will only have to grasp the hand of the arm and move it the way he or she wants the hydraulic arm to move. A computer system will calculate the coordinates of the small-scale arm and will activate the hydraulic system as necessary to move the large arm until it achieves the same orientation as the smaller one.

The Alvin has served us well during its many years of service and has given us great insight into life at the bottom of the ocean, as well as into the features the ideal submersible might have. No doubt the replacement for the Alvin will teach us even more—both about deep ocean ecosystems and about submersible design!

What's the Story?

1. List three systems on the Alvin that Bob's team is planning to redesign for the Alvin's replacement.

2. How is the Alvin an example of the relationship between engineers and scientists?

Designing with Math and Science

3. Imagine that you've just inflated a kick ball and are holding the air in the ball with your finger over the opening. What happens when you remove your finger and the air can pass freely through the opening? Explain why this happens in terms of pressure difference and fluid movement.

4. How is the compressibility of gases used in a designed system described in this chapter? How is the incompressibility of liquids used in a different designed system described in this chapter?

5. A hydraulic system in the elbow joint of the Alvin is pressurized so that there is a pressure difference of 20 PSI between the working fluid on one side of a piston and the working fluid on the other side. What is the surface area of the piston if it is pushed with a force large enough to lift a five-pound rock? (Remember: $P=F/A$)

What Do You Think?

6. Pneumatic systems are similar to hydraulic systems, but they use a gas, such as air, as a working fluid. Conduct library or Internet research, and write a description of a technology that uses a pneumatic system. How is the pneumatic system designed to work using pressure differences? How is the fact that gases are compressible incorporated into the design?

7. Develop and sketch a design for a robotic arm that can pick up a paper cup. Will your robotic arm be moved by a hydraulic or pneumatic system? Why?