Section 4.3

Swimming and Scuba

Going to the beach would be much less fun without the water. While you can play on the sand or soak up some sun, much of the appeal of the seashore is the sea itself. The water makes it possible for you to float, to propel yourself about with your hands and feet, and to splash your friends. Many aspects of water resemble those of air discussed in Section 4.1. But water's large density provides an interesting contrast to air and compels us to look at several new and important issues. For example, we spend most of our time swimming at the boundary between water and the air—a type of boundary not found in the air alone. We should also look at what happens when people dive below the surface and how they can take air with them in tanks in order to remain below for some time.

Questions To Think About: *What determines whether an object floats or sinks? Why do objects float at the surface of water, rather than hovering at a particular depth? How do swimmers propel themselves forward efficiently? Why is it difficult to breathe through a long snorkel? Why must scuba divers take high-pressure air with them? Why do scuba divers use up their air faster when they dive deeper?*

Experiments To Think About: *If you know how to swim, the best way to warm up to this topic is to jump into a swimming pool. Try to float at the surface. Notice that taking a deep breath of air helps you float. Now let yourself sink. What do you do differently in order to sink? Are you moving your hands or feet in either case? If you are, what are you doing to the water? Now try to float motionless somewhere between the bottom of the water and the surface. You will find it difficult or impossible. Why do your ears hurt when you dive far below the surface of the water?*

Even without swimming you can try to float an object half way down in a glass of water. Add pins to small piece of cork. You will find the object will either float or sink. It will not hover. Why not?

Floating and Sinking

Almost all water sports—swimming, surfing, scuba diving, and boating—ultimately depend on floating in water. If everything sank, just about the only thing you could do at the seashore would be to go for a brief stroll along the bottom. Floating in water depends on the buoyant force, the same force that supports a hot-air or helium balloon in the atmosphere. As always, the upward buoyant force on an object is equal in magnitude to the weight of the fluid the object displaces. An object that's less dense than water, such as a wooden ball, is lighter than the water it displaces and accelerates upward. An object that's more dense than water, such as a cement block, is heavier than the water it displaces and accelerates downward.

Just as in air, the buoyant force in water has its origin in pressure—the water pressure below an object is greater than that above the object, so the object experiences a larger upward force from below than downward force from above. However, the basis for pressure in water is somewhat different from that in air. While air pressure is caused by air molecules colliding with one another and with surfaces, water pressure is caused by the forces that water molecules exert on one another while they're touching. Although the water molecules are kept in contact by attractive forces that appear when they begin to separate, these molecules will also push one another away if they begin to approach too closely. This tendency to pull together when stretched and push apart when squeezed makes water almost incompressible—its density changes very little when you try to squeeze it or stretch it. Water's density is always about 1000 kg/m^3.

In the absence of gravity, the pressure in a container of water would be uniform and would depend only on how hard the water was being squeezed by the walls of the container. However, gravity creates additional pressure near the bottom of the container because the water there must support the weight of the water above it. Just as the air pressure in the atmosphere increases as you descend toward the ground, so the water pressure of the ocean increases as you dive deeper below its surface. The pressure deep in the ocean is enormous because the water there must support the immense weight of the water above it.

Because water is nearly incompressible, its density is almost constant, regardless of depth. An object always displaces the same weight of water so it always experiences the same buoyant force. That's not the case for a balloon in air because the atmosphere becomes less dense as the altitude increases. A balloon in air experiences a flight ceiling above which the buoyant force is too small to accelerate the balloon upward. But there is no flight ceiling in water. If an object floats in water, it floats upward all the way to the surface of the water. If it sinks, it sinks all the way to the bottom.

One of the reasons that swimming is so interesting is that we can control whether we sink or float. Our average densities are almost exactly that of water. If we were made of stone we would always sink, and if we were made of wood we would always float. Fortunately, our bodies are mostly water. While the rest of our constituents vary, with bones and muscle that are more dense than water and fat that is less dense, our average densities are nearly that of water. Whether we sink or float depends in large part on how much air is in our lungs. A big breath may lower your average density enough for you to float and letting it out may raise your average density enough for you to sink.

Body type affects a person's ability to float. A person with extra fat will have a relatively low average density and should float easily while a person with less fat will tend to sink. A person with very little fat may be unable to float even after taking a huge breath of air. Since his downward weight exceeds the upward buoyant force, he can remain at the surface of the water only with the aid of an additional upward force. He may obtain this force by "treading water"—pushing downward on the water so that the water pushes upward on him.

Floating and sinking are easy compared to hovering at some particular depth. That's because hovering requires your average density to be exactly that of water. Such perfect equality is nearly impossible to achieve without continuous adjustment. Passive objects—ones that can't make adjustments in their average densities—either float or sink. People, fish, and submarines are able to hover between the surface and the bottom because they can carefully adjust their average densities to be almost exactly equal to that of water.

Since tissues and bones are more dense than water and tend to sink, skin divers use the air in their lungs to lower their average densities to that of water. Because fish have no lungs, something else must keep them from sinking. In a remarkable evolutionary advance, *bony fish* developed an internal air-filled *swim bladder* that lowers their average densities to exactly that of water. More primitive *cartilaginous fish* such as sharks have no swim bladders and would sink if they didn't obtain additional upward forces. These dense fish "fly" through the water much as an airplane flies through air—the forces needed to keep them from sinking are obtained by pushing water downward.

This careful balancing act is more complicated for a scuba diver, since the scuba equipment and wet suit tend to lower the scuba diver's average density. To raise the scuba diver's average density to that of water, the scuba diver must wear a heavy weight belt. In an emergency, the scuba diver can remove the weight belt and will then float upward to the water's surface.

An object that sinks eventually experiences enough upward support force from the sea bottom to bring it to rest. But why does a floating object remain at the surface of the water? That's because, once the object floats upward far enough to project out of the water, the buoyant force on it decreases. It stops displacing water and begins to displace air instead. Since air is much less dense than water, the buoyant force on the object diminishes quickly as it rises out of the water. As long as the object is more dense than air and less dense than water, it will float partly in water and partly in air. It adopts a height at which the weight of the water and air it displaces is exactly equal to its weight.

People, driftwood, rowboats, and battleships all remain at the surface of water for this same simple reason—they all weigh less than the water they would displace if they were fully submerged. They rise out of the water until they displace a mixture of fluids, water and air, equal in weight to their own weight. While it might seem that a metal battleship should never float, that ship contains vast amounts of air and has an average density much less than that of a solid block of wood. That's why a battleship floats high above the surface of the water. If you bore a hole in the boat and permit water to replace the air inside, its average density will soon be greater than that of water and it will sink.

Before we leave the topic of floating, there are two more issues to discuss. First, there is a way to change the density of water: add chemicals to it. Adding salt to water increases its density. Because ocean salt water is about 3% more dense than fresh water, it exerts a larger buoyant force on objects immersed in it. People find it easier to float in ocean water than in fresh water. Trapped inland seas can be even more salty than the ocean. The waters of the Dead Sea and the Great Salt Lake are so salty and dense that people float effortlessly in them.

Second, a floating or sinking object doesn't accelerate continuously as it rises or falls through the water. That's because it experiences *drag*, a friction-like force that opposes the object's motion through the water and converts its ordered energy into thermal energy. The magnitude of this drag force increases as the object's speed through the water increases. For example, the drag force on a sinking object is in the upward direction and grows stronger as the object's downward velocity increases. The upward drag force eventually becomes strong enough to stop the sinking object from accelerating downward and the object then descends at a constant velocity, its *terminal velocity*. Similarly, a floating object, such as an air bubble, eventually reaches an upward terminal velocity.

CHECK YOUR UNDERSTANDING #1: A Clinker Sinker
Cubic zirconia, a popular imitation diamond, is 1.65 times as dense as the real thing. If you find a heavy liquid in which a diamond just barely floats, what will happen to a cubic zirconia copy?

Moving in Water

Suppose that you are floating motionless at the surface of a still lake. How can you move toward the shore? On land, you cause yourself to move by exerting frictional or support forces on your surroundings. Those surroundings push back on you and you accelerate. In water, friction and support forces are usually not available. If you had a long pole, you might push on the lake bottom—the lake bottom would push back and you would accelerate. This scheme is quite effective for propelling certain boats, notably trade and passenger boats on shallow rivers, but it isn't helpful for swimmers. Usually, the only thing that can push on you is the water itself.

Somehow, you must cause the water to exert a force on you in the direction you wish to accelerate. Whether you are swimming, paddling a canoe, or riding in a motor boat, the method is the same: you push on the water itself and the water pushes back on you, propelling you in the direction you wish to travel. The water accelerates in one direction and you accelerate in the other.

We have encountered this action-reaction concept before. We noted in Section 2.3 that one way to propel yourself off frictionless ice on a frozen lake is to throw your boot toward the shore as hard as you can. Your boot accelerates in one direction and you accelerate in the other direction. This effect is an example of the conservation of momentum in a system that's isolated from outside forces. When you and your boot are together and motionless on the slippery ice, you have zero momentum. After you throw your boot, it has momentum in one direction and you have momentum in the other direction. The total momentum of the combined system, you and your boot, is still zero. If the ice is truly frictionless, both you and the boot will slide off the ice in opposite directions. Of course, there's no such thing as perfectly frictionless ice and sliding friction eventually slows you to a stop. You have to keep throwing things to reach the shore.

The same notions apply to swimming. As you throw or push water in one direction, you accelerate in the opposite direction. Again, the momentum of the combined system, you and the water, is conserved. If the water exerted no further force on your body, you would travel at a steady pace across the lake. However, once you begin to move through the water, you experience drag forces that slow you down. You must keep pushing water behind you to reach the shore.

While it's good news that you can propel yourself forward by pushing water backward, there's also some bad news. First, drag wastes some of your energy by turning it into thermal energy. You can reduce this wasted energy slightly by wearing a smooth bathing suit and covering your hair. But there is a second bit of bad news: the water that you push backward also ends up with some of your energy. As you swim, you waste a substantial fraction of your effort moving water instead of your body. That's one reason why swimming is so exhausting. But while you have no choice about transferring energy to the water, you have some control over the amount of energy you give it. A good swimmer tries to minimize the energy that she gives to the water.

Drag slows you down by transferring a certain amount of backward momentum to you each second and you propel yourself forward by transferring that backward momentum to the water. To be an efficient swimmer, you should transfer the momentum to as much water as possible, so that the water ends up moving slowly, with relatively little kinetic energy. Water's momentum is proportional to its speed while its kinetic energy is proportional to the square of its speed. That's why a small mass of water moving rapidly has more kinetic energy than a large mass of water moving slowly, even though the two have the same momentum. Thus it's more energy efficient for you to push a large mass of water backward slowly than to push a small mass of water backward rapidly—you experience the same forward force but give the water less energy in the process.

Part of the art of swimming well is learning to push large masses of water directly backwards at modest speeds, rather than churning the water about at wild angles and high speeds. Wearing flippers, as a scuba diver does, increases the surface area of your feet and lets you move more water backward at lower speeds. In this manner, you can give the water backward momentum without transferring much energy to it.

Powerboats also propel themselves forward by pushing water backward. They, too, are most energy efficient when they move large masses of water directly backward. Powerboats usually push on the water with a propeller, a fanlike rotating device that's driven by an engine. A propeller has several ramps, commonly called *blades*, wrapped around a rotating central cylinder (Fig. 4.3.1). Any water that's caught by a blade is accelerated backward as the blade moves. The water pushes the blade forward and propels the boat. We'll look at propellers more carefully in Section 5.3.

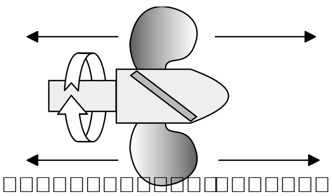

Fig. 4.3.1 - A propeller functions by rotating a cylinder that has several ramp-like blades attached to it. As the cylinder turns, the blades exert forces on the water and accelerate it backward. The water exerts equal but oppositely directed forces on the blades. These reaction forces propel the boat forward.

CHECK YOUR UNDERSTANDING #2: Fountain Power

Some sport boats have no propellers. Instead, they use pumps to shoot jets of water from their sterns. These jets may leave the boats above the surface of the water. How can such a jet propel the boat forward?

Scuba Diving

Suppose you're tired of floating at the surface and decide to explore the water below. You buy a very long soda straw, tie a rock to your waist, and descend 10 m to the sandy bottom. You try to breathe through the straw and discover that you can't. How do you breathe and why does being underwater make it so difficult?

On land you draw air into your lungs by increasing their volume with the muscles of your chest and diaphragm. As your lungs expand, the air molecules inside them must fill a larger volume so the air's average density and pressure decrease. Air near your mouth then experiences a pressure imbalance between atmospheric pressure outside and the lower pressure inside your lungs.

We have encountered unbalanced pressures before in dealing with the buoyant force. Unbalanced pressures exert net forces on objects. Each small volume of air near your mouth experiences a net force into you mouth. While a volume of air may not seem like much of an object, it responds to unbalanced pressures and accelerates toward your lungs.

To breathe out, you compress your lungs with your chest and diaphragm, packing the air molecules more tightly and causing the air's density and pressure to rise above those of the outside air. A pressure imbalance then causes air to accelerate out of your lungs and mouth.

So you breathe by changing the pressure inside your lungs. When you make that pressure less than atmospheric, air rushes into your lungs. When you make that pressure more than atmospheric, air rushes out of your lungs.

This scheme works fine as long as everything around you is at the same pressure. But when you're 10 m below the surface of water, it's not just atmospheric pressure that's pushing on your chest. It's also the pressure of 10 m of water. Remember that atmospheric pressure comes about from having to support the weight of several kilometers of atmosphere above the surface of the earth. Air is very light compared to water. Supporting 10 m of water takes as much pressure as supporting the whole atmosphere.

You can determine the pressure at any depth in water by considering that the weight of water above a 1 m^2 surface increases by about 10,000 N for each meter of depth. 10,000 N is the weight of 1 m^3 of water. To support this increased weight, the water pressure must increase by 10,000 Pa for each meter of depth.

Ten meters below the water's surface, your chest experiences twice the pressure it did on land. This pressure on your chest compresses the air in your lungs until its density and pressure are also twice those of the atmosphere. While you may not feel this compression happening in your lungs as you dive below the surface, a similar compression occurs in the air trapped inside your ears. As that air compresses, the tissues of your ear distort and you feel pain.

Unfortunately, the air in your breathing straw is not supporting any water and is still at atmospheric pressure. With the air in your lungs at twice the pressure of the air in the straw, no air is going to flow into your lungs. Since you're not strong enough to expand your lungs and reduce the pressure inside them below atmospheric pressure, you can't breathe in. You can only exhale.

For you to be able to breathe air far below the surface of the sea, the air entering your mouth must be compressed so that its pressure is about the same as the pressure your chest is experiencing. If you're 10 m below the surface, the air pressure you breathe must be about twice atmospheric pressure or two "atmospheres." If you're 100 m below the surface, the air pressure must be about eleven atmospheres. The factor of eleven comes about because, at 100 m, your chest is supporting the weight of 10 atmospheres worth of water and 1 real atmosphere. This pressurized air can be sent to you through a pipe from the surface, like the old deep-sea divers, or you carried it with you in a scuba tank.

The purpose of the scuba equipment is to provide air at essentially the ambient pressure. A special pressure regulator ensures that the pressure of air delivered to your mouth is just equal to the water pressure surrounding you and your chest. When you expand your lungs with your chest muscles and diaphragm, this pressurized air is gently accelerated inside. You exhale by contracting your lungs and pushing the air into the water as bubbles.

In scuba equipment, air is stored in steel tanks that can withstand enormous pressures. Air molecules are packed very tightly into the tanks so that each tank contains enough air for many minutes of breathing. Because the density of air in a tank is very high, its pressure is also very high. That pressure is typically 200 atmospheres (about 20,000,000 Pa); much too high for breathing. The scuba equipment reduces the air pressure with a pressure regulator. The regulator permits small amounts of the high-density air to expand into a separate volume. As the air molecules move apart, the air's density and pressure diminish. You breathe air directly from this second volume, which includes the mouthpiece.

The pressure regulator must determine just how many air molecules to allow into the second volume. If the pressure it provides is too low, you won't be able to breathe in, and if it's too high, you may blow up like a balloon. Adjusting the pressure is the delicate task of an ingenious regulating device.

The regulating device compares the pressure in the mouthpiece to the pressure in the water. The regulator uses a flexible membrane to control the flow of air from the high-pressure volume (Fig. 4.3.2). On one side of the membrane is the water and on the other side is air from the mouthpiece. The membrane experiences zero net force only when the pressures on its two sides are exactly equal.

If the pressure in the mouthpiece is too low, the membrane experiences a net force. It opens the regulator valve to let more air from the tank flow to the mouthpiece. When the air pressure in the mouthpiece reaches the water pressure, the membrane closes the valve. As you breathe air from the mouthpiece, the regulator permits more air to flow in so that the air pressure in the mouthpiece is always very close to the water pressure.

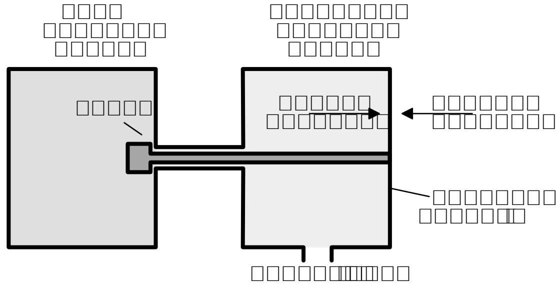

Fig. 4.3.2 - The pressure regulator in scuba equipment uses a valve and a pressure-sensitive membrane to control the flow of high pressure air to the diver's mouthpiece. If the mouthpiece pressure is too low, the membrane opens the valve to allow more air molecules to flow into the mouthpiece region. The pressure inside the mouthpiece rises as a result. When the mouthpiece pressure is equal to the outside water pressure, the membrane closes the valve to prevent further flow.

Actually, the pressure regulator in scuba equipment has two stages of pressure regulation. The first stage reduces the enormous pressure in the storage tanks to about 10 atmospheres and the second stage reduces it to the ambient pressure. The first stage regulator is needed because the second stage regulator doesn't work well when the air it starts with has too high a pressure.

While the second stage regulator compares its outlet air pressure to the ambient pressure, the first stage regulator compares its outlet air pressure to a fixed reference—a spring. The air leaving the first stage regulator pushes on one side of a membrane while the spring pushes on the other side of that same membrane. If the air pressure on that membrane is too low, the spring dominates and the first stage regulator lets air flow through it. If the air pressure rises too high, the air dominates and the first stage regulator stops the airflow. Spring-operated pressure regulators are commonly used with propane tanks for home heating and cooking, and on carbon dioxide cylinders for soda machines. These regulators ensure that gas is delivered at a constant low pressure, substantially below the pressure that exists inside the storage tanks themselves.

The deeper a scuba diver goes, the more pressure the regulator must supply in order for him to be able to breathe in. This increased pressure has several consequences. First, the air's density increases with pressure. At great depth, the regulator puts more air molecules into each breath than it does at shallow depth. Since the air tanks contain a certain number of air molecules, the stored air is depleted faster at great depth than at shallow depth. The deeper the diver goes, the sooner his air supply will run out.

Second, increasing the air's density also affects its ability to flow. At its normal sea-level density, air flows easily and we rarely notice its movement into our lungs. At 10 times normal density, air is noticeably thicker and breathing becomes more difficult.

Third, pressure affects the solubilities of air molecules in water. A gas dissolves when its molecules become separated and caught up in the moving molecules of water. The more pressure the air exerts on the water's surface, the more frequently its molecules will become caught in the water. Once caught, those gas molecules travel about in the water until they find a route to the surface, either as individual molecules or as bubbles of many molecules together.

How long gas molecules will remain in the water depends in part on any forces that the gas molecules and water molecules exert on one another. Carbonated beverages are made by exposing water to carbon dioxide gas under several atmospheres of pressure. Carbon dioxide dissolves easily in water because carbon dioxide molecules feel a strong attraction to water molecules. The two merge to form carbonic acid, which gives soda much of its taste. When you open a bottle of soda, the pressure is released and some of the carbon dioxide gas comes back out of solution. Carbon dioxide molecules deep in the water find one another and begin to form bubbles of gas. The soda fizzes as these bubbles of carbon dioxide float to the surface of the beverage.

Nitrogen molecules experience less of attraction to water molecules, so nitrogen is less soluble in water than is carbon dioxide. However, under pressure, nitrogen can be dissolved in moderate quantities. When a diver is far below the surface of the water, his blood and tissues dissolve a relatively large amount of nitrogen from the air he breathes. If he returns to the water's surface too quickly, the reduction in pressure will permit the nitrogen to come back out of solution. It's just like opening a bottle of soda.

While the nitrogen bubbles are quickly cleared from a diver's blood stream, the bubbles that form in his tissues are slow to dissipate and the diver experiences a painful case of "the bends" or decompression sickness. To avoid trouble, a diver must return to the surface slowly so that the nitrogen will come out of solution gradually and be exhaled from his lungs. Nitrogen gas is slow to diffuse into and out of tissues, so that a diver who remains deep underwater for a long time must take a long time to return to the surface. With only one air storage tank, a diver probably can't stay under water long enough to be at serious risk of the bends. However, two or three air tanks permit longer dives and increased quantities of tissue-dissolved nitrogen. Only experienced divers, able to carry out gradual decompression, can safely use two or three air tanks.

At very great depths, so much nitrogen dissolves in the blood that it becomes toxic. At these depths, a diver must breathe air that contains little or no nitrogen. Since breathing pure oxygen is also not healthy, helium is used to dilute the oxygen. Helium, an inert gas, is so weakly attracted to other molecules that it's virtually insoluble in water, blood, or tissue, regardless of pressure.

CHECK YOUR UNDERSTANDING #3: No One Likes Inflation

Scuba divers are cautioned to breathe out as they ascend. What would happen if a diver held her breathe and rose upward rapidly?