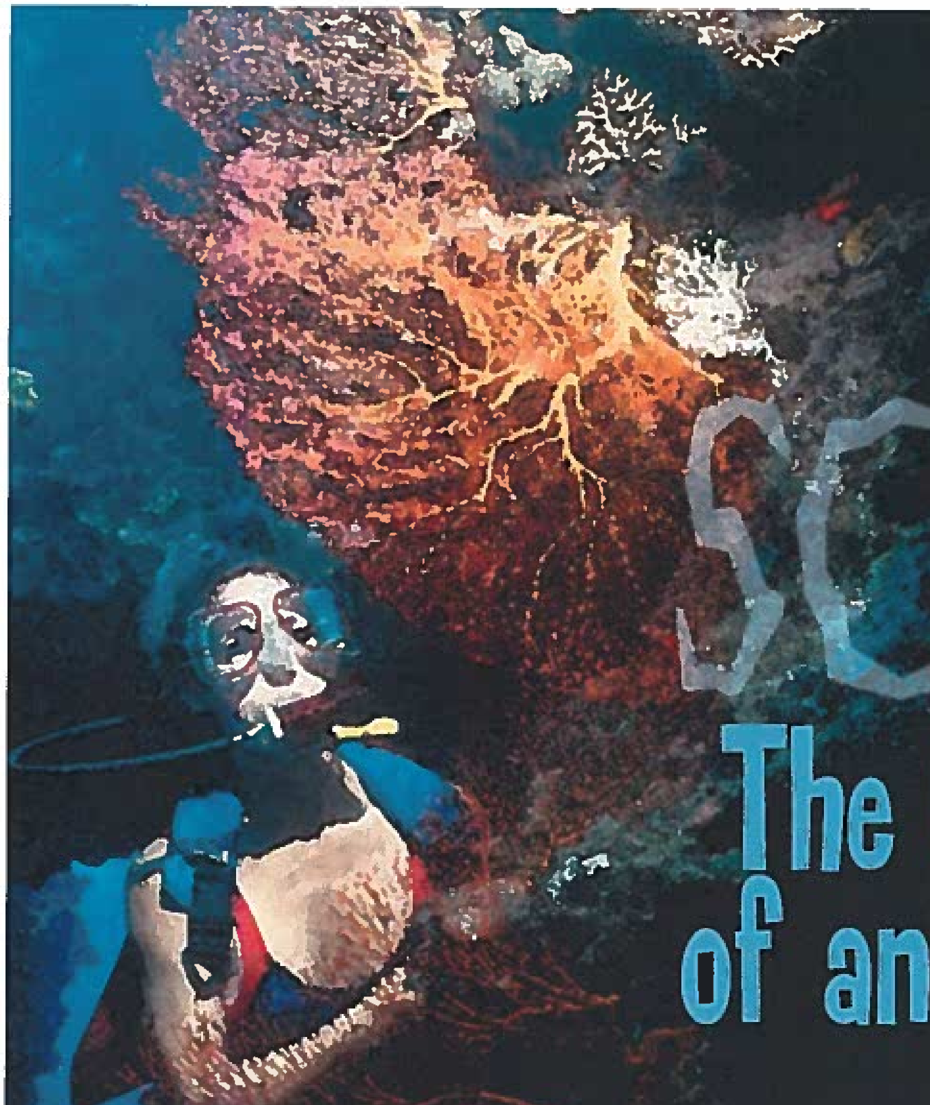

SCUBA
The Chemistry of an Adventure

By Melissa Belleman

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When I took my first scuba diving class in Okinawa, Japan, 10 years ago, learning to dive was my only goal. But I soon found that the wonders of the underwater world are connected to some pretty interesting science. Thinking about that science, much of which I remembered from high school and college, made the adventure even greater.

SCUBA, the acronym for "Self-Contained Underwater Breathing Apparatus", is a water sport requiring the use of a breathing apparatus. The breathing apparatus of choice for most recreational divers is a "regulator", which is attached to an air tank. Most tanks hold about 3000 psi (pounds per square inch) of your standard mix of air—approximately 79% nitrogen, 21% oxygen, with traces of other gases mixed in. This amount is usually good for about 30–45 minutes of diving at depths to 60 feet below sea level.

When I embarked on my first open-water dive as a scuba student, I was unprepared for the ways the water environment altered my sensory perceptions. The underwater wildlife was amazing, of course, but everything was so different! Colors changed. My bright pink wet suit looked almost purple. Distances changed. When I reached for my dive buddy's hand, I missed. Sounds changed. The sounds of sea life were louder than I expected, and they seemed to come from everywhere. Even external temperatures seemed altered. My temperature gauge displayed 78 °F, a temperature that would be plenty warm at the surface, but I felt cold.

As I watched my instructor trying to gather my class of eight beginners into a group, the cliché "herding cats" entered my mind. Half the students were stuck at the surface, having difficulties descending. The others seemed to sink like rocks.

Years later, when I decided to become a scuba instructor, I learned that all of these phenomena are based on some basic scientific principles and laws related to water, a simple compound with some unique properties. A water molecule consists of two hydrogen atoms and one oxygen atom. Because the oxygen atom attracts the molecule's electrons more strongly than the hydrogen atoms, the oxygen atom in a water molecule develops a slight negative charge while the hydrogen atoms are slightly positive. This polarity in water molecules causes them to attract each other. Although the atoms within a water molecule are held together by covalent bonds, the attraction that exists between water molecules is due to something called a hydrogen bond. These hydrogen bonds give the water many unique properties, including its relatively strong surface cohesiveness or tension.

Another feature of water explains why I felt so cold. It turns out that water has a high heat capacity. The specific heat capacity of a substance measures how much heat must be added or removed from a given amount of the substance to change the temperature of 1 gram of it by 1 °C. Water readily drains away heat energy from warmer submerged objects—in this case, me! And a continuous flow of water meant that I was constantly sur-

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rounded by cooler water, even if I wasn't moving. Divers compensate for this phenomenon by wearing wet suits. The wet suit traps a layer of water between the material and the diver's skin. Thus, the diver's skin is able to heat the small amount of water that is inside the wet suit. This heated water stays in contact with the skin and doesn't flow away to mix with the surrounding environment.

The absorption of light in water explains the problem with my wet suit's color. The human eye sees only a narrow segment of the electromagnetic spectrum. The differences in wavelengths cause us to see different colors. When light enters water, wavelengths with the least amount of energy—the reds—tend to be filtered out. At greater depths, oranges and then yellows are filtered out as well. When an instructor takes students on their first deep dive—usually around 80–100 feet—she may take a set of colorful plastic objects, like toy baby keys, so that students can see the colors diminish as they descend—first red, then orange, then yellow.

Underwater viewing is affected by other factors. Turbidity is the relative concentration of suspended particles in water. The particles can be organic, such as plankton, or inorganic, such as silt. Diffusion is the scattering and deflection of light as it enters water, causing underwater shadows to disappear.

Refraction explains why I missed when I reached for my dive buddy's hand. Refraction is the bending of light as it travels from one medium to another. Had I been swimming without a mask, refraction would not have caused a problem. My eyes would have been in the same medium as his—water. However, I was wearing a mask. Light bends as it travels from the water back into the air inside the mask, causing objects to appear closer by a 4:3 ratio. When I thought my buddy's hand was 3 feet away, it was really 4 feet away. I missed!

Scuba divers depend on specialized gear to regulate body temperature and air pressure.

Possibly the strangest sensory experience underwater is the change in auditory perception. In Okinawa, I could actually hear sounds made by shrimp! Their clicking was surprisingly loud, and it seemed to come from all around, although the shrimp were tucked into the crevices of a coral sea wall. The explanation involves both chemistry and physics. Sound waves are a mechanical form of energy transmitted only within matter. The denser water is more elastic than air, and the more elastic the medium, the faster the sound waves travel. Although the specific value depends on the temperature of the water, sound travels at a speed of approximately 1450 m/s in fresh water and 1530 ms/s in salt water—values over four times the speed of sound in air (330 m/s). The result is that divers hear underwater noises very well. They also hear noises from a farther distance than they would on land.

SCUBA and the gas laws

Divers are surrounded by constantly moving water molecules exerting pressure on their bodies. Dive to the bottom of the deep end of a swimming pool, and you'll feel a great deal of pressure. Because water is much denser than air, pressure changes are much greater for a given change in water depth than for the same depth change in air. For example, water exerts over 100 lbs of force on the surface of a one-gallon metal can pushed just one foot below the surface. For every 10 meters (about 33 ft) in depth, divers experience one atmosphere of additional pressure.

The changes in pressure experienced by divers are most noticeable on the body cavities that contain air, such as the lungs, the middle ear, and the sinus cavities. Boyle's law describes how these gas volumes respond to changes in pressure. For a constant amount of gas at a constant temperature, Boyle's law states: The volume of a gas sample varies inversely with its pressure.

If divers descend without scuba gear, the volume of these body cavities decreases as the surrounding water pressure becomes greater. However, this effect is not experienced by divers using scuba gear because the regulator on the air tanks delivers air at the same pressure as the surroundings. But if divers must make emergency ascents from this depth, they must remember to breathe out steadily as they return to the surface. If

Colors fade during descent—first red, then orange, then yellow.

One drawback of this effect is that when sounds travel so fast, there is no recognizable delay between ears as the sound reaches the diver. This makes it difficult for divers to discern the source direction of sounds underwater. The sound delay between ears on the average human underwater is only about 1/4 the delay in air. Furthermore, surface noises are very faint to the diver since sound waves do not transfer well from air to water or vice versa.

As for the weightless feeling you get when scuba diving, that's explained by buoyancy. And buoyancy is best described with Archimedes' principle: Any object wholly or partly immersed in fluid is buoyed up by a force equal to the weight of fluid displaced by the object (See "Question From the Classroom" in this issue of *ChemMatters.*) An object that displaces a given volume of fluid will experience a greater buoyant force if it is immersed in a denser fluid. And that explains why objects float better in salt water, which has a density of 64 pounds per cubic foot, than in fresh water, which has a density of 62.4 pounds per cubic foot. Scuba divers usually have to wear a little more weight to descend in salt water than in fresh water.

From a diver's point of view, buoyancy amounts to something like this: If the average density of myself plus my diving gear is greater than the density of the water into which I am diving, I sink. If my total average density is less than that of the water, I float.

The body's average density depends upon its specific composition. Generally, fat has a density of between 0.7 and 0.9 g/mL, bone about 1.9 g/mL, and muscle around 1.08 g/mL. A lean muscular diver with a higher average density tends to sink faster than a diver with a greater amount of body fat. That diver has a harder time descending. The added gear and wet suit generally reduce the diver's average density. That's why divers often wear weight belts.

After my first open water dive, I was hooked on scuba! And now, as an instructor, I enjoy conveying my love of the sport, as well as my appreciation for the science that underlies it. And for science students, scuba may just be the ultimate lab! ▲

$P_{gas} = K_H C$

they don't, the pressure of the air in their lungs will cause their lungs to expand, causing rupturing of lung tissue.

Not only does the pressure affect the volume of trapped gases, but it also influences the solubility of gases in liquids. Here's where Henry's law comes in: The amount of gas that will dissolve in a liquid at a given temperature varies directly with the pressure above the liquid. Thus, during a dive, any gases entering the lungs are absorbed more readily into the diver's blood. The diver's body will experience an effect similar to opening a can of soda if the diver ascends too rapidly to the surface (See "Henry's Law and Noisy Knuckles" in the December issue of *ChemMatters.*) To minimize the risk of gas bubble formation, a condition that divers call "the bends", they observe time limits for dives to depths greater than 10 m. They may ascend to shallower depths periodically to allow some of the dissolved nitrogen to escape. The final ascent involves several "hold points" to allow for gradual decompression back to one atmosphere of pressure.

At very great depths, 30 m or more, so much nitrogen enters the blood that divers experience a narcotic effect called "rapture of the deep". The diver's behavior may become dangerously irrational as the effect increases. For this and many other reasons, responsible divers never work alone underwater.

Refraction, the bending of light as it enters another medium, explains why submerged objects appear to be closer in water than in air.

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