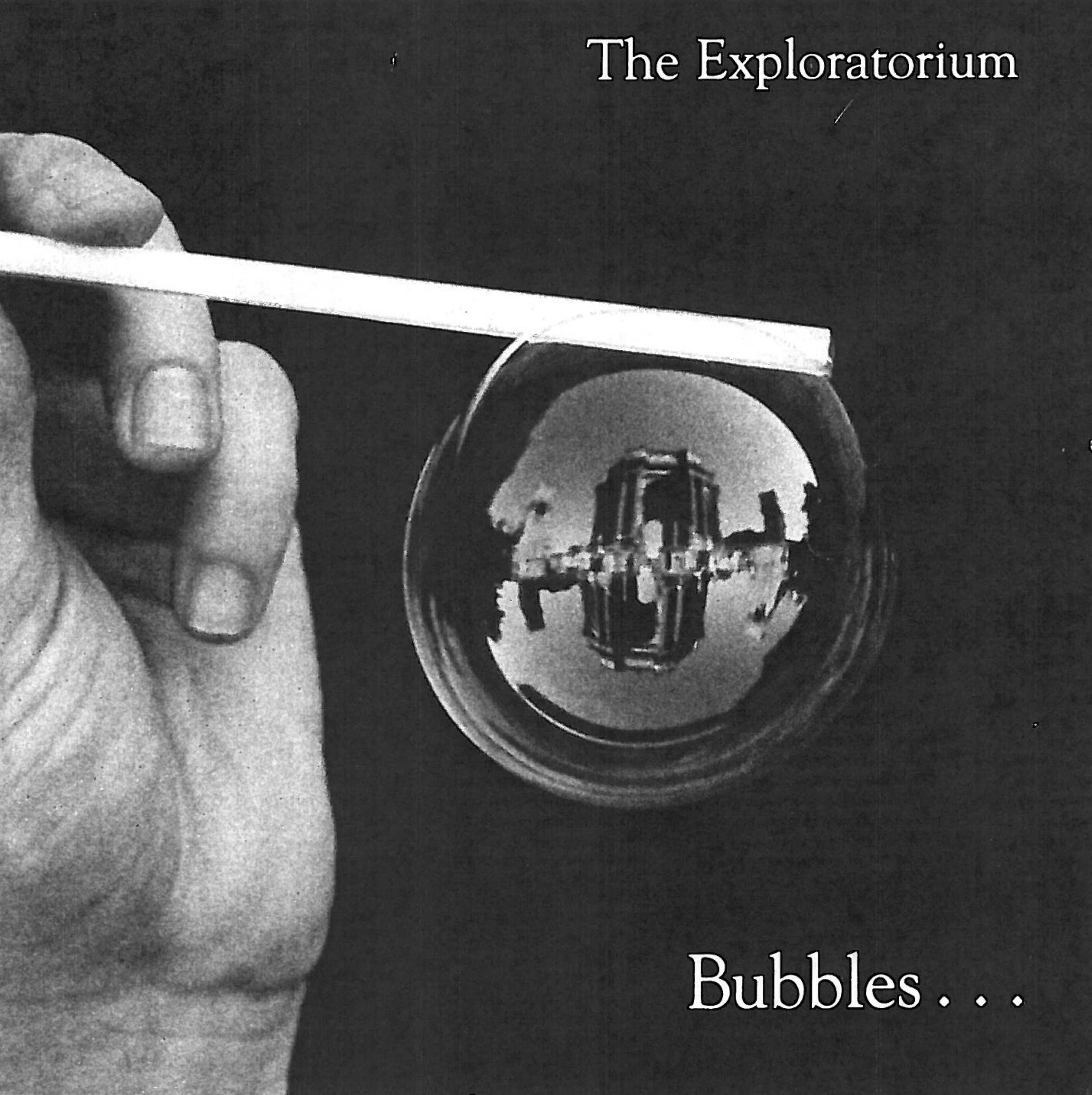
The Exploratorium



Bubbles . . .

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Editor:
Paul Preuss
Art Director:
Jad King
Design:
Joan Venticinque
Production:
Joan Venticinque, Peter Still, Susan Schwartzenberg
Photographer:
Nancy Rodger

Frank Oppenheimer
Director
Virginia Carollo Rubin
Executive Associate
Wendy Radin
Administrative Officer

Cover:
This bubble has captured two images of the Palace of Fine Arts. The curved (convex) outer surface of the bubble reflects the building right side up; the curved (concave) inner surface of the bubble inverts and reverses the image, just as the inner surface of a shiny spoon inverts and reverses the image of your face.

Introduction
by Paul Preuss

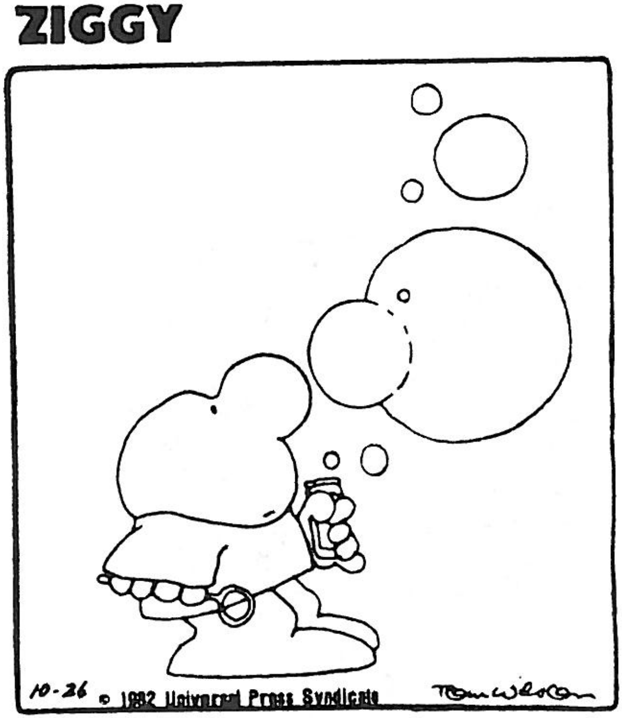
"The world's a bubble, and the life of man
Less than a span."

So wrote Francis Bacon near the end of his life. The beauty, fragility and evanescence of soap bubbles have often commended them to writers seeking a metaphor or symbol for the insubstantial, the unreal, the unattainable —as when Shakespeare described the typical soldier, "Seeking the bubble reputation/Even in the cannon's mouth."

Well, there are bubbles, and there are bubbles. We commonly use the word for two different sorts of phenomena, one describing a continuous membrane or sac which separates an inner volume from its surroundings, the other describing a pocket or void inside some substance. The first definition includes soap bubbles, but it also embraces living cells, which can be very long-lived. Indeed, without a membrane to separate the delicate inner workings of the cell from its active chemical environment, life could not have survived its earliest beginnings in the oceans of ancient Earth.

There are many examples of the other kind of bubble, the pocket or void, and they are responsible for much of life's savor and delight. Consider the holes in Swiss cheese! Some bubbles even change definitions in mid-ascent, like those in a glass of sparkling wine, which start as pockets in the liquid and then emerge into the air as spherical membranes, carrying the bracing aroma of the wine up to our waiting noses.

This bubble world? It is just that, a whole bubble universe in fact, if you find Einstein and any number of his cosmological successors convincing. In this issue of



The Exploratorium magazine we investigate many sorts of bubbles—soap bubbles, bubbles in bread, in carbonated beverages, in rock and steel, even bubbles in blood. And yet we have only touched the surface of our subject—as lightly as, umm, a bubble . . . .

Bubble People
by Linda Dackman

When we started planning this volume of *The Exploratorium* Magazine we immediately thought of Mr. Eiffel Plasterer of Huntington, Indiana. The first time we called to talk to Mr. Plasterer his wife said he was out in the fields. "When's a good time to call back?" we asked. "Well, he's out in the fields all day," she said, "and the rest of the time he's in his workshop blowing bubbles."

Eiffel Plasterer, who is eighty-four years old, began blowing bubbles in 1925. A physicist and teacher, he got involved because of the educational potential of bubbles. "Very shortly after I started teaching high school, I inquired of my students how they would make a bubble solution," he told us when we finally reached him. "I wanted to use the bubbles as a basis for investigating science. It was a very poor solution we started with, but we got bubbles from it anyhow. I've been at it ever since."

Since the early days when he blew bubbles solely with Ivory Soap, Plasterer's investigations with bubbles have led him to devise at least six different carefully concocted bubble solutions. "With one of my solutions I can do the sorts of bubbles that are very big formations, where I can encase a full-grown man. I have another solution for what I call my long-lived bubbles. The longest-lasting one survived 340 days. It was breath-blown just like any other bubble."

As far back as 1917, Sir James Dewar kept a bubble for 108 days—but his bubbles were blown with purified air. Plasterer's bubbles, because they are breath-blown, are particularly remarkable. Human breath contains CO_2. CO_2 is bad for soap bubbles.

The bubble solution makes all the difference. "I make a concentrated form without water. That'll keep for twenty years. In other words, the soap components are in a glycerine and they keep indefinitely. When you add water to make the solution, you are ready to go. All you need to do is add two parts distilled water to one part concentrate."

Photo courtesy of Eiffel G. Plasterer

Eiffel Plasterer, Mr. Bubbles, as he appeared in one of his "Bubbles Concertos" in 1948. (While the strings of bubbles in his hands resemble Tom Noddy's caterpillars, perhaps Mr. Plasterer would prefer to think of them as Eiffel Towers.)

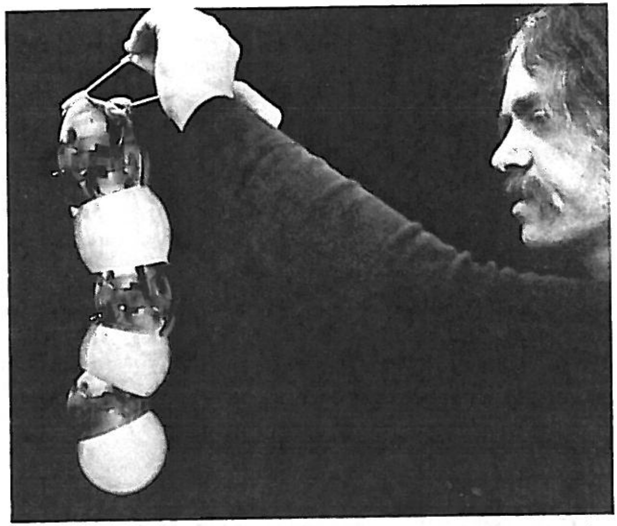
In the beginning Plasterer's 340-day-old bubble was four inches in diameter. Gradually it got smaller. Plasterer says, "It's pretty much like the old automobile tires were years ago. Fifty years ago you pumped up a tire and you checked it every two weeks. Most soap bubbles are like the old type of rubber that went into tires. There is a gradual movement of the air through the bubble wall."

Are all Plasterer's long-lived bubbles capable of lasting 340 days? No. "If the solution is wet, very wet," he says, "a bubble will shrink faster. When I first blow a bubble it is around three hundred times thicker than when it has aged and become what I call a 'dried-out' bubble. Of course they're not really dry—they're liquid all the time. I keep them in jars with a lid on."

Imagine keeping bubbles in jars on your shelf! At the time we talked to him Plasterer had two or three on the shelf that had already lasted over 200 days. "A long lasting bubble drains slowly—it is harder to blow than a fast-draining bubble, like the kind that children blow. The kind of solutions that children buy in the stores don't have any glycerine in them because glycerine weighs bubbles down and holds moisture. The secret of those lovely commercial bubbles is that they are so light. With one of my long lasting bubbles, you can actually see the solution dropping off of it as it drains. You can see it getting thinner as the days pass."

Among the demonstrations that Mr. Plasterer has created over the years are a bubble baroscope, which shows the difference in air pressure at a standing person's head and feet, and a cardioscope which shows the effect of heartbeat on bubbles. Sensitive, educational and scientifically accurate, his demonstrations also delight. "I try to have the element of surprise—like a magic show . . . I have one that uses hydrogen and oxygen that explodes like a gun. They wouldn't let me demonstrate it in New York City."

They outlawed a bubble in New York City. Now we've heard everything. Well, almost everything. Tom Noddy

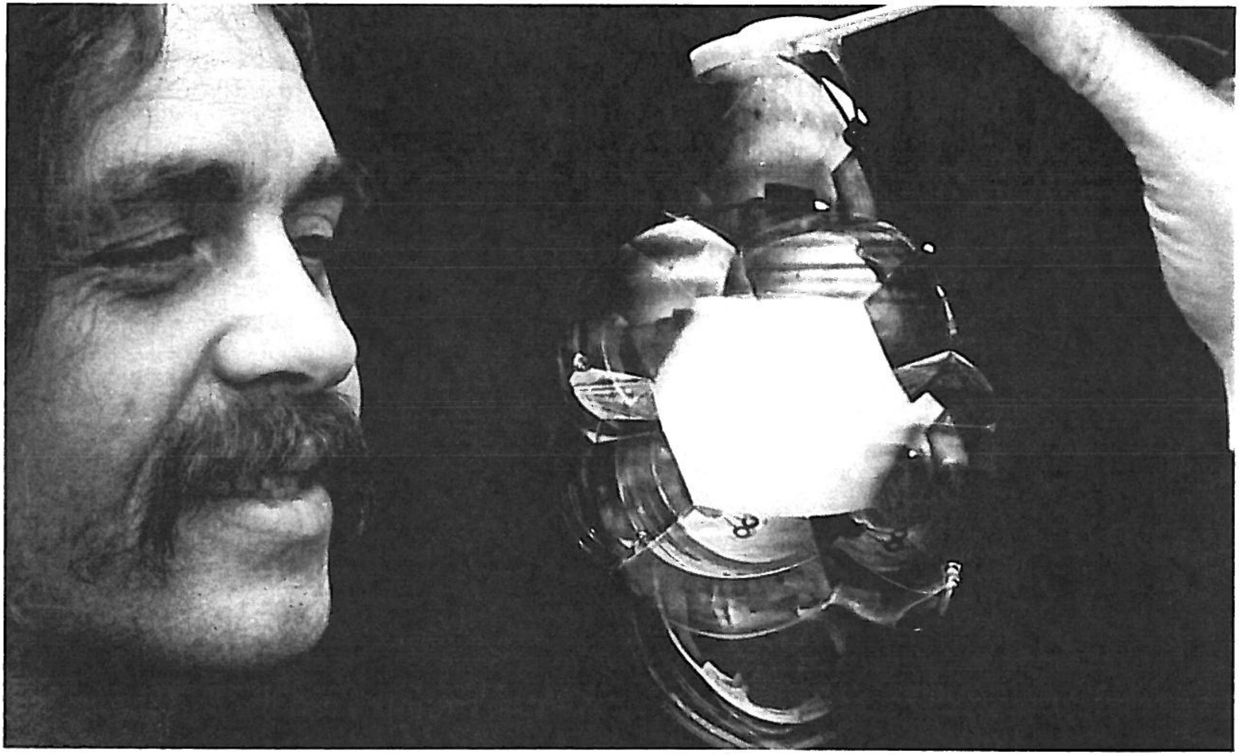


Bubble virtuoso Tom Noddy constructs a bubble caterpillar. Every other bubble is filled with smoke.

is another of our "Bubble People" acquaintances. Tom blows bubbles inside of bubbles. Smoke bubbles. Inside-out bubbles. Caterpillar bubbles. Bubbles outside bubbles. Yin-Yang bubbles. Bubble cubes. Tetrahedron bubbles. Triangular-prism-shaped bubbles. Pentagonal-prism-shaped bubbles. Dodecahedron bubbles. Carousel bubbles which spin inside other bubbles.

Take the bubble cube: bubbles are supposed to be round because a sphere is the minimal surface structure to enclose a particular volume; Tom Noddy's bubble cube is created by blowing a cluster of six bubbles to form, in effect, a mold, and then blowing a bubble in the center of those six to form a conventional six-sided cube!

Eleven years ago, while trying to save money for a trip to Europe, Noddy bought some dime store bubbles as a source of cheap entertainment in the evenings. He spent ten months blowing bubbles while he saved his money. Once he reached Europe, he encountered others who knew about bubbles. One man taught him to blow a



Somehow Tom Noddy has managed to construct a nest of twelve bubbles with their interior surfaces meeting to form an inner bubble, here filled with smoke. This bubble is in the shape of a twelve-sided regular solid, a dodecahedron.

bubble inside another bubble. He gathered bubble knowledge as he hitch-hiked through Europe, elaborating and improving on what he had learned. Now something of a bubble troubador, Noddy travels around the United States, seeking physicists, mathematicians, chemists, biologists, architects, magicians and kids who know something about—or simply love—bubbles.

In Huntington, Indiana, he met Eiffel Plasterer. At the University of Wisconsin in Madison, he was shown the "anti-bubble" by a physicist there. He summarizes the culmination of that bubble person's life work: "Bubbles are a thin layer of liquid separating air from air. Anti-bubbles are a thin layer of air, separating liquid from liquid. Both are spherical."

But clearly, scientists are not the only people fascinated by bubbles. Noddy says, "I have the same rapt attention whether I show my art at a logger's bar on the Olympic Peninsula, at the Santa Cruz County Jail, at a child care center or at a university. The fascination is universal. Bubbles touch the child that each of us carries within."

Soap Bubbles

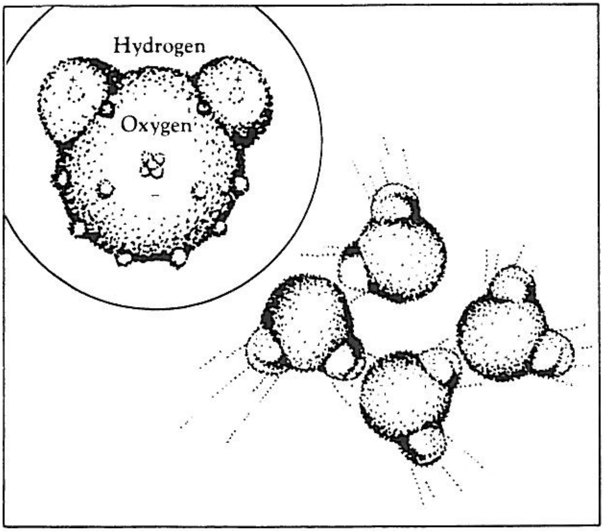
by Ron Hipschmann

Photo by Susan Schwartzenberg

What is so fascinating about bubbles? The precise spherical shape, the incredibly fragile nature of the microscopically thin soap film, the beautiful colors that swirl and shimmer, or most likely, a combination of all these phenomena? Why does a bubble form a sphere at all? Why not a cube, tetrahedron, or other geometrical figure? Let's look at the forces that mold bubbles.

Sticky Water

If you could see molecules of water and how they act, you would notice that each water molecule electrically attracts its neighbors. Each has two hydrogen atoms and one oxygen atom, H_2O. The extraordinary stickiness of water is due to the two hydrogen atoms, which are arranged on one side of the molecule and are attracted to the oxygen atoms of other nearby water molecules in a state known as "hydrogen bonding." (If the molecules of a liquid did not attract one another, then the constant thermal agitation of the molecules would cause the liquid to instantly boil or evaporate.)



Hydrogen atoms have single electrons which tend to spend a lot of their time "inside" the water molecule, toward the oxygen atom, leaving their outsides naked, or positively charged. The oxygen atom has eight electrons, and often a majority of them are around on the side away from the hydrogen atoms, making this face of the atom negatively charged. Since opposite charges attract, it is no surprise that the hydrogen atoms of one water molecule like to point toward the oxygen atoms of other molecules. Of course in the liquid state the molecules have too much energy to become locked into a fixed pattern; nevertheless, the numerous temporary "hydrogen bonds" between molecules make water an extraordinarily sticky fluid.

Within the water, at least a few molecules away from the surface, every molecule is engaged in a tug of war with its neighbors on every side. For every "up" pull there is a "down" pull, and for every "left" pull there is a "right" pull, and so on, so that any given molecule feels no net force at all. At the surface things are different. There is no up pull for every down pull, since of course there is no liquid above the surface; thus the surface molecules tend to be pulled back into the liquid. It takes work to pull a molecule up to the surface. If the surface is stretched—as when you blow up a bubble—it becomes larger in area, and more molecules are dragged from within the liquid to become part of this increased area. This "stretchy skin" effect is called **surface tension**.

Surface tension plays an important role in the way liquids behave. If you fill a glass with water, you will be able to add water above the rim of the glass because of surface tension. You can float a small needle on the surface of a glass of water (the needle must be a little greasy so the water doesn't stick to it); the needle is supported by the surface-tension skin of the water. "Water striders" are insects which can walk on the surface of a pond; they are really standing on the top few layers of water molecules, pushing down the surface of the water in a series of small dimples.

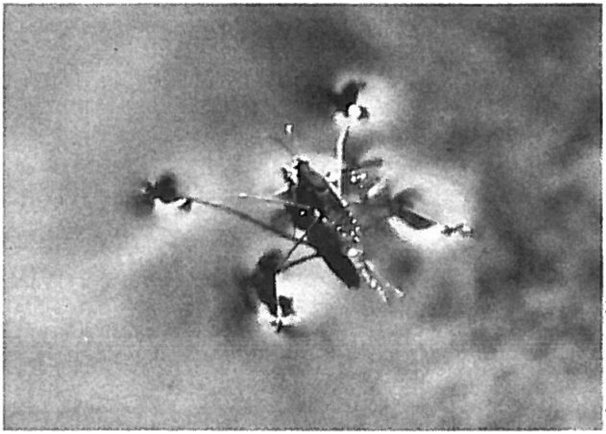
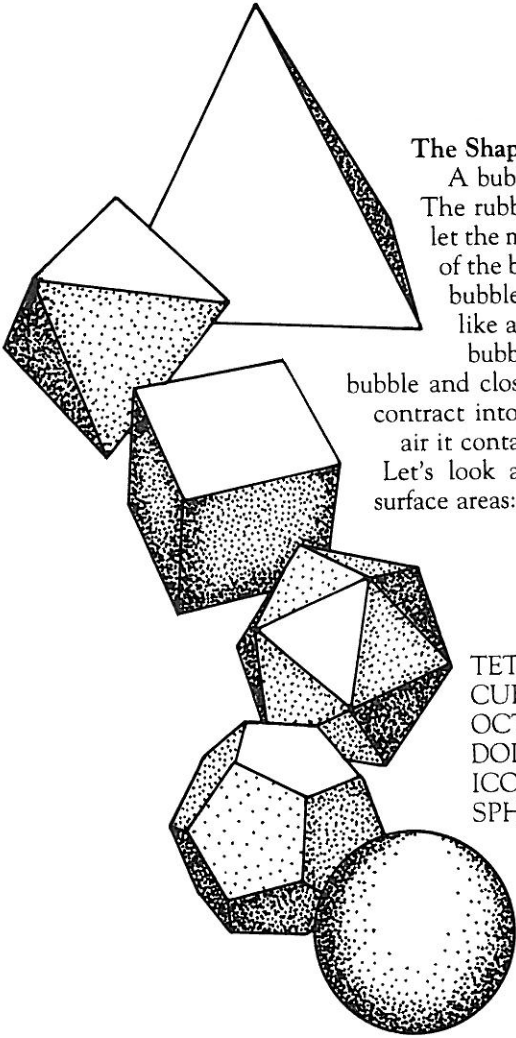


Photo by Joan Venticinque

The water strider is an insect that hunts its prey on the surface of still water; it has widely spaced feet rather like the pads of a lunar lander. The skin-like surface of the water is depressed under the water strider's feet.



The Shape of Bubbles

A bubble, like a balloon, is a very thin skin surrounding a volume of air. The rubber skin of the balloon is elastic and stretches when inflated. If you let the mouthpiece of the balloon go free, the rubber skin squeezes the air out of the balloon and it deflates. The same thing happens if you start blowing a bubble and then stop. The liquid skin of the bubble is stretchy, somewhat like a piece of thin rubber, and like a balloon it pushes the air out of the bubble, leaving a flat circle of soap in the bubble wand. If you blow a bubble and close the opening by flipping the wand over, the bubble skin tries to contract into a shape with the smallest possible surface area for the volume of air it contains. That shape happens to be a sphere.

Let's look at some examples of solids and compare their volumes to their surface areas:

SHAPE	# of sides	VOLUME	SURFACE AREA
TETRAHEDRON-----	4	1 cubic inch	14.7 square inches
CUBE -----------------	6	1 cubic inch	6.00 square inches
OCTAHEDRON------	8	1 cubic inch	5.72 square inches
DODECAHEDRON --	12	1 cubic inch	5.32 square inches
ICOSAHEDRON -----	20	1 cubic inch	5.15 square inches
SPHERE--------------	inf.	1 cubic inch	4.84 square inches

Notice that the sphere has the least surface area of any of the geometric solids listed.

Soap

Have you ever tried to blow a bubble with pure water? It won't work. There is a common misconception that water does not have the necessary surface tension to maintain a bubble and that soap increases it, but in fact soap *decreases* the pull of surface tension—typically to about a third that of plain water. The surface tension in plain water is just too strong for bubbles to last for any length of time. One other problem with pure water bubbles is evaporation: the surface quickly becomes thin, causing them to pop.

Soap molecules are composed of long chains of carbon and hydrogen atoms. At one end of the chain is a configuration of atoms which likes to be in water (hydrophilic). The other end shuns water (hydrophobic) but attaches easily to grease. In washing, the "greasy" end of the soap molecule attaches itself to the grease on your hand, letting water seep in underneath. The particle of grease is pried loose and surrounded by soap molecules, to be carried off by a flood of water.

In a soap-and-water solution the hydrophobic (greasy) ends of the soap molecule do not want to be in the liquid at all. Those that find their way to the surface squeeze their way between the surface water molecules, pushing their hydrophobic ends out of the water, separating the water molecules from each other. Since the surface tension forces become less as the distance between water molecules increases, the intervening soap molecules decrease the surface tension. If that over-filled cup of water mentioned earlier were lightly touched with a slightly soapy finger, the pile of water would immediately spill over the edge of the cup; the surface tension "skin" is no longer able to support the weight of the water.

Because the greasy end of the soap molecule sticks out from the surface of the bubble, the soap film is somewhat protected from evaporation (grease doesn't evaporate) which prolongs the life of the bubble substantially. A closed container saturated with water vapor (as in the Exploratorium "Soap Film" exhibit) also slows evaporation and allows soap films to last even longer.

Bubble Colors

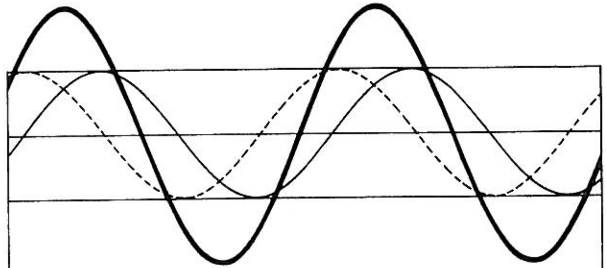
Color, one of the most beautiful aspects of bubbles, also provides us with an extremely accurate tool for measuring the thickness of the soap film.

Light waves, like ocean waves, have peaks and valleys (crests and troughs). Red light has the longest wavelength and violet the shortest.

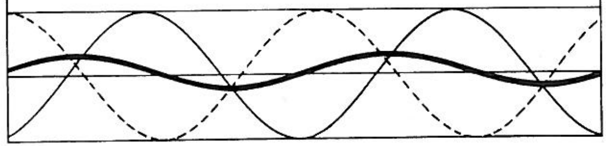
All waves, including light, have a curious property: if two waves combine, the waves can meet each other crest-to-crest, adding up and reinforcing the effect of each other, or they can meet crest-to-trough, cancelling each other out so that they have no effect. When they meet crest-to-trough, for every "up" vibration in one wave, there is a corresponding "down" vibration in the other wave. This combination of equal ups and downs causes complete cancellation, or **interference**. Interference is responsible for the pearly luster of an abalone shell, the beautiful colors in some bird feathers and insect wings, and the flowing patches of color in an oil slick on the street after a rain shower—and for the color of bubbles.

White light is made up of all colors, all wavelengths. If one of these colors is subtracted from white light (by interference, for instance) we see the complementary color. For example, if blue light is subtracted from white light, we see yellow. The skin of a bubble glistens with the complementary colors produced by interference. If we were to look at a highly magnified portion of a soap bubble membrane, we would notice that light reflects off both the front (outside) and rear (inside) surfaces of the bubble, but the ray of light that reflects off the inside surface travels a longer distance than the ray which reflects from the outside surface. When the rays recombine they can get "out of step" with each other and interfere. Given a certain thickness of the bubble wall, a certain wavelength will be cancelled and its complementary color will be seen. Long wavelengths (red) need a thicker bubble wall to get out of step than short wavelengths (violet). When red is cancelled, it leaves a blue-green reflection. As the bubble thins, yellow is cancelled out, leaving blue; then green is cancelled, leaving magenta; and finally blue is cancelled, leaving yellow. Eventually the bubble becomes so thin that cancellation occurs for all wavelengths and the bubble appears black against a black background.

This surprising **complete** cancellation is due to the different way light reflects from the two surfaces. When light reflects from the outside surface of the bubble (an air-to-water surface) the direction of vibration of the wave is reversed—all "up" vibrations are turned into "down" vibrations and vice versa. (The same thing happens if you send a vibration along a rope tied to a wall; the reflected pulse is upside-down after reflection from the wall.) When light reflects from the inside surface of the

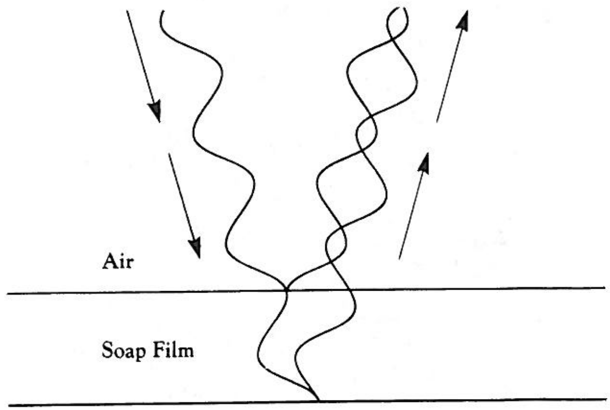


Constructive Interference

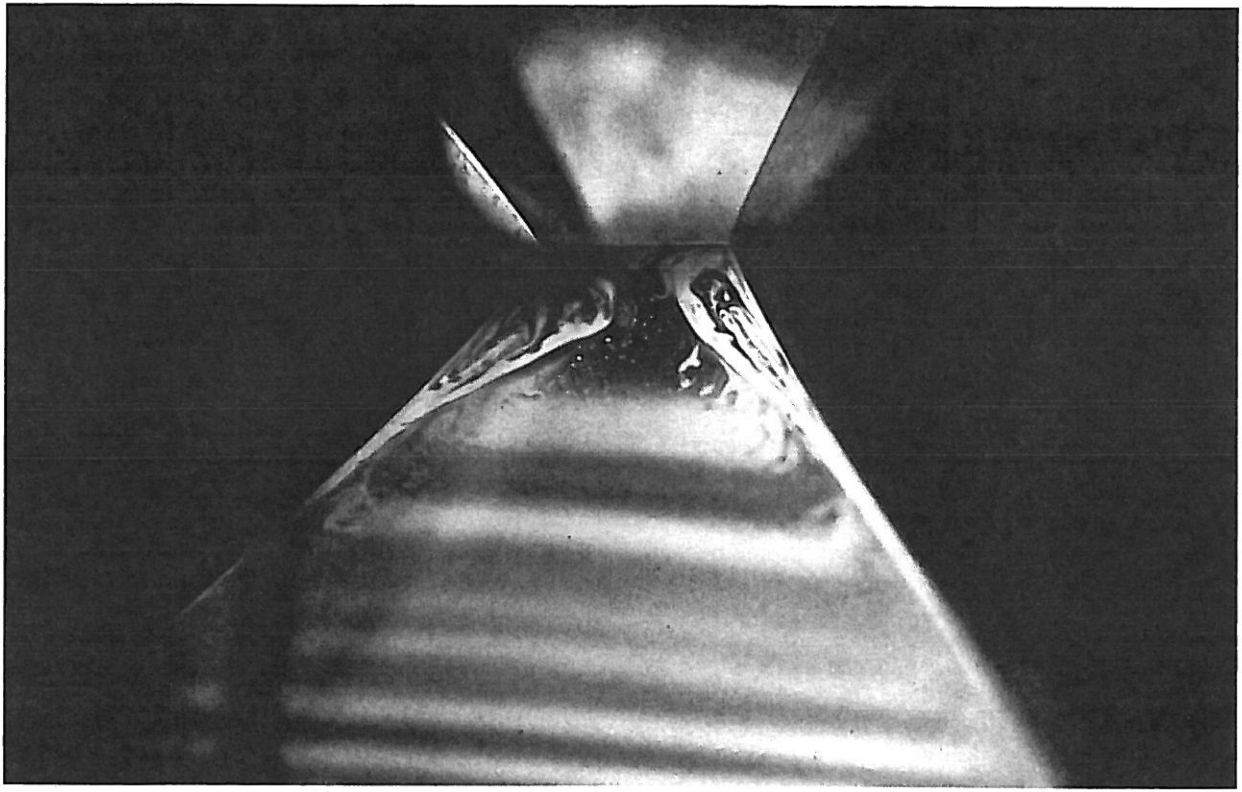


Destructive Interference

If the crests of two or more waves are in step, or almost in step, they can combine into a larger or more intense effect. If the crest of one wave meets the valley of another, they cancel each other out. When two light waves cancel each other, the result is darkness.



White light is separated into colors as it reflects from the two surfaces of a thin film. Where the two reflections interfere constructively, they produce a band of color. Where they cancel each other, that color is subtracted from the spectrum.



The alternating bands of light and dark on this soap film are actually bands of color, produced by the reflection and interference of light waves. The colors depend upon the film's thickness. The film shown here is thinnest at the top, becoming thicker toward the bottom. As the film's thickness changes, the colors also change, forming regular bands.

bubble (a water-to-air surface) the direction of the vibration is **not** changed. If the skin of the bubble is very thin, much shorter than the wavelength of visible light, then the two reflected rays of light will always meet crest-to-trough and destructively interfere. There will be *no* visible reflection, and the bubble looks black. When you see this happening at the top of a soap bubble you know the bubble is only about one millionth of an inch thick and will soon pop.

If you let a bubble hang from a bubble wand for awhile, the interference colors begin forming horizontal stripes—because the bubble film is thicker at the bottom than at the top, forming a wedge shape. As the bubble drains, the wedge of bubble solution gets thinner and thinner. The black film which then appears at the top of the bubble is a harbinger of an upcoming disaster. The bubble is now so thin only a few moments remain until . . .POP!

Boiling and Bubble Chambers

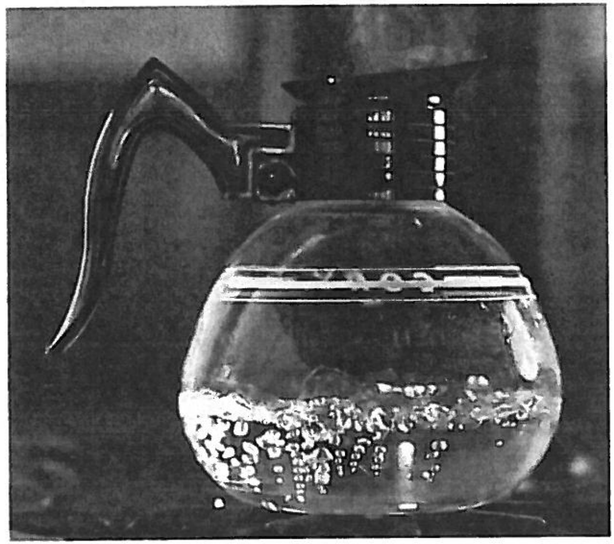
by Frank Oppenheimer

Almost everyone has rushed over to a stove to remove a pot that has suddenly started to boil over, often causing quite a mess.

As a pot of water heats up, water molecules leave the surface more and more rapidly, evaporating to make **water vapor**. In a closed and sealed container the water vapor builds up to produce pressure. The hotter the water, the greater the pressure of the vapor. Equilibrium eventually occurs between the number of water molecules leaving the surface and the number of water vapor molecules that hit the surface and stick to the water.

In an open container water evaporates faster and faster from the surface as the temperature is raised. But the pressure of the air prevents any bubbles from forming below the surface of the water until the temperature reaches the boiling point. At this temperature the pressure of the water vapor is equal to the pressure of the atmosphere; below this temperature the atmosphere presses harder than the vapor throughout the liquid and squeezes any bubbles that might start to form down to nothing. But once the vapor pressure is equal to or slightly greater than the atmospheric pressure, bubbles can form throughout the pot of water. Putting more heat into the pot, once the water has reached the boiling temperature, does not raise the temperature of the water, but it makes the bubbles form and grow larger more rapidly. They then take up so much room that they push the contents of the pot out onto the stove.

The boiling temperature depends on the air pressure. If the air pressure is reduced, as it is, for example, high up in the mountains, the water does not have to be as hot as at



Heat applied at the bottom of the kettle drives the formation of bubbles of water vapor. The bubbles grow larger as they rise—not so much because the hydrostatic pressure of the liquid decreases near the surface (it does, though only by an insignificant amount in a shallow container), but because each newly-formed bubble provides an inner surface for more water molecules to enter the vaporous state.

sea level to create a vapor pressure great enough to allow the vapor bubbles to form and expand against the atmospheric pressure. At 10,000 ft. elevation the air pressure is a little over two-thirds the sea level pressure, and water boils at about 195° Farenheit rather than 212° at sea level. It might take eight or nine minutes to boil a "4 minute egg" at that elevation.

But whether at sea level or at high altitude, all the water in a pot does not start to boil at once. There are two reasons why the process takes some time. First, one has to keep adding heat to keep the water boiling, and second, it takes some time for enough molecules of water vapor to come together to grow a large enough bubble to see, and even longer for the bubble to get big enough to rise to the surface.

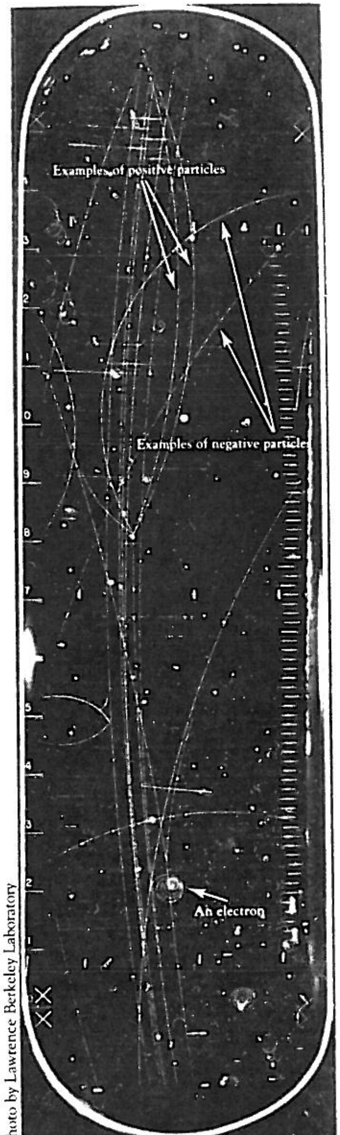


Photo by Lawrence Berkeley Laboratory

A view of the bubble tracks through the window of the six-foot hydrogen bubble chamber that was developed by Louis Alvarez at the Lawrence Berkeley Laboratory. A magnetic field acts on the fast-moving, electrically charged particles as they pass through the cold liquid hydrogen. The magnetic field causes the incoming negative particles to curve to the right. The positive particles created by a collision near the center of the chamber curve to the left. An electron knocked off one of the hydrogen atoms by an incoming particle circles in a tight spiral near the lower edge of the chamber.

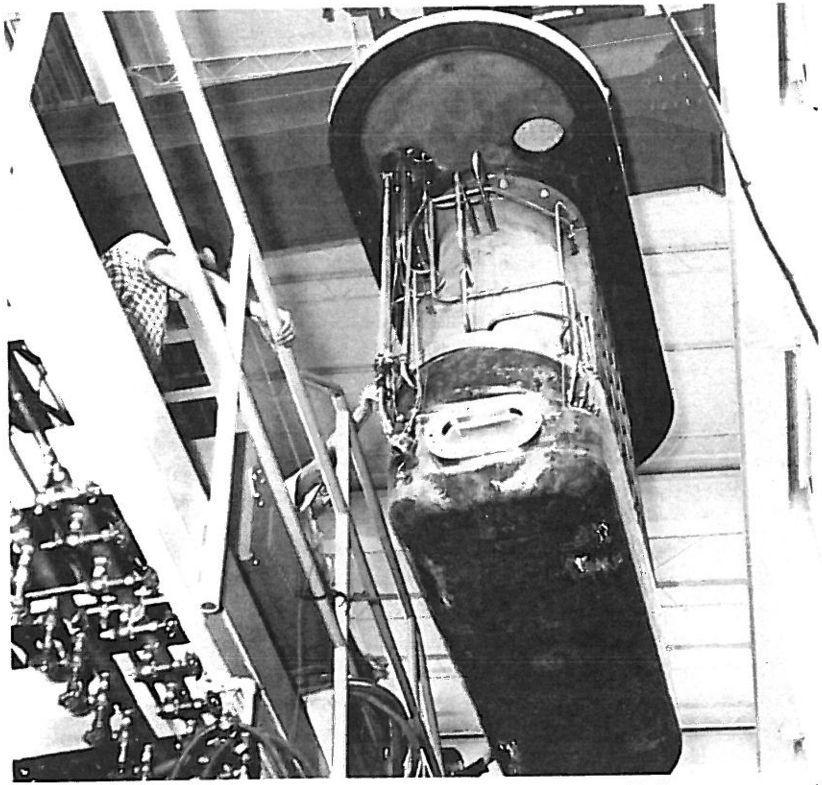


Photo by Lawrence Berkeley Laboratory

Luis Alvarez's six-foot bubble chamber, a bathtub normally filled with liquid hydrogen, is temporarily removed from its position near the Lawrence Berkeley Laboratory's Bevatron accelerator.

Bubble Chambers

A bubble chamber is a boiling chamber that enables us to see the pathways of invisible atomic particles.

Donald Glaser received a Nobel Prize in 1955 for inventing the bubble chamber because it contributed so very much to our ability to discover the nature of the particles and forces that exist within and hold together the tiny central nuclei of atoms. Even the hydrogen nucleus, just one proton, has a complex internal structure. The bubble chamber made it possible to study in great detail the effects produced by the very high energy accelerators which were developed around 1960.

After Glaser's invention of the bubble chamber principle, Wilson Powell, Luis Alvarez (also a Nobel prize-winner) and others developed specialized, practical versions of it. The six-foot chamber developed by Alvarez operated at very low temperatures. It was actually a bathtub of liquid hydrogen—a bathtub filled with protons.

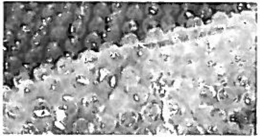
A high energy proton, moving with almost the speed of light, makes a visible path as it traverses the entire length of Alvarez's chamber. It occasionally encounters other protons along this path and uses its energy to create additional charged particles that also make visible paths in the bubble chamber.

The liquid in a bubble chamber, whether liquid hydrogen or some other liquid, is kept at a pressure that is great enough to keep it from boiling, but at a temperature that is high enough to cause it to boil if the pressure is slightly reduced. There are no bubbles in the liquid to start with, but when the pressure is suddenly reduced, boiling can take place. If the liquid were allowed to stand at this reduced pressure for any length of time, boiling would take place throughout the liquid. But at the instant pressure is reduced, one can not see any bubbles. It takes a little time for bubbles to form.

If a high-speed proton from an accelerator goes through the liquid during this first instant, it can make a path by leaving a visible trail of bubbles. The high speed proton misses most of the tiny hydrogen nuclei in the bathtub but collides with the much larger hydrogen atoms, knocking off their electrons and producing a trail of local heating along its path. The local heating then causes the liquid to boil in a narrow line along the path of the high speed proton or any other electrically charged particle. At this very instant, a bright light flashes and photographs are taken of all the bubble trails in the chamber. These trails or tracks are later analyzed as to their energy, momentum, speed, mass, and electric charge. From these measurements, the physics of each nuclear event is disentangled.

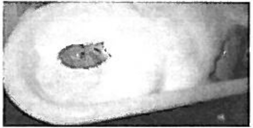
The invention and development of the bubble chamber, together with the development of high-energy accelerators, of computers, and of devices for analyzing the tracks in the photographs, occurred during the decade of the 1960's. These devices unearthed a maze of new and puzzling phenomena in which physicists became thoroughly lost. Fortunately a few illuminating pathways through this maze were found during the 1970's.

Bubble Miscellany



Bubble Pak: whoever invented it didn't realize it would become an instrument of mindless pleasure—pop, snappity pop—as well as an effective packaging aid.

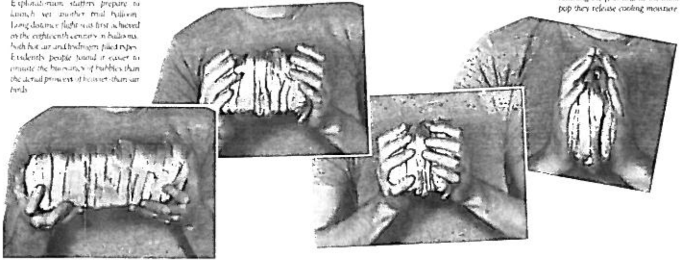
A lightbulb is a bubble of inert gas which keeps oxygen away from the glowing filament, preventing it from burning up quickly.



Exploratorium staffers prepare to launch yet another trial balloon. Long distance flight was first achieved in the eighteenth century in balloons, both hot air and hydrogen filled types. Evidently people found it easier to imitate the buoyancy of bubbles than the actual prowess of heavier-than-air birds.

The air bubbling into an aquarium partially dissolves into the water and becomes available for fish to breathe.

Firemen use foam to extinguish some fires. The foam keeps oxygen from reaching the fire, and as the bubbles pop they release cooling moisture.



Why Whales Don't Get the Bends

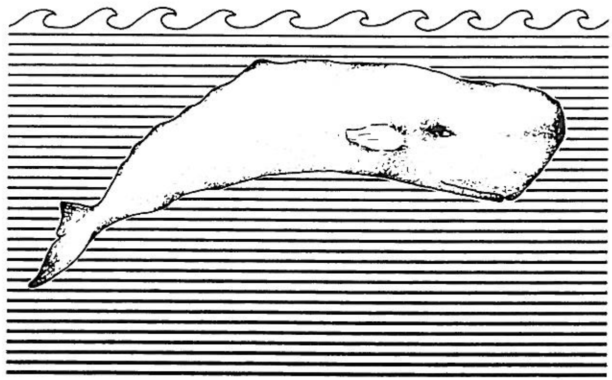
by Charles Carlson

One of the things a scuba diver worries about most as he or she begins to resurface after a dive is the possibility of developing that painful and dangerous circulatory condition known as "the bends." The bends, so named because its victims double up in agony, is caused by tiny bubbles in the blood which tend to concentrate at the joints; it can lead to death if enough bubbles are trapped in the capillaries, preventing blood flow through the tissues, or if bubbles interfere with the functioning of the heart.

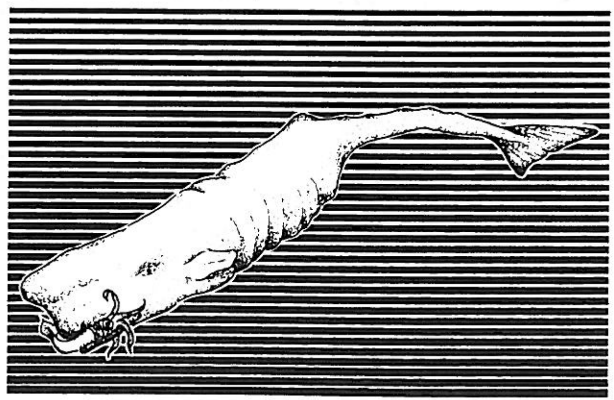
The first scientific observer of this phenomenon was Robert Boyle, who around the year 1670 subjected a snake to rapid changes in atmospheric pressure. At low pressure, he saw a bubble form inside the snake's eye.

Since Boyle's early observations much has been learned about the relationship between gases and liquids; the amount of gas dissolved in any liquid depends primarily upon pressure. The amount of pressure directly affects the concentration of gas molecules: at high pressures many gas molecules can be squeezed into a small volume, while at low pressures the same number of molecules take up a large volume. When Boyle rapidly lowered the pressure around his snake, he caused gas in the snake's bodily fluids to come out of solution and form a bubble in the snake's eye.

A great deal of time and energy has been devoted to understanding the bends and devising ways to avoid the problem. Yet many species of air-breathing animals frequently dive to great depths and stay down for long periods without experiencing any ill effects. Of the natural divers, whales demonstrate the most amazing abilities.



The familiar animal above is a sperm whale as it looks near the surface of the ocean, where pressures are moderate. These are the only circumstances under which humans have seen free-swimming whales. At a depth of several thousand feet, a sperm whale's body might look like the artist's conjecture below. Tremendous pressures collapse much of the whale's body, but the sperm whale is quite at home under these bizarre conditions.



Why don't whales get the bends?

Sperm whales feed on deep-dwelling giant squids. Their hunting ground is from two to five thousand feet below the surface of the sea. The weight of the seawater above exerts an enormous pressure, over a ton per square inch. This is 152 times greater than the weight of the atmosphere at sea level. Like most animals, some ninety percent of a whale is water. Since water, being a liquid, is incompressible, most of the whale is not crushed. But any remaining gas spaces within the whale's body *are* crushed. The whale's lungs are squeezed to a smaller and smaller volume as the leviathan plunges deeper and deeper, and as the lungs collapse, the soft internal organs such as the stomach, liver, and intestines may get pushed towards the chest cavity, actually changing the whale's shape.

Any gas spaces remaining inside the whale exert a pressure outward which is exactly equal to the inward pressure exerted by the water, though their volume is greatly decreased. Thus it might seem that during the whale's headlong rush to the surface, the sudden release of pressure would result in an increase in gas volume and a tremendous amount of foaming and bubbling in the whale's blood and body tissue, making for a horrible case of the bends.

Until about fifty years ago, scientists couldn't understand how diving animals avoided the bends. Odd physiological functions and anatomical structures were postulated for removing the dissolved gases from the blood; for example, a special bacteria-like cell found in the blood of some whales was supposed to gobble up nitrogen gas. It later became obvious that these cells were only bacterial contaminates. In addition, it has been postulated that whales' blubber absorbs and safely stores dissolved nitrogen gas from their blood, since nitrogen is highly soluble in fat. But even if true, this process cannot be very important.

The real secret is simple. Unlike us humans, who automatically take a big breath before ducking our heads under water, a whale or other natural diver usually begins its dive by *exhaling*. This reduces buoyancy and greatly decreases the amount of gas in its lungs. A whale has an enormous volume of blood in which oxygen is dissolved, plus tremendous stores of dissolved oxygen in its muscles. During a dive, blood-flow to most of its body is greatly reduced by a special system of valves and by the collapse of the soft organs. A whale's brain is large, but relatively small when compared to the rest of its body; it continues to function by using oxygen stored in the blood. A sperm whale can stay underwater for as much as an hour and fifteen minutes and not get the bends upon resurfacing because it doesn't breathe underwater!

Since any gas in contact with a liquid can reach equilibrium, depending on pressure, humans living on land under relatively constant atmospheric pressure remain safely in equilibrium. The body at sea level is subject to about fifteen pounds of pressure per square inch, or one atmosphere. A person would have to climb a mountain 15,000 feet above sea level to lower air pressure to one-half atmosphere, or descend 15,000 feet into a mine to increase it to two atmospheres.

Getting the bends became a problem to humans only when they began to explore beneath the surface of the

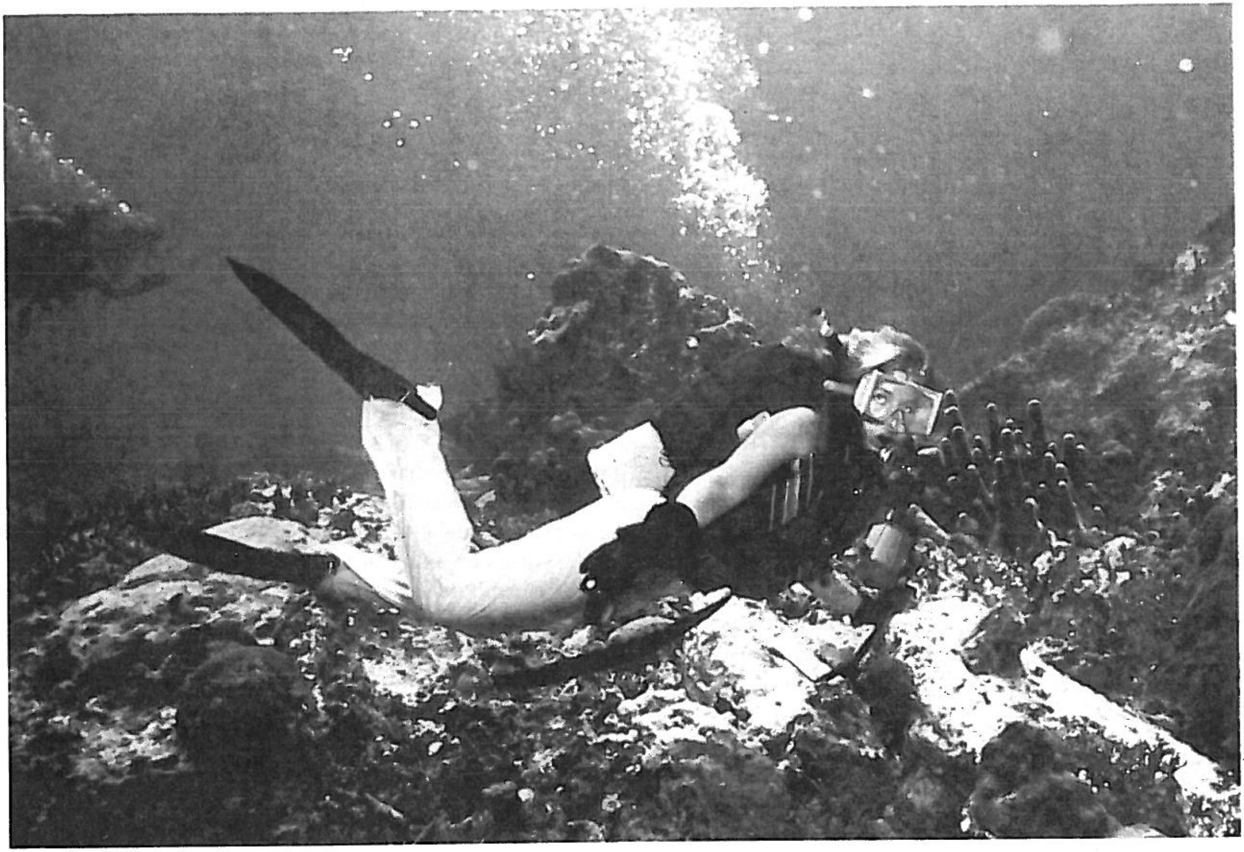


Photo by Bud Davis

ocean. Water at sea level is roughly a thousand times denser than air, and pressure increases one atmosphere (14.7 pounds per square inch) every thirty feet below the surface. When a scuba diver is below the surface, he is breathing air which is of equal *pressure* to the surrounding water. So, in fact, the diver breathes several times the *quantity* of air molecules that he or she would at sea level. This pressurized gas dissolves into the diver's blood and tissues until it reaches a new equilibrium. The deeper the diver goes, the greater the amount of gas that dissolves in the blood. Upon returning to the surface, the diver must allow time for the gases to dissolve out of his or her blood and tissues in order to prevent the bends. A scuba diver can safely stay at a depth of 60 feet (a pressure of 44 pounds per square inch) for only one hour before he or she has to worry about decompression. The bends are a problem for any humans who venture underwater on extended deep dives, or who work in pressurized chambers. In fact, they were first experienced by workers building underwater bridge foundations and tunnels.

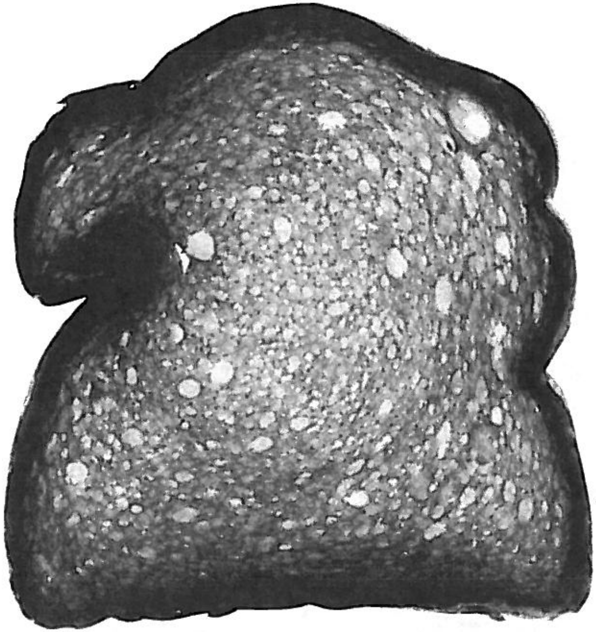
Bread and Bubbles

by Esther Kutnick

In Mexico they call yeast doughs *almas*, or souls, because of their sensitive yet powerful nature. Yeast is the prima donna of baking catalysts—volatile and temperamental, but capable of delivering, with seemingly boundless energy, the gas bubbles that are responsible for the wonderfully light and fluffy breads that are a part of our daily diet.

Saccharomyces cerevisiae, the type of yeast most often used by bakers and brewers, is a single-celled fungus with about 3,200 billion cells to the pound. The baking process involves a complex interplay of physical, chemical and biological reactions, and the most fundamental of these is **fermentation**. Fermentation is the enzymatic conversion of carbohydrates into alcohol and carbon dioxide, a process which occurs under anaerobic conditions (having no free oxygen) within the yeast cell. Fermenting action was used to put bubbles in bread as early as 5,000 years ago, but only in the last two centuries have we begun to understand the chemical reactions involved.

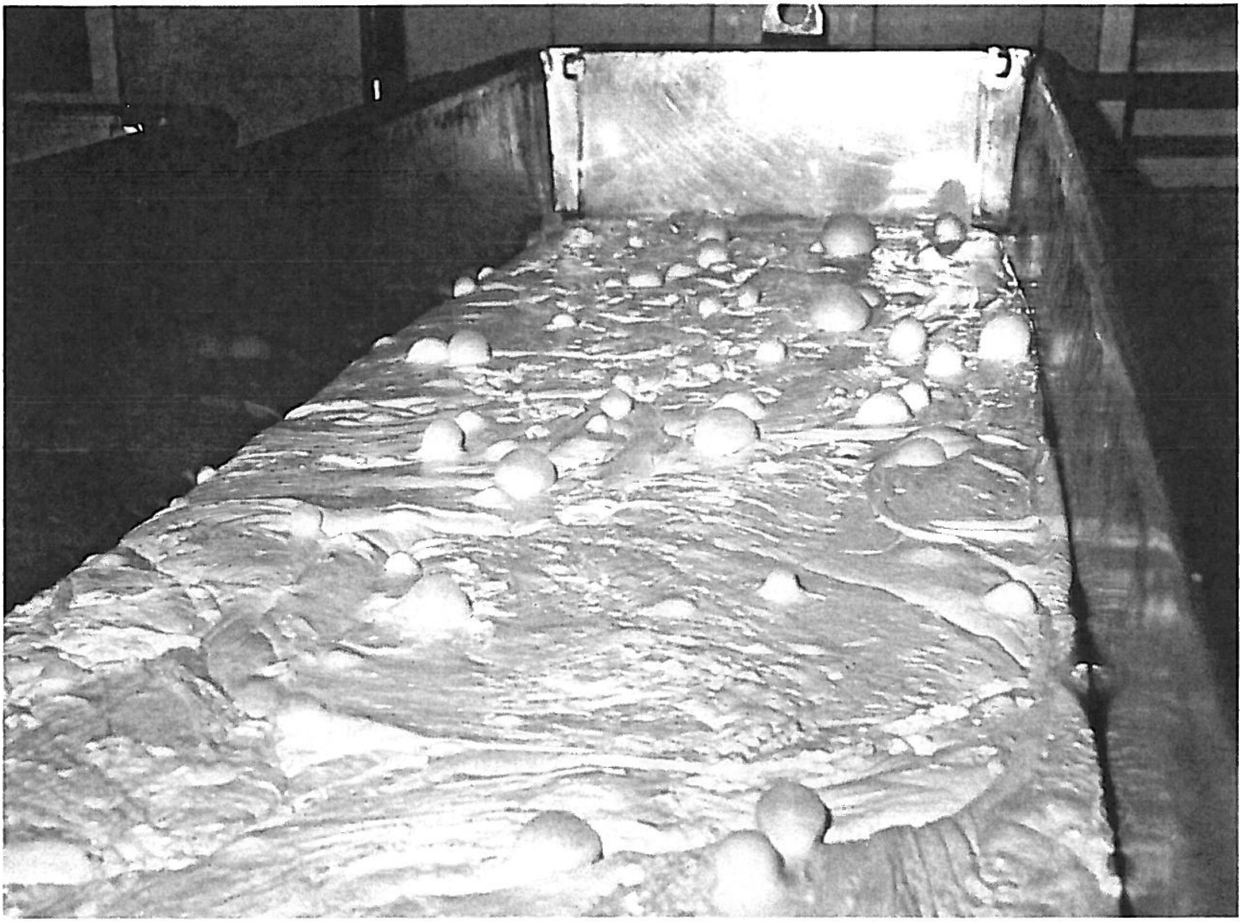
If you give a batch of yeast something to eat, sugar or starches which the yeast can convert to sugar, it will gobble up the food and excrete alcohol and carbon dioxide. Yeast becomes active at about fifty degrees Farenheit; the yeast cells begin to die around 120° and are useless for baking after 143°. Varying the temperature at different stages of the breadmaking process can accelerate or depress the rate of fermentation (a variable which can be used to compensate for mistakes along the line). In general, yeast is most active during two stages of breadmaking: in its "first life" the yeast is combined with the sugar or starch and allowed to grow freely, initiating the bubbling process. When the rest of the ingredients are added, the yeast growth is



inhibited, chemically and mechanically. The last stage before baking is known as the "second life" of the yeast and takes place in a very warm and usually humid place where the yeast is again encouraged to make bubbles.

Both carbon dioxide and alcohol leave the dough during the baking process, but meanwhile, the heat of the oven has solidified the dough into the shape the gas bubbles have helped to form. The mixture of proteins in flour, when kneaded, becomes a cohesive network of elastic strands called **gluten**. Yeast-produced carbon dioxide becomes temporarily trapped inside the gluten structure, finding a home within tiny air pockets in the dough or creating its own miniscule cavities.

The heat of the oven builds up the pressure of the still-developing gas, expanding and stretching the elastic

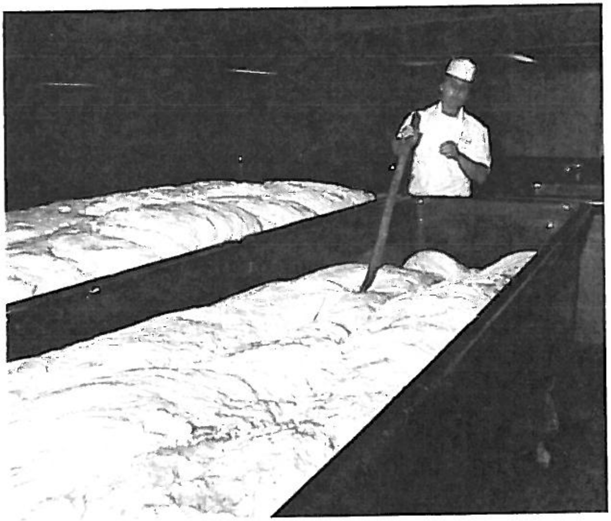


The yeast is very energetic in the "first life" stage, quickly forming pronounced bubbles that expand the sponge mixture.

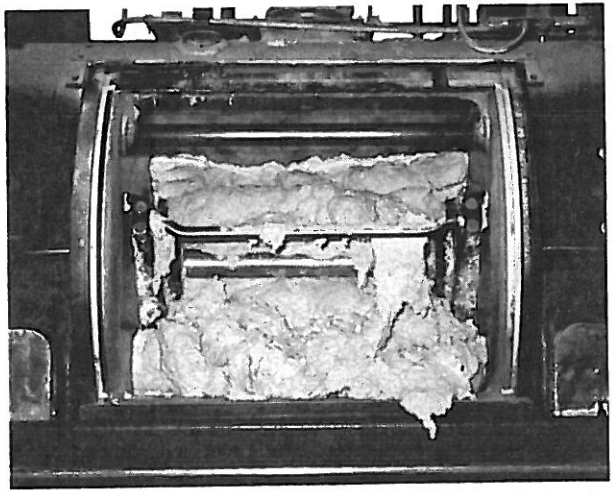
strands of gluten to increase the volume of the dough. *Too* much expansion can cause the gluten to lose its strength and elasticity, and the weakened structure will collapse.

Kilpatrick's Bakery in San Francisco controls the texture of their bread—the size of the bubbles—in two ways. They start with what is called a "sponge," which is a mixture of yeast, flour, yeast food (monocalcium phosphate, calcium sulfate, corn starch, salt, ammonium sulfate and potassium bromate) and a mold inhibitor. This mixture is allowed to rise in huge vats for about five hours. The bubbles are beaten out of it three or four times during this first life of yeast growth.

Just before the bread goes into the "proofing room" for the final rising, it passes through three sets of "degassing rollers" that mechanically squeeze the bubbles out of the dough. In this warm (100°) and humid room the yeast has its second life, stretching the dough very close to its final shape. Near the end of our tour of the Kilpatrick's Bakery, master baker Butch Edison picked a still-warm loaf of caramel-colored wheat bread off the rack and pulled it apart, carefully examining the texture of the slices. "See," he smiled, "all it is is air. Balloon loaf, we call it. People love it—it's our best-selling loaf."



Kilpatrick's bakers use a long rod to beat down the sponge, releasing the trapped CO_2.



Large rollers knead the dough in order to mix the sponge with the other ingredients and elasticize the gluten.

In the making of sourdough bread, the first life of the yeast has been carefully watched over for nearly 100 years at San Francisco's Parisian Bakery. Parisian's bakers believe that it is the acidity of the air in San Francisco that makes the unique and very sour culture, but just how this works is not understood. When combined with the rest of the ingredients in a loaf of sourdough bread, the still-active yeast keeps eating the sugar and starches in the dough, leaving quite a bit of gluten behind, which gives sourdough bread its characteristic rubbery texture and distinguishes it from the lighter and fluffier texture of sweet French bread. When asked what ingredients they used to control the fermentation process, Parisian's Production Manager Barry Gatts said, "All we use is time, temperature and love." ⊙

Bubbles in Solids: Two Special Cases

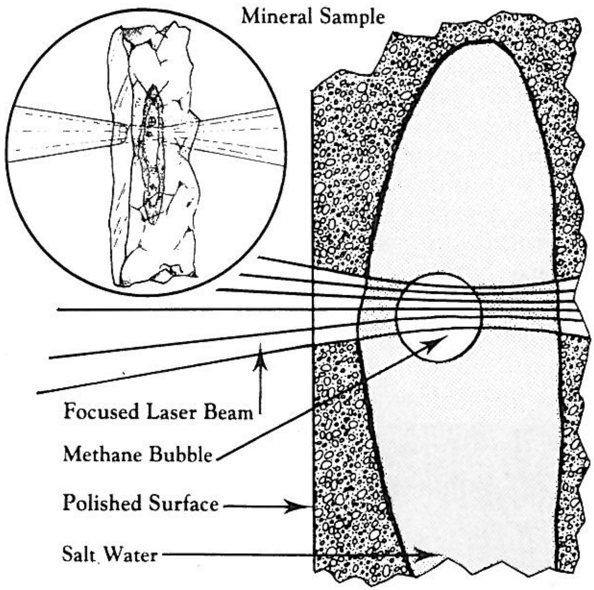
by Ilan Chabay

As molten rock cools it can trap small pockets of gas. These bubbles of gas, called inclusions, are capsules of history; each contains a sample of gas, and sometimes of liquid as well, present in the environment at the time the rock solidified—perhaps tens of millions of years ago. (In some cases the gas or liquid bubbles entered the rock at a later time through cracks which subsequently sealed.)

Occasionally the bubbles are encapsulated in a mineral which is itself virtually impenetrable by gas or liquid, so there has been no contamination by the outside environment since the mineral solidified. Because the bubbles are generally only a millimeter or two in diameter, investigating their contents isn't easy. One way is to crush the rock and examine the gas which is released. Another is to use light from a laser to "interrogate" the bubble.

The first technique involves passing the gas through instruments which separate the various molecules according to their chemical characteristics, identify the different kinds, and measure their proportions. This is a sensitive method, but it does have the disadvantage that the rock is destroyed in the process.

The laser technique is based on the fact that molecules of different gases scatter light in different ways; this technique can be used only if the rock in which the gas bubbles are trapped is nearly transparent. First the mineral is polished to create a transparent face, a window, directly above the bubble. The laser beam is directed into the bubble, where the light interacts with gas molecules. By examining the spectrum of the light bounced back out of the bubble, we can learn details of the different kinds of molecules, their relative quantities, and even the pressure of the trapped gas, all without destroying the rock or the bubbles in it.



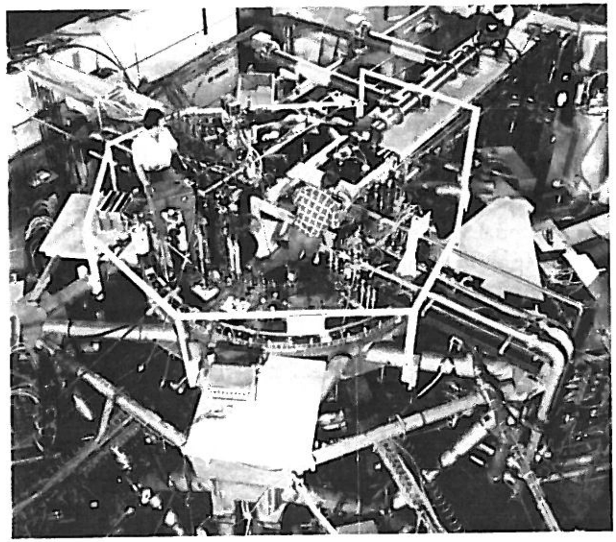
For example, salt water was encapsulated with a gas bubble inside fluorite mineral from Illinois. The laser light scattered from the bubble identified the gas as methane (natural gas, such as is used in homes for cooking) and indicated that its pressure was 27 times that of the atmosphere. In another case, a bubble of carbon dioxide gas was found in an inclusion in Brazilian quartz. The bubble coexisted with liquid carbon dioxide and water. Using a microscope, a laser and sensitive detection, each part of a complex inclusion can be examined.

Man-Made Bubbles

Bubbles can be trapped in solids like rocks and glass as the molten stuff solidifies, but they can also be injected into a *cold* solid. Recently research scientists have been implanting positively-charged helium atoms (ions) in metal, with fascinating results. Much of the current work has concentrated on bubbles in thin foils of aluminum. The aluminum is bombarded with high-energy helium ions, which penetrate the surface of the metal and lose their energy, eventually becoming trapped. The individual ions all migrate to a limited number of places, where they aggregate to form bubbles. Electron-microscope photographs have been used to determine that most of these bubbles are between one and fifty millionths of a millimeter in diameter. These are smooth-walled, spherical bubbles, but occasionally larger bubbles form which are not spherical, having flat, faceted walls instead.

The shape of a bubble results from a balance between internal pressure and outer resistance, in this case the framework of metal atoms. Large bubbles aren't spherical because the force between the metal atoms at the surface of the bubble—the surface tension of the metal—predominates.

The smaller, spherical bubbles have truly incredible internal pressures—as high as 10,000 times that of Earth's atmosphere at sea level! Under these conditions the density of the gaseous helium is nearly three times the density of liquid helium (which only forms at extremely low temperatures). It's remarkable that a gas can be so much more dense than the liquid form of the same material, but this is true of all materials with gaseous and liquid states, and depends on the temperature at which the pressure is applied. Above some temperature, which depends upon the particular material, the molecules are moving so rapidly that they cannot stick together long enough to form connections between themselves and thus cannot form a liquid regardless of pressure.



Barely discernible within this maze of pipes, wires, and struts is the circular shape of the Princeton Large Torus, an experimental fusion reactor. Fusion of hydrogen nuclei to form helium nuclei, releasing energy, takes place inside a steel vacuum vessel shaped like a donut, or torus. Helium bubbles forming in the walls of such a vessel could cause leaks that would destroy the reactor.

The study of bubbles in metals is fascinating in its own right, but it has practical applications too. Schemes for fusion power depend upon fusing hydrogen nuclei to produce helium inside vacuum chambers. But some of these many helium ions can become trapped in the metal walls of the containment vessels, forming small bubbles which might eventually lead to the structural failure of the metal. Therefore the success of fusion power may depend partly on learning more about helium bubbles in metal.

Fizz Ed.
by David Barker

"Tiny bubbles, in the wine,
Make me feel happy, make me feel fine.
Tiny bubbles, make me glad all over . . . ."*

Don Ho's sentiment is widely shared; people have always had a fascination with effervescent beverages. The exotic bubbles in a glass of champagne or the foamy head on a beer make these drinks special, and even kids aren't immune to the titillation of fizzy sodas.

So how are drinks made bubbly—and therefore special? *Carbonation* is the answer—the process of dissolving carbon dioxide gas in a liquid. Two conditions regulate the amount of carbon dioxide which can be dissolved in a liquid: temperature and pressure. At fifteen degrees Celsius and one atmosphere of pressure, a single volume of carbon dioxide gas (a cubic centimeter, for example) is soluble in a similar volume of water. Doubling the pressure doubles the amount of gas that can be dissolved, while heating, on the other hand, causes carbon dioxide to come out of solution. Another factor contributing importantly to the flavor of carbonated drinks is the propensity for some of the carbon dioxide (CO_2) to combine chemically with the water (H_2O) to form weak, unstable carbonic acid (H_2CO_3).

The relationship between temperature and pressure explains why carbonated beverages must be stored in pressurized containers and served cold, or at least cool. There's a story about the inauguration of a tunnel built under the Thames River in London. Cases of champagne were broken out in the tunnel shaft for local politicians and dignitaries, but the drinkers found the champagne to be flat and lifeless. Apparently it didn't stop them from imbibing anyway, and when they ascended from the cool, pressurized tunnel to the street above, the dissolved CO_2 began to come out of solution, and "the wine popped in their stomachs, distended their vests, and all but frothed from their ears. One dignitary had to be rushed back into the depths to undergo champagne recompression." (Jearl Walker, *Flying Circus of Physics*).

Naturally carbonated waters like Perrier bubble up from deep under the surface of the earth. Carbonates from underground limestone caves react chemically with the cool pressurized acidic water to create carbonic acid, which later decomposes to escape as bubbles of carbon dioxide, the same phenomenon that creates the "fizz fizz" accompanying the "plop plop" of Alka Seltzer in water.

The father of the soft drink is Joseph Priestley, better known for his discovery of oxygen. Living beside a brewery in Leeds, England, Priestley was aware of the presence of "fixed air" (as carbon dioxide was then known) hovering above the open-air fermentation vats. He poured water back and forth between two containers directly over one such vat, and within a few minutes produced "a glass of exceedingly pleasant sparkling water." Soft-drink manufacturers accomplish the same effect by injecting chilled liquid with pressurized carbon dioxide and bottling the drink under pressure. The old-fashioned seltzer-bottle favored by slapstick comics utilized a small pressurized CO_2 cannister to carbonate the soda water on the spot.

Since prehistoric times humans have taken advantage of the eating habits of the tiny single-celled plant *Saccharomyces cerevisiae*, a yeast, to produce natural carbonation in a process called fermentation. Yeast transforms carbo-

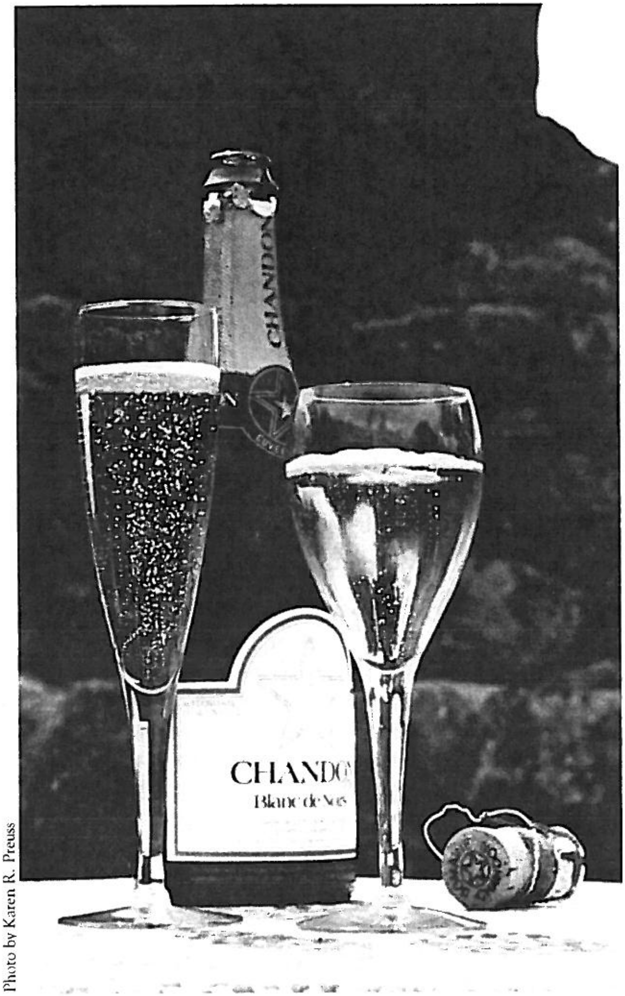


Photo by Karen R. Preuss

Makers of fine sparkling wines recommend glasses with narrow openings, like the "flute" on the left or the "tulip" on the right, rather than flat coupes *which they call "birdbaths." The idea is to concentrate the bubbles and aroma of the wine underneath the drinker's nose. Note the special cork, much wider than the neck of the bottle, made in horizontal layers. The cork is compressed and forced into position, then surrounded by a wire basket for safety.*

hydrates into ethyl alcohol and carbon dioxide, two by-products that make beer and champagne alcoholic as well as fizzy.

Fermented beverages are of two types. Wines derive their carbohydrate yeast food from soluble sugars in fruit juices, primarily grape, while beers and ales use carbohydrates from starches present in grains, the common ones being barley, corn and rice.

"Sparkling wine" is the correct name given all carbonated wines, whereas the frequently used term "champagne" properly refers only to sparkling wine produced by licensed communes in the Champagne region of France. Most wine doesn't bubble because it's fermented in unsealed tanks and the CO_2 gas escapes into the air. But sparkling wines are fermented a second time—this process is quaintly known as *prise de mousse*, literally "grabbing the bubbles." More sugar and yeast are added to the wine and the container is tightly sealed. The gas produced in the second fermentation does not escape and is dissolved into the wine under its own pressure.

Cheap sparkling wines undergo second fermentation in large tanks, and then are filtered and bottled under pressure. Champagne and other fine sparkling wines such as those produced by Domaine Chandon in California's Napa Valley are created by a more complex and romantic process known as the *methode champenoise*, the principal distinguishing feature of which is that the second fermentation takes place in the same bottle in which the wine is eventually sold. Specially designed bottles (thick walls, gentle curves instead of sharp corners, concave bottoms) and thick corks wired to the mouth help to contain the six and a half atmospheres of pressure that the carbon dioxide builds up. Champagne bottles do occasionally explode at the winery during second fermentation.

Bubbles not only tickle your nose, they tickle your tongue too. Some of the carbon dioxide resides in the membrane around the airborne bubbles in the form of carbonic acid. The acidic taste offsets the otherwise sweet flavor of the wine. That's why sparkling wine gone flat (or sodas for that matter) taste far sweeter than in their carbonated state.

But before any bubbles can form in a carbonated beverage there must be a surface of some kind where the carbon dioxide molecules can escape the surrounding water. The top of a glass, bottle, or can provides such a surface, but so do tiny pockets of air trapped in miniscule scratches in the interior of a glass. Advertising photographers who want a showy stream of bubbles in a champagne or beer glass will deliberately scratch the bottom of an otherwise perfect goblet.

Beer and ale are the other popular fermented alcoholic beverages. Beer is fermented in a sealed vat, with grains, primarily barley, providing the carbohydrates to feed the yeast. But grain starches are insoluble and therefore unfermentable and must be split by enzymes before this vital step can proceed. To accomplish this, the barley is malted, a process of germination and drying that releases enzymes in the barley and allows them to break the starches into usable sugars.

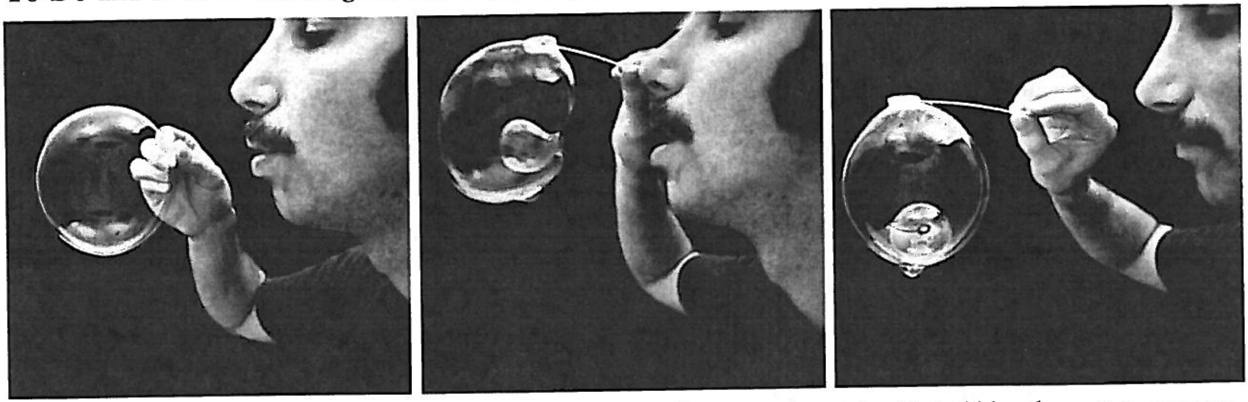
Beers contain a considerable amount of protein, one benefit being that bubbles tend to clump in the thicker material. The result is a frothy head. Darker stouts,

Stout (on the right) has a higher protein content than beer (on the left), which makes for a thicker head of foam.

Guinness in particular, have higher protein content and produce stiffer, longer-lasting heads, hence the age-old habit of "blowing the foam off the beer."

Here's a trick for blowing the foam back "into the beer." If a can of beer or soda is shaken up by being dropped (or by a practical joker), or if a bottle of champagne has been roughly handled, the turbulence will create lots of sites for the formation of carbon dioxide bubbles all throughout the liquid (these so-called "nucleation sites" are areas of low pressure, sometimes containing air, sometimes containing water vapor, forming the surfaces necessary to allow the carbon dioxide to come out of solution). Everyone usually dives for cover when a shaken bottle or can is opened because the pressurized liquid, with all its dissolved gases trying to escape at once, usually sprays all over the place. To prevent explosive decompression, try tapping the can sharply with your fingertip—then open 'er up while your companions cringe. Voila! No foam! The tapping dislodges the nucleation sites, and the carbon dioxide is once again safely held in solution, (better try this over a sink first!) ⊙

To Do and Notice: Blowing a Bubble Inside a Bubble



To blow a bubble inside a bubble, you must start with a big bubble. The bigger your initial bubble, the easier the trick. Ron Hipschman, the Exploratorium's resident bubblologist, suggests a bubble no smaller than four inches in diameter, and says that blowing the big bubble is really the hardest part of the trick.

Start with a bubble wand dipped in bubble solution. Ron recommends using Wonder Bubbles with an ordinary bubble wand and practicing indoors where vagrant breezes will not burst your bubbles. The size of the bubble you blow will depend on the velocity of your puff and the shape of your mouth. A high velocity stream of air delivered through an o-shaped mouth yields dozens of small bubbles, not the big bubble you need. To get the big bubble, blow a soft and steady stream of air through what Ron calls a "mouth-shaped mouth," that is, a mouth in no particular shape at all. When the bubble reaches the right size, flip the wand quickly over to seal the bubble.

Once you have the big bubble, the rest is comparatively easy. Make your mouth into an o-shape and hold the bubble, still attached to the bubble wand, about an inch from your mouth. Now, cough gently into the side of the bubble. Ron recommends a "society cough," a genteel cough. "Don't puff," Ron cautions. "Don't make a "p" sound. You'll pop the bubble or blow it off the wand."

If you cough correctly, you'll end up with a small bubble floating inside your big bubble, a marvelously transient achievement. If you don't succeed with an ordinary bubble wand, you might want to try using Bubblo's "bubble-in-a-bubble wand," a wand that has a smaller circle within the larger hoop of the wand. According to Ron, most people can learn to blow a bubble inside a bubble in about half an hour. As one of Ron's students, I advise patience. Bubble blowing, like anything else worth doing, takes practice.

We're Forever Blowing Bubbles

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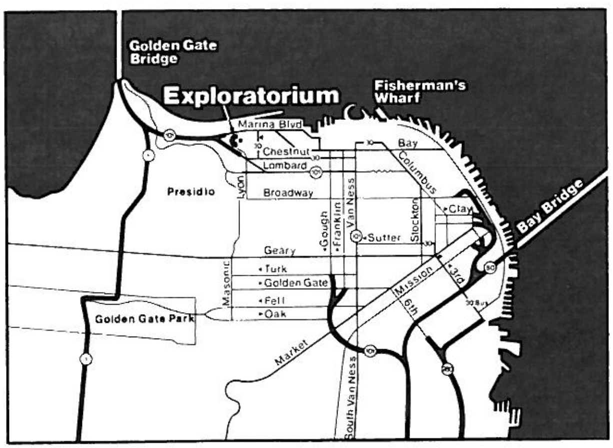

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