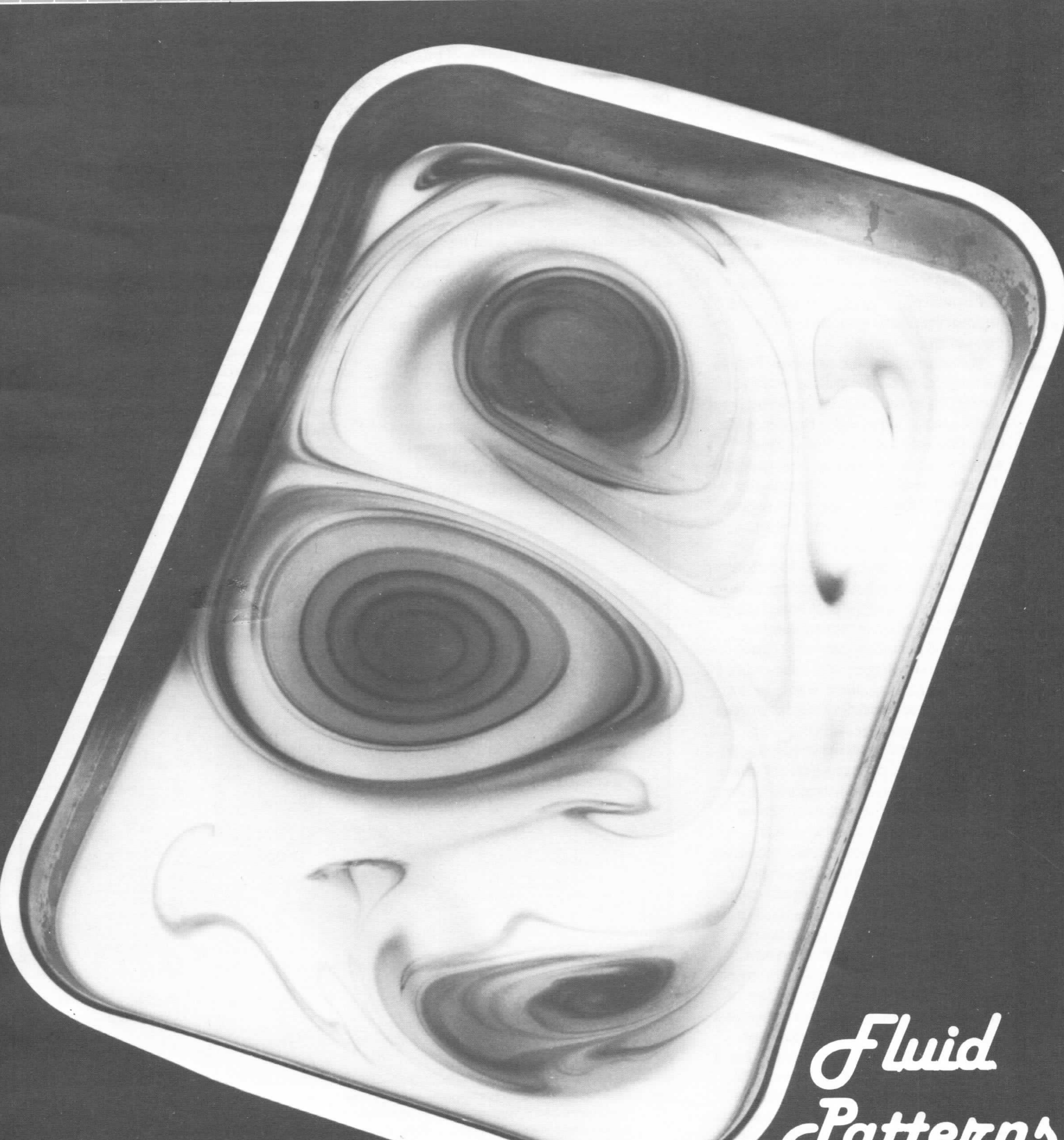
AAAS SCIENCE RESOURCES FOR SCHOOLS

IDEAS IN SCIENCE



Fluid Patterns

Fluid Patterns

Introduction

We breathe air in and out without thinking about its presence. Because it is invisible, we draw conclusions about some of its properties by the movement it creates. Outdoors, leaves rustle on trees and debris and paper blow about in the wind. Indoors, smoke from a cigarette, or fine particles of dust in bright sunlight indicate that, even in a still room, the air is moving. Because such happenings are so common, we often overlook the beautiful forms and patterns that these movements create. Smoke rises and folds in on itself, forming a continually changing flux of spirals and curves, sensuous and visibly entrancing.

Water also can take on many beautiful shapes, from the rolling waves at the beach to the fascinating whirlpool that forms as a bathtub empties. Milk dropped into a still cup of coffee forms mushroom shapes that quickly dissolve. In all of these continually changing situations, there are repetitions of some basic forms. Patterns emerge after long observation.

The aim of this packet is to help you and your students discover the beauty and fascination of air and water movement. It is a phenomenon that has fascinated people since early time. Stories, mythologies and elements of religious practice, such as the Taoist symbol, were modeled on the properties of the vortex or spiral.

Many natural systems involving air or water create patterns that are some type of vortex. It has intrigued biologists for some time that even living organisms take on the form of frozen movement. The gnarls in the trunk of some trees and the mushroom itself look like solid models of liquid movement. At the same time, much of our modern technology depends on an understanding of fluid movement. Airplanes and boats provide the most obvious examples. But the design of automobiles, the circulation of air in a large building, and the working of heart valves are other examples (Fig. 1).

The *Doing Science* section of the packet suggests a series of activities which can start you and your students exploring fluid motion. They show how air and water movement can be made visible and help to provide a focus for these explorations. The first two *Doing Science* sheets are meant to show that air movement outdoors and indoors is not chaotic but somewhat ordered. The third and fourth show how very beautiful patterns can be created with water in a more controlled environment. The beautiful vortices formed with the food color or detergent in water in the last two activities show spiraling motion more clearly than the bubbles and smoke of the first two activities. Also, the *Doing Science* series goes from the large scale to the small scale with the explicit suggestion that approximate models of large scale phenomena can be done on a small scale. Overall, *Doing Science* sets up situations in which enticing phenomena will encourage close observation and intuitive understanding of fluid motion.

The sheets for *Doing Science* are aimed at the student. This approach will allow you to do the activities either as a whole class pursuit, or as special projects for individual students. In either case, it is important that you try out the activities before introducing them to the students. The experience of working with the materials will also help you to understand the other comments in the Notes to the Teacher. Always be aware that however effective your presentation, some students will need help in understanding and interpreting the procedures and directions in the *Doing Science* sheets.

The remaining commentary in this booklet is meant to provide background which will help you understand the phenomena being investigated and place the studies in the context of how the scientist works. What follows attempts to answer such questions as what motivates scientists to study a particular phenomenon and the methods they use to investigate it.

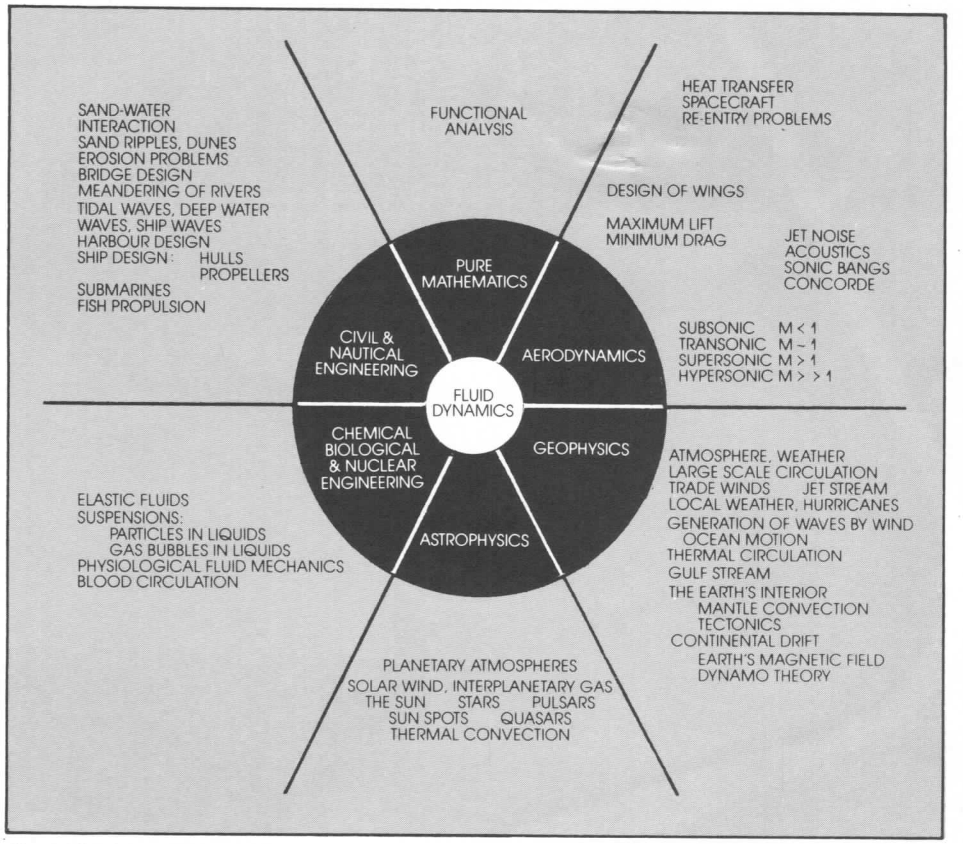


Fig. 1 Fluid dynamics touches upon many different areas of modern technology as well as a diverse range of natural phenomena. Grouped under the different disciplines are specific problems which illustrate the diversity. Adapted from a Chart by H.K. Moffatt, from Fluid Dynamics, *ed. Balian and Peube, 1977, Courtesy Gordon and Breach, London.*

Science, Art and Fluid Patterns

If you look closely at the steam coming off a freshly brewed cup of coffee, you will see that a variety of spirals, curling vortices and curving lines continually appear and disappear. When you slowly add cream to the coffee, you produce yet more mushroom-shaped patterns which swirl atop the surface. A blown-out match gives off smoke similar in pattern to that of the steam. In the *Doing Science* activities, you will observe smoke from a burning string or incense, and move food color through a solution of starch and water. The moving patterns produced in all of these situations are beautiful to watch. In fact, you can drop food color in water for hours on end because of the hypnotic quality of the motion.

Similar kinds of patterns can be found on a much larger scale. Large whirlpools can form in fast-moving rivers or streams. Tornadoes are spawned from giant thunderheads, displaying a beautiful form, but destroying everything in its path.

Today we too often regard science and art as two separate undertakings. This is true as far as the overall process and the final product are concerned. But science and art often share a common origin in fascination with the natural world. Both scientists and artists seek patterns in nature, and have been interested in air and water movement through the ages. The paintings of J.M.W. Turner and Vincent Van Gogh reflect this fascination.

Sometimes these two different approaches to the study of nature reside in one person. Leonardo da Vinci is among history's most creative scientific inventors and at the same time one of the greatest artists. The drawings in his notebooks were based on close observation and continual experimentation; they were as much works of art as records of his experimentation. One phenomenon that fascinated da Vinci throughout his life was the movement of air and water. His notebooks contain sketches of flowing water that show in detail the vortex patterns in rivers and streams. He was the first to closely observe turbulent motion and to study vortices created by obstacles in flowing water.

There is a great sensual delight in watching smoke from a fire, clouds scudding across the sky, and the changing colors and shapes of an oil slick on a gently moving pool of water. And scientists are not immune to that delight, even though scientists use a great deal of machinery and instrumentation. They do have interests in the beauty of everyday phenomena, esthetics, and elegance. The fundamental motivation for creative scientists is the recognition of patterns in nature.

Scientists begin to diverge from artists when it comes to explaining the patterns. Scientists need to undertake systematic observations and experiments to understand the common characteristics in a set of similar phenomena. Further refinement results in abstract formal relationships expressed in mathematical terms.

Fluid motion itself incorporates a wide range of related phenomena. Fluids move in other fluids and around solid objects. Smoke drifts up into the sky from a tall chimney, and currents in the ocean mix waters of different temperatures and densities on a grand scale, the salmon swims upstream in a fast moving river to spawn, and the whale navigates great distances in the ocean.

The fundamental rules of fluid dynamics can be applied to these diverse environments and movements. But much is still not understood. New experimental techniques and theories are continually being developed to expand and clarify the various manifestations of fluid motion (Fig. 1).

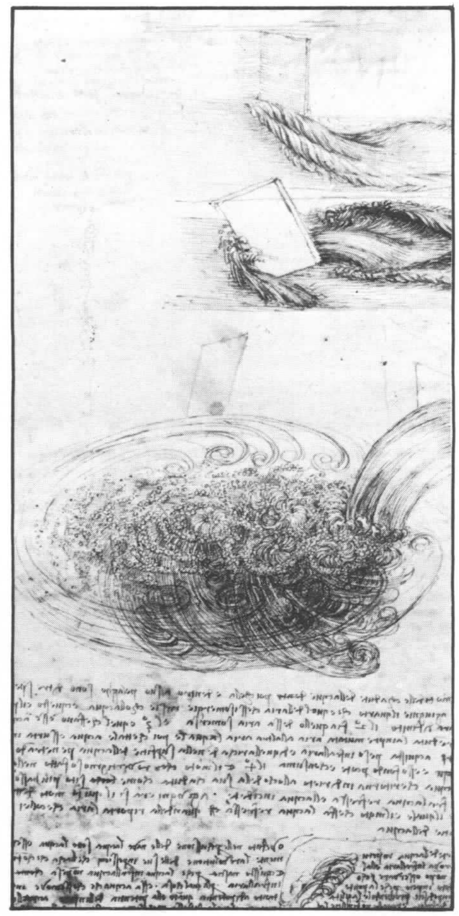


Fig. 2 *These two examples are among many drawings of water in motion found in da Vinci's notebooks. The portrait may be of da Vinci himself.*

Making Fluid Motion Visible

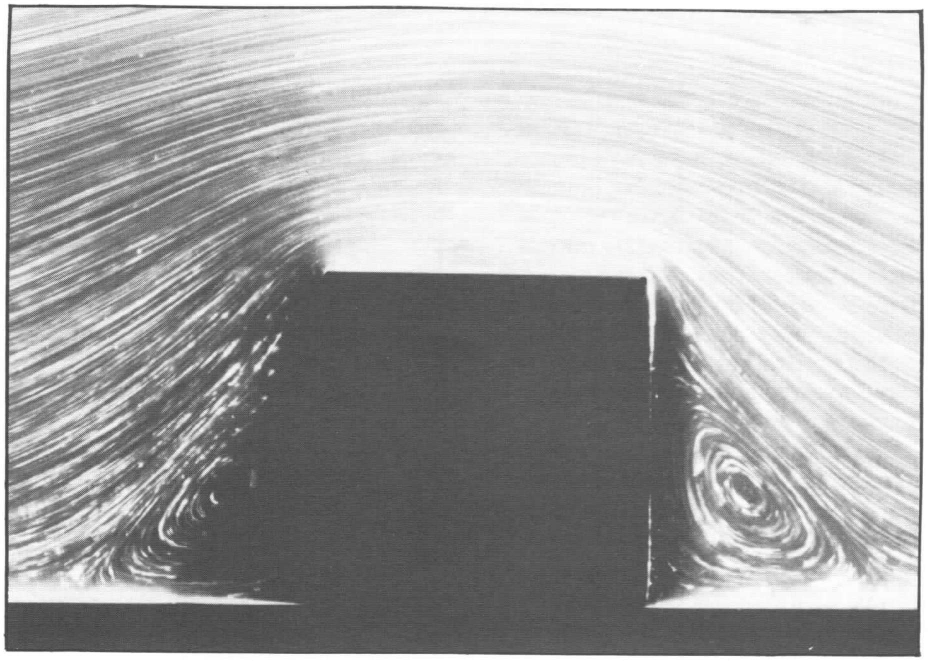


Fig. 3 Glass beads in slow moving glycerine show a symmetrical separation in front of and behind a block.
Photo: S. Taneda, 1977 J. Physical Society of Japan; Courtesy M. Van Dyke, An Album of Fluid Motion, *1982.*

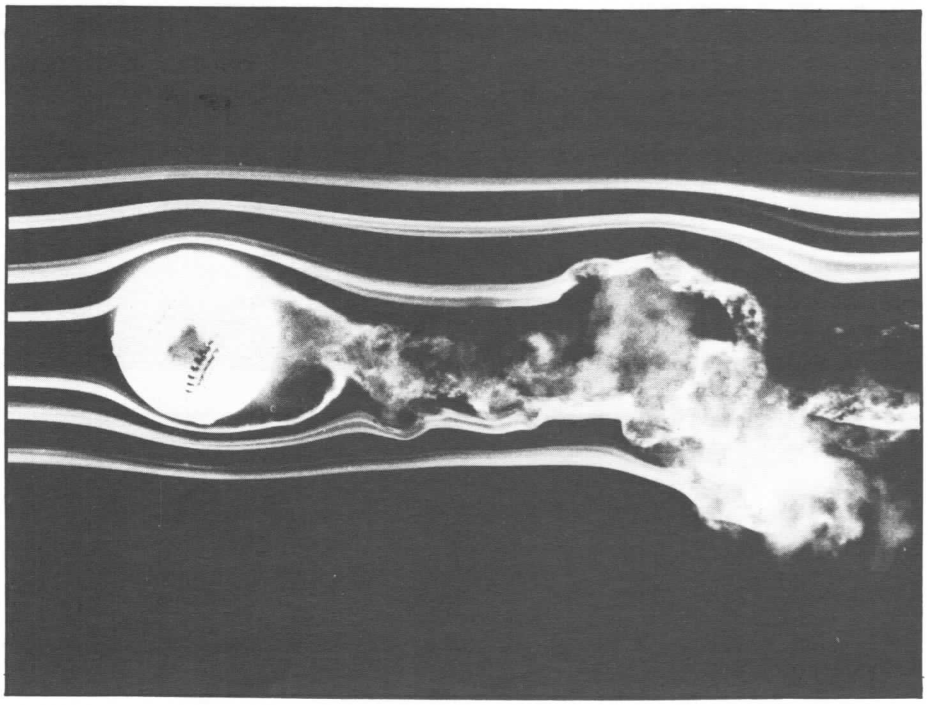


Fig. 4 A baseball is rotated at 630 rpm in a stream of air traveling at 77 ft./sec. Visualization is by means of smoke.
Photo: T. J. Mueller, 1981, Courtesy M. Van Dyke, An Album of Fluid Motion, *1982.*

In each of the activities in *Doing Science*, students use a simple material to make visible air and water movements: bubbles and smoke for wind and air currents; food color and detergent for water. Each environment requires a suitable material for observation. You would find that even small soap bubbles are inadequate for detecting drafts of air indoors, but that smoke is an effective indicator.

Scientists take a similar approach when they want to study how air or water moves around objects. They also use smoke or dye; but the photos in Figures 3, 4 & 5 show they have devised other techniques. These include glass beads and very fine solid particles of metal.

Another approach is to observe how light changes as it passes through a moving fluid. For instance, when you pour hot water into a bathtub filled with cold water and shine a light down into the tub, you will see shadows flitting across the bottom of the tub, created as convection currents produce layers of water of different densities. Similarly, air traveling at a very high velocity, near the speed of sound, can produce waves as it moves past the test object. The air in the pressure wave has a different density from the surrounding air. When light passes through the flowing air in the wind tunnel, the shadows it produces show where the pressure waves are. You can see this in the accompanying photograph.

Scientifically, fluid dynamics techniques only work if the substance introduced into the fluid follows the fluid's motion exactly. Smoke, for example, is a valid indicator for wind tunnel tests only when the turbulence of the fluid is relatively low. As the motion becomes more turbulent, the smoke diffuses in patterns that no longer represent the flow. Similarly, blowing bubbles only provides a valid indicator of air movement on blustery days, when the wind carries the bubbles with it continuously. In calm weather, the occasional breeze may indeed carry the bubbles along with it. But once the breeze dies down or changes direction, the bubbles often continue to move in the original path, because of their momentum. Of course, particles introduced into moving fluids for making the motion visible and measurable must be of suitable weights and sizes.

The experimental techniques available determine the kind of questions that a scientist can ask. Until the special techniques of producing shadowgraphs emerged, it was very difficult to understand the interactions of objects moving at high speed with the air. When a new technology is invented, it opens up new areas to explore. Galileo took advantage of new ways of making lenses and assembled a telescope. Despite the poor images, he could see that the moon had mountains and "seas," and that natural satellites ringed the planet Jupiter. Those observations changed the popular conception of the heavens. Most modern experiments that produce unexpected results do so less dramatically. Nevertheless, these discoveries show that laboratory instruments and techniques are simply extensions of our senses, like the telescope, expanding our experiences and opening up new worlds for exploration.

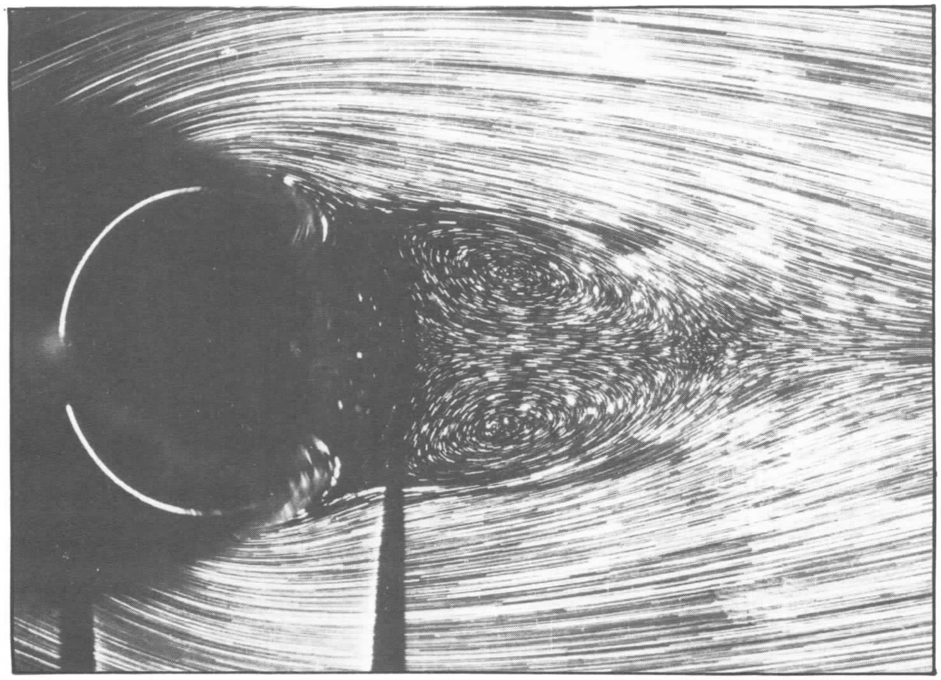


Fig. 5 The flow around a circular cylinder is shown by illuminating the magnesium cuttings in oil. Photo: M. Coutanceau and R. Bouard, 1977, J. Fluid Mechanics, Courtesy M. Van Dyke, An Album of Fluid Motion, *1982.*

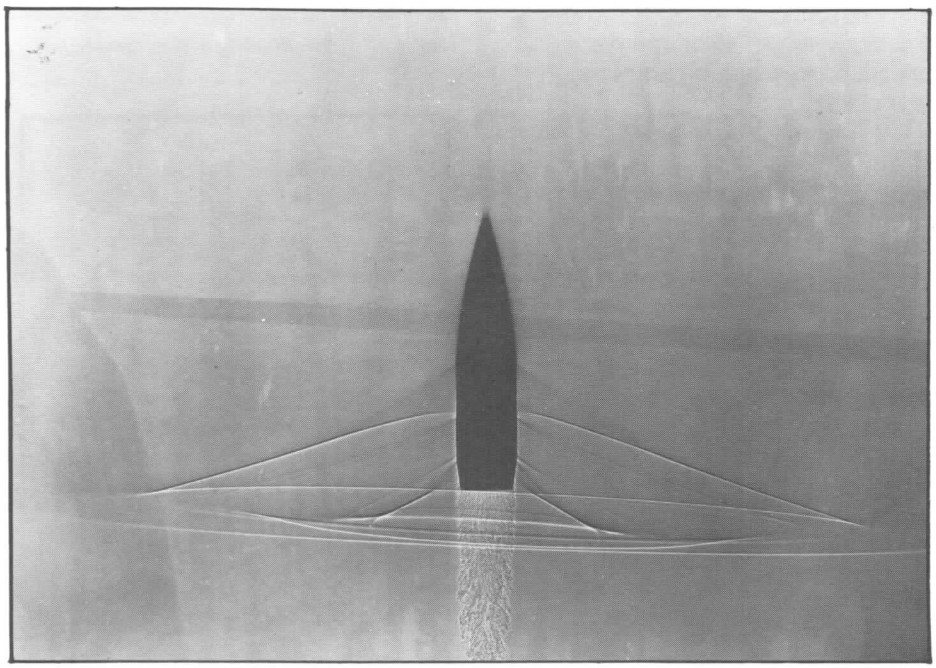


Fig. 6 A shadowgraph reveals the shock wave pattern of a projectile moving at near-sonic speed. Photo: A. C. Charters, 1947, Courtesy M. Van Dyke, An Album of Fluid Motion, *1982.*

A Practical Application of Visualizing Fluid Movement

by Peter Gwynne

Energy auditors, who measure the amount of heat that escapes up the chimney or through the doors and windows of a residence, often rely on fluid dynamics in their search for leaks. One simple principle is to discover drafts of cold air moving into a warm house. The old way was to use a candle; drafts would cause the flame to flicker away from the direction of the draft. But the method was primitive at best, and potentially dangerous at worst. Thus the auditors have created two new techniques.

The first uses a very fine colored powder that can be scattered into the air around windows, doorways, and other suspected sources of leaks. So fine are the particles that they follow the prevailing drafts, giving the auditor an idea of the location and size of the leak. More sophisticated is infrared sensing. Monitors aimed at an individual house or a row of houses spot the convection currents produced when heat rises from the residences.

Characterizing Fluid Patterns

Laminar and Turbulent Flow

At first glance bubbles outdoors seem to move all over the place, and rising smoke from a burning string forms a changing variety of shapes. In contrast, food color in water presents more definite configurations. Long and careful observation will reveal repeating patterns of motion in all of the examples, however.

Scientists specify two basic types of fluid motion—laminar and turbulent—exemplified by the following examples:

- While a steady wind in a completely open field blows leaves, dust, and other debris in a straight line, erratic winds create little dust devils, upward spirals of moving air.
- In a very still room, smoke rises straight upward for several inches, but then drifts into curved shapes.
- Water from a spigot flows out smooth and clear when the flow is relatively slow. Reaching a particular speed, however, it becomes rough and cloudy.

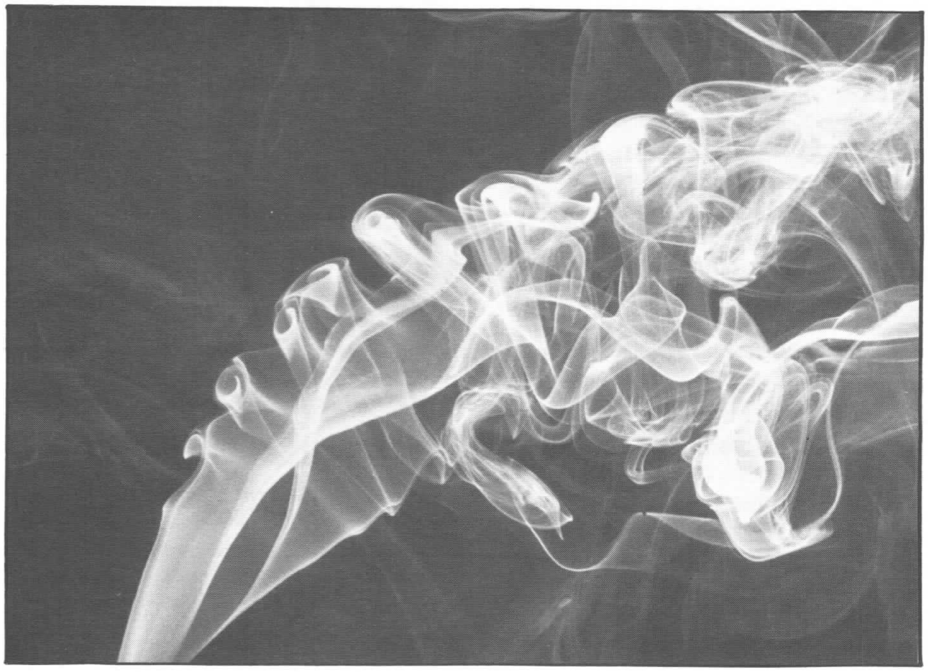


Fig. 8 Laminar and turbulent smoke flow.

Fig. 7 Dust Devil.

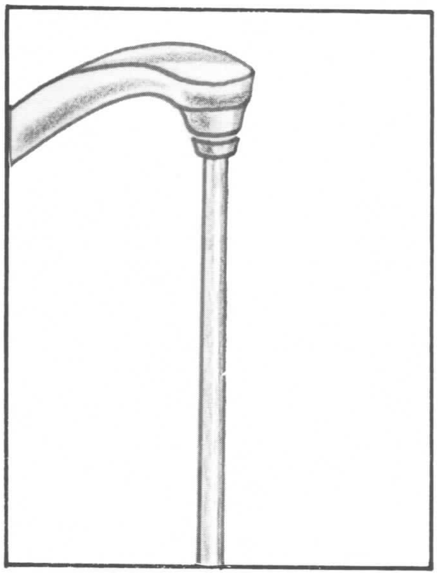


Fig. 9 Laminar flow from a spigot.

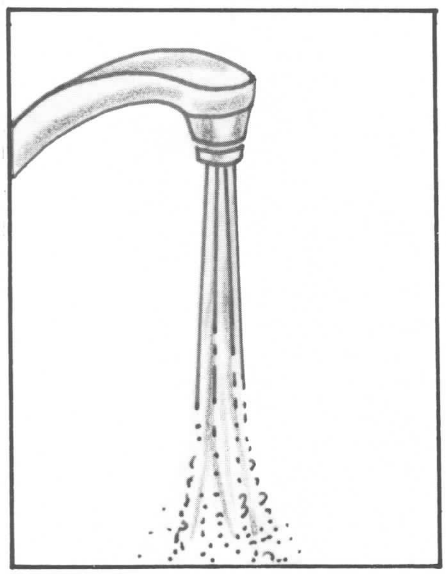


Fig. 10 Turbulent flow from a spigot.

Photos: John Urban
Illustrations: Susan Manning

Scientists call smooth flow **laminar**, while they know the erratic, irregular variety as **turbulent**. Laminar flow is steady and uniform. But turbulent flow also contains a sense of **order**. Viewed under certain controlled conditions, turbulent flow exhibits specific patterns. If you give a gentle push to a drop of food color in a tray of water, you will create beautiful forms.

Plainly, even turbulent motion is not as disordered as it may seem. The basic patterns that emerge in such motion actually occur frequently.

Both laminar and turbulent flow occur in a variety of circumstances. One of the most common involves the movement of fluids around solid objects, such as rocks in streams and rivers, wind blowing by trees and towers. The roles are reversed when fish swim in the water or cars and planes move through the air, but the effect is the same. Common to both are the disturbances created in the fluid as it and the object move relative to each other. Laminar flow before it reaches the obstruction transforms into turbulent flow as it passes by.

Even the turbulent flow created in this way is not totally chaotic. To understand why, picture what happens when water in a gently moving brook encounters a rock in midstream. As it reaches the rock, the water parts into two sections. When they meet again on the far side of the rock, though, the two sections don't completely merge. Instead, a boundary forms between them. Along the boundary, the two moving fluids create rhythmic, spiral motion. The most common pattern produced in this circumstance is a vortex.

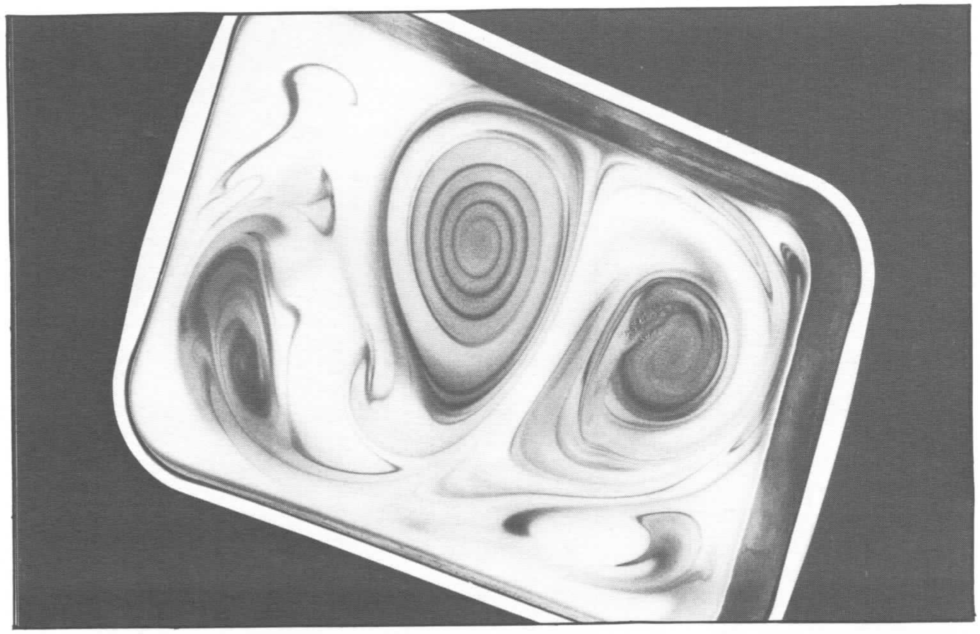


Fig. 11 Vortices made visible with food coloring in a tray of water.

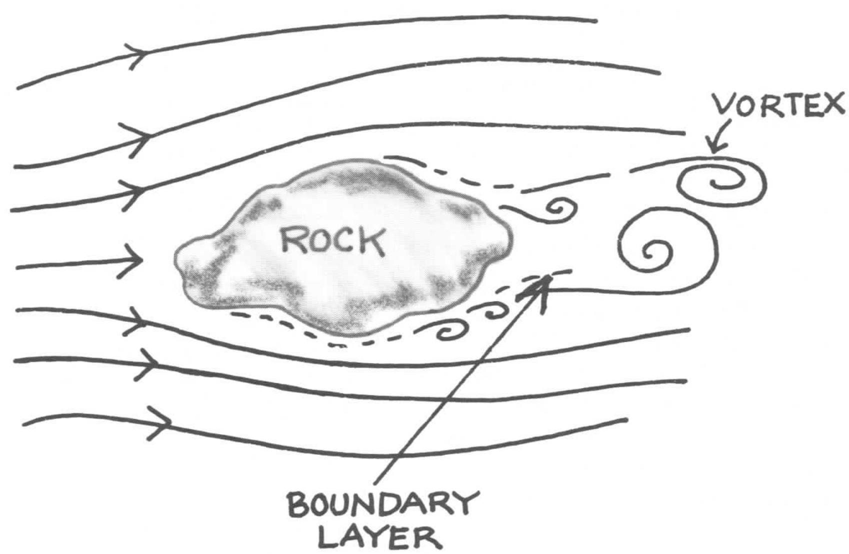


Fig. 12 Movement of water beside and behind a rock.

Vortices at Different SCALES

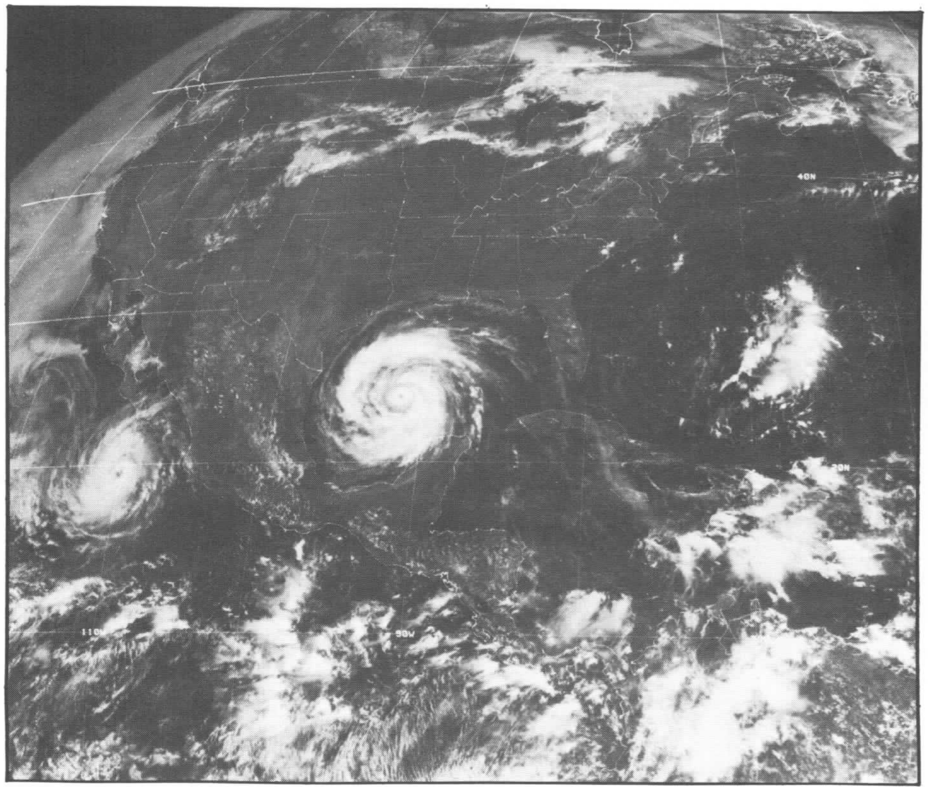


Fig. 13 Hurricane in the Gulf of Mexico. *Photo: NOAA, Courtesy Satellite Data Services Division.*

Occasionally known as a whirl or eddy, a vortex is the rotational movement of natural particles around a common center. The water draining out of a bathtub, the disturbances in the water behind a moving canoe paddle, and the tiny cyclones of dust skittering through the air on a windy day are all examples of vortices. In some sense, every movement of matter that involves rotation can be regarded as a type of vortex. The chart shows the range of vortices from the microscopic to the continent-sized.

In a single source there are different sizes of vortices generated. Take, for example, the disturbed air flow behind a tree or the wake aft of a boat. Small vortices are readily visible at the surface of the water. But close examination of shadows on the bottom of a slow flowing stream reveals larger diameter disturbances, which are defined technically as eddies. In the *Doing Science* Activities, students can create a special kind of vortex known as the Von Karman **vortex street**. All they need to do is move a stick slowly through a solution of Ivory dishwashing detergent and food color.

	Diameter
Vortices generated by insects Vortices behind leaves Vortex rings of squids	.001-.1 m
Dust whirls on the street Whirlpools in tidal currents Dust devils	1-10 m
Vortex rings in volcanic eruptions Whirlwinds and waterspouts Convection clouds	100-1000 m
Vortices shed from the Gulf Stream Hurricanes High- and low-pressure systems	100-2000 km
Ocean circulations General circulation of the atmosphere Convection cells inside the earth	2000-5000 km

Fig. 14

This chart gives a sampling of vortices generated at different scales in nature.

Adapted from H. Lugt, **Vortex Flow in Nature and Technology,** *John Wiley, NY. 1983.*

Vortices on a Large Scale

by Peter Gwynne

Frequently on windy days we encounter spiraling gusts known as **dust devils.** In severe storms, a rotational movement on a much larger scale is a tornado, a form of meteorological violence that kills more Americans every year than any other weather phenomenon except lightning.

Unlike hurricanes, tornadoes are so small that they are almost impossible to observe during their formation. Even the famed tornado hunters of the University of Oklahoma, who drive furiously after tornadoes to monitor them at close range, rely on individuals' observations to learn where and when a tornado has actually touched down and started to move along the ground. But the work of the hunters, combined with observations at greater distances using the recently-perfected Doppler radar, has given meteorologists at least a rudimentary understanding of those wicked, whirling winds.

Tornadoes generally form in areas where a warm, humid layer of air at the surface meets a region of cool, dry air above it. In these conditions, a small fraction of the energy in a thunderstorm can be concentrated into an area no more than a few hundred yards across. That concentration sets off a rotational movement that is continually driven by heat energy.

The tornado itself is a vortex. A central core of low-pressure air pulls in streams of air from the ground. As the air moves into the core, it rotates (almost always in a counterclockwise direction in the northern hemisphere) faster and faster. As the tornado develops, it picks up dust and debris that make it clearly visible. Some tornadoes also signal their presence by sound; they roar like freight trains as they approach. And once a tornado has built up to full power, it can pick up objects as large as buses, and pull the roofs off houses.

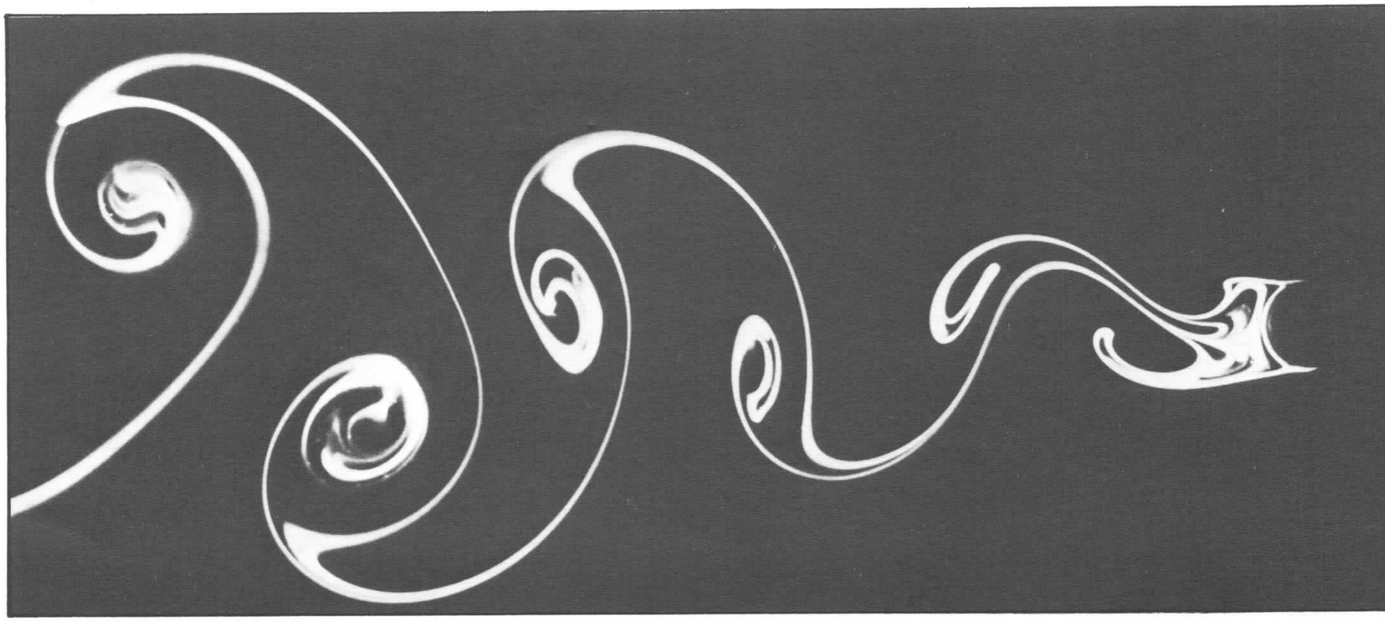


Fig. 15 Vortex Street created in water. Photo: S. Taneda, 1977 J. Physical Society of Japan; Courtesy M. Van Dyke, An Album of Fluid Motion, *1982.*

Vortices are one example of fluid motion. The movement of fluid very close to solid objects gives another. By the simple expedient of dropping small fishing floats across a stream, anyone can show that the speed of the water becomes slower the closer the water is to the bank. Put more generally, fluid moves more slowly as it approaches its boundary layer—the thin section immediately adjacent to a solid object.

Within the boundary layer, the liquid is completely still at the very surface and gradually increases its flow a short distance from this surface. Students can test that by dropping food color at the edge of a tray of water that has been stirred; some of the food color will linger on the side of the tray where it was deposited.

The speed of the fluid increases steadily with distance from the bank, or the surface of any object in the fluid. It's as if the fluid consists of a series of layers parallel to the bank, with each adjacent layer moving at a slightly faster speed out to midstream. Students can see this layering effect by putting two different food colors into a tray of water and starch, and moving a stick slowly among them. The movement will create a vortex within which the two colors form independent spirals. The concept of layering is not restricted to simple demonstrations of fluid motion. It has played a major role in the development of theories of fluid dynamics.

Modeling Fluid Motion

In the *Doing Science* activity "Moving Water Around Objects" a stick moving through Ivory dishwashing solution creates turbulence. If done slowly, a parade of vortices is produced, each vortex increasing in size as it moves away from the stick. A similar kind of pattern on a much larger scale can be seen behind the post of a bridge in a fast moving river. Smoke from a cigarette often exhibits patterns similar to certain kinds of cloud formations. These similar flow patterns suggest that small scale phenomena might serve as models for those of a larger scale. In fact, persons who study fluid motion do just that—in the design of airplanes, ships, and low-drag automobiles; in the study of ocean currents, air and cloud movements in the atmosphere; and, conversely, in the study of very small phenomena like blood flow and movements of microorganisms in fluids.

Also, in the same *Doing Science* activity you can observe the effects of changing the size of the object that moves through the dishwashing solution and the effects of changing the speed of the motion. As you increase the size of the stick moving through the solution you create more turbulence. The same happens for moving the stick more quickly. Changing the liquid also makes a difference. If you move the stick through alcohol, which is less dense than water, the effect is less turbulence. If you use pancake syrup or thick tomato soup, both more viscous or gooier than water, there is also less turbulence.

These variables—size, speed, density, and viscosity—play an important role in laboratory studies of fluid motion. Often, experimental studies of fluid motion make use of models to approximate complex fluid phenomena that are either too large or too small to control systematically. These four variables provide an empirical rule for assessing the validity of modeling large-scale movement of fluids (or small-scale) with laboratory-size models of the movements, such as modeling the movement of thin air past an airplane at 40,000 feet with small amounts of smoke in a wind tunnel. The rule is based on a ratio

$$\frac{\text{Size x speed x density}}{\text{viscosity}}$$

called the Reynolds number. The rule is: fluid flows with the same Reynolds number will exhibit similar flow patterns and turbulence.

A scientist or engineer can adjust the variables of speed, size, density, and viscosity for a small model ship in a tank of liquid and create vortex patterns similar to an actual ship on one of the Great Lakes. An aeronautical engineer can adjust the same four variables for the wind flowing past a small model airplane in a wind tunnel to create flow patterns similar to an airplane in the sky. With today's modern computers modeling of fluid motion has become part of very sophisticated simulations in the wide variety applications listed in the chart on fluid dynamics on page 1.

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This issue of *Ideas in Science*, the accompanying *Poster Plus* and *Doing Science* sheets #1, #2, #3, #4, #5 were produced by the staff of **The Children's Museum**, 300 Congress Street, Boston, MA 02210.
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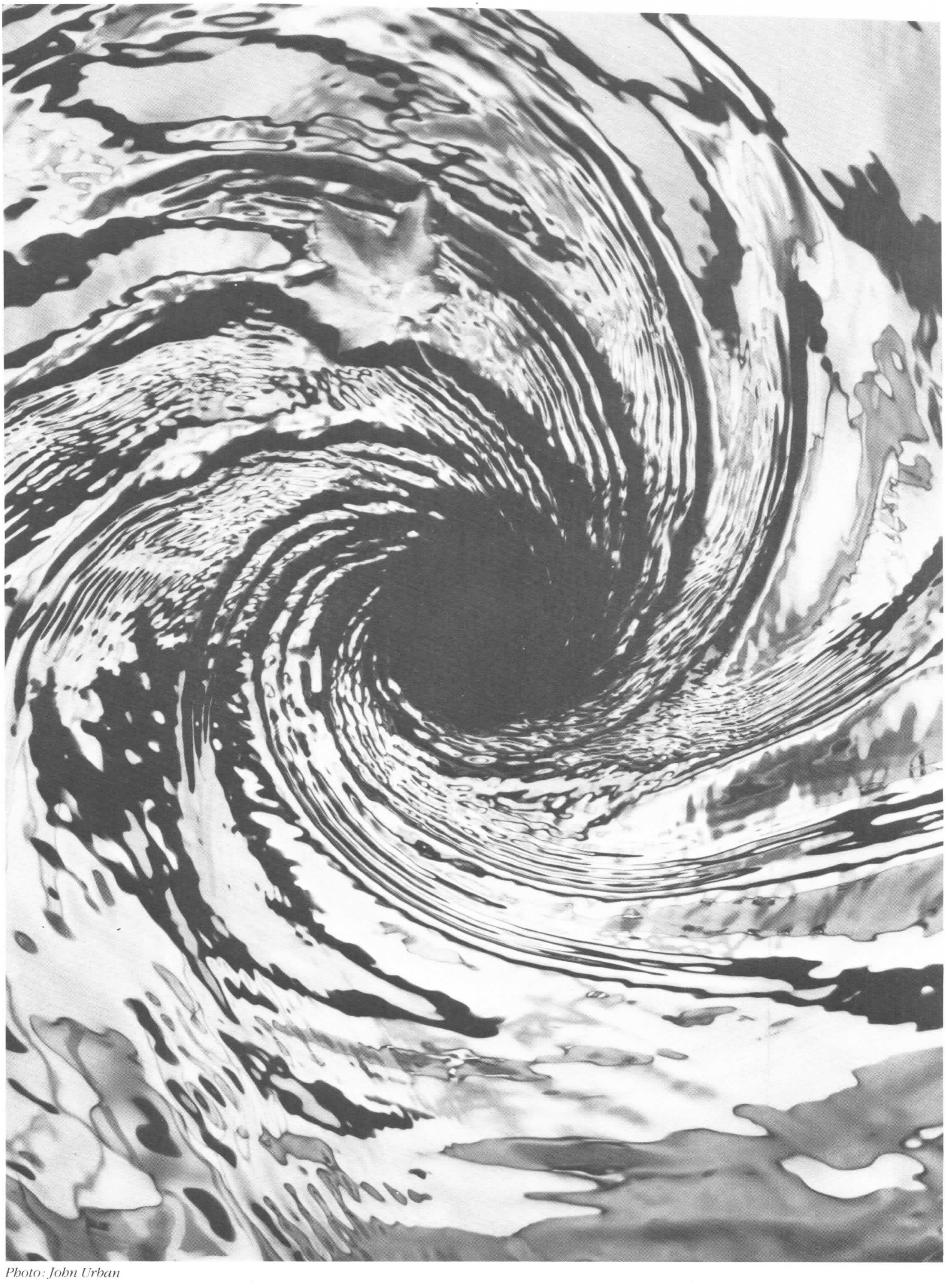

Photo: John Urban