Organisms That Capture Currents

A variety of species, from marine sponges to prairie dogs, have harnessed aerodynamic and hydrodynamic forces to increase the flow of air or water through themselves or their abodes

by Steven Vogel

In any ecological system the chemical energy stored in food is a precious commodity. It is not only limited in quantity but also energetically costly for an animal to obtain; hunting, gathering and filter feeding are all energy-consuming activities. As a result a variety of animals have evolved ways of harnessing plentiful forms of mechanical energy in the environment, such as water currents or the wind, to perform tasks that would normally require the expenditure of chemical energy. These animals, ranging from turret spiders to prairie dogs, have achieved a considerable adaptive advantage in the rigorous energy economy of the living world.

The major source of mechanical energy in the environment is the difference in velocity between a fluid and the solid substratum over which the fluid moves. (Ultimately these flows—air currents in the atmosphere and water currents in the ocean—are driven by energy from the sun.) Given the appropriate transducing system, the velocity difference created near the interface between a current and a substratum (such as the ground or the surface of an animal) can be converted into useful forms of energy. Because the energy of a current resides in the movement of a fluid, one simple and direct biological application is to cause part of that same fluid to move through some internal plumbing system. Indeed, most organisms that capture currents do so to pump air or water either through themselves (to facilitate respiration or filter feeding) or through a nest or burrow (for ventilation or humidification).

What are some simple ways in which currents can be harnessed to induce the flow of air or water through an organism or a burrow? One mechanism is based on the principle of the conservation of energy in a steadily moving fluid, first formulated by the Swiss mathematician Daniel Bernoulli in 1738. The principle states that if a fluid moves horizontally so that there is no change in gravitational potential energy, the pressure of the fluid must decrease whenever its velocity increases so that its total energy remains constant. For example, if the fluid is moving through a horizontal pipe that narrows and widens at various points, the fluid must speed up in passing through the constricted areas, and so it exerts the least pressure where the diameter of the pipe is smallest. Bernoulli's principle explains the function of the airplane wing: since air moves faster over the top of the wing than it does over the bottom, it creates a difference in air pressure between the top and the bottom, or lift.

Now consider a small *U*-shaped pipe connecting two points of a larger channel, with both ends of the small pipe perpendicular to the channel. The fluid in the small pipe will move from the end where the flow in the channel is slower (exerts a higher pressure) to the end where flow in the channel is faster (exerts a lower pressure). The velocity of current flow over one of the openings can be increased by elevating the opening or altering its shape so that it is sharper-edged or less sheltered. In this way flow can be induced in the small pipe independent of the direction of current flow in the larger channel. For example, the flow of smoke up a chimney increases when the wind blows, whatever the direction of the wind.

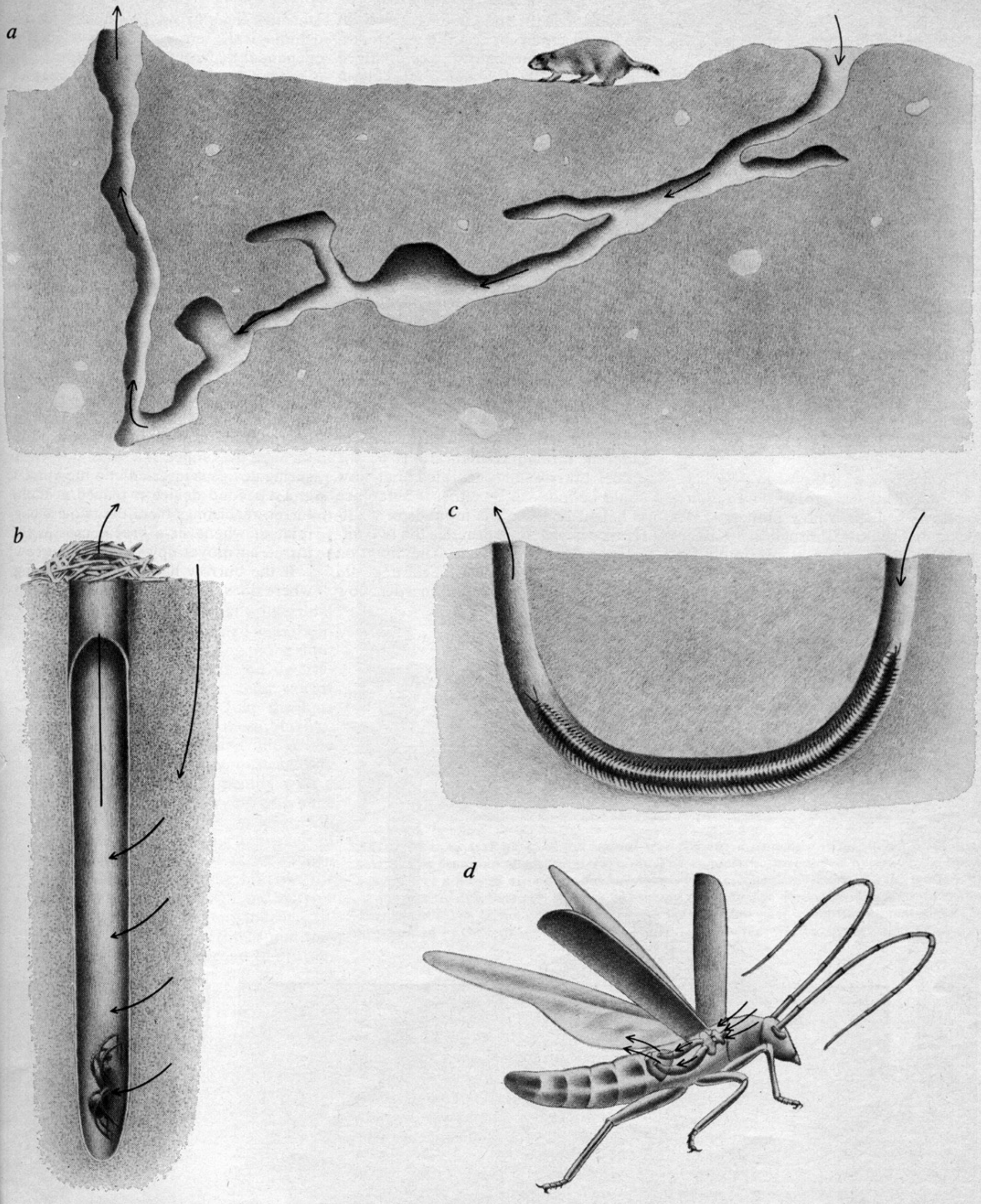
Flow can also be induced by the dynamic pressure of the current as a less direct consequence of Bernoulli's principle. If a small pipe is bent at a 90-degree angle and oriented in a larger channel so that one end is directed upstream and the other opens perpendicularly to the flow of current, the perpendicular opening will be exposed only to the static pressure of the stream whereas the opening facing the current will also be subjected to the dynamic pressure of the oncoming fluid. Flow will therefore be induced in the pipe from the upstream opening to the perpendicular one.

A third mechanism for inducing flow is based on the viscosity (resistance to flow) of real fluids, whether gas or liquid. The movement of a fluid past the opening of a pipe oriented perpendicularly to the current will draw fluid out of the pipe, a phenomenon known as viscous entrainment. The wider the opening of the pipe is or the faster the current is, the greater the entrainment will be.

These three physical effects may work singly or together to induce flow in a biological system. One simple geometrical system often found in nature, which I call Type I, consists of a *U*-shaped pipe through a solid substratum with openings at each end. If air or water is to be persuaded to flow through the pipe, the openings must differ in size, shape, elevation above the substratum or exposure to water currents or the wind. Internal flow will travel from the smaller, blunter, lower or more sheltered opening (where the fluid pressure is higher) to the larger, sharper, higher or less sheltered opening (where the velocity of current flow is greater, the fluid pressure is lower and viscous entrainment is promoted by the larger size of the opening or the greater current).

An excellent example of a Type I system for inducing flow is provided by the burrow of the black-tailed prairie dog, a species indigenous to the Great Plains of North America. These rodents are consummate burrowers, digging tunnels that in well-compacted soil may be as deep as 10 feet and as long as 50 feet. Although a prairie-dog "town" often appears to be a complex network of tunnels, the burrows are usually simple, two-ended passages with only one or two side chambers.

From existing data on the metabolism of the prairie dog, soil properties and diffusion rates it is an easy matter to calculate that the free diffusion of oxygen through either the soil or the tunnel is insufficient to meet the respiratory needs of even a single animal sitting in a nesting chamber at the bottom of the burrow. Moreover, in the warm months cool air is trapped in the chambers, making free convective currents negligible. How then does adequate oxygen reach the prairie dogs inside the burrow? Presumably the animals could force air through the tunnels by erecting their fur and running through the pas-



FLOW OF AIR OR WATER through the burrow of an animal or the animal itself for the purpose of ventilation, respiration or filter feeding can be enhanced by harnessing the energy of external currents. The examples shown here share a common geometry, termed Type I, in which the movement of a fluid over a substratum induces the flow of the same fluid through a *U*-shaped pipe passing through the substratum with openings at each end exposed to the current. Air or water is forced through the pipe because of physical effects resulting from the fact that the two openings differ in size, shape, elevation above the substratum or exposure to water currents or the wind. In the prairie-dog burrow (*a*) air flows from the lower, rounded "dome" mound to the higher, sharper-edged "crater" mound, providing needed ventilation. In the vertical burrow of the turret spider (*b*) air enters through the porous surface of the soil and exits through the elevated burrow opening, bringing up moist air that protects the animal from desiccation. The burrow of a marine worm (*c*) resembles the burrow of the prairie dog in that one opening is elevated above the substratum, inducing the flow of water through the channel. In a large flying beetle (*d*) the wind generated by the forward movement of the insect and the beating of the wings induces the flow of air through large tracheas (internal air pipes) that open directly to the outside, thereby enhancing supply of oxygen to the beetle's flight muscles.

sages like pistons, but as we shall see an energetically cheaper alternative is available.

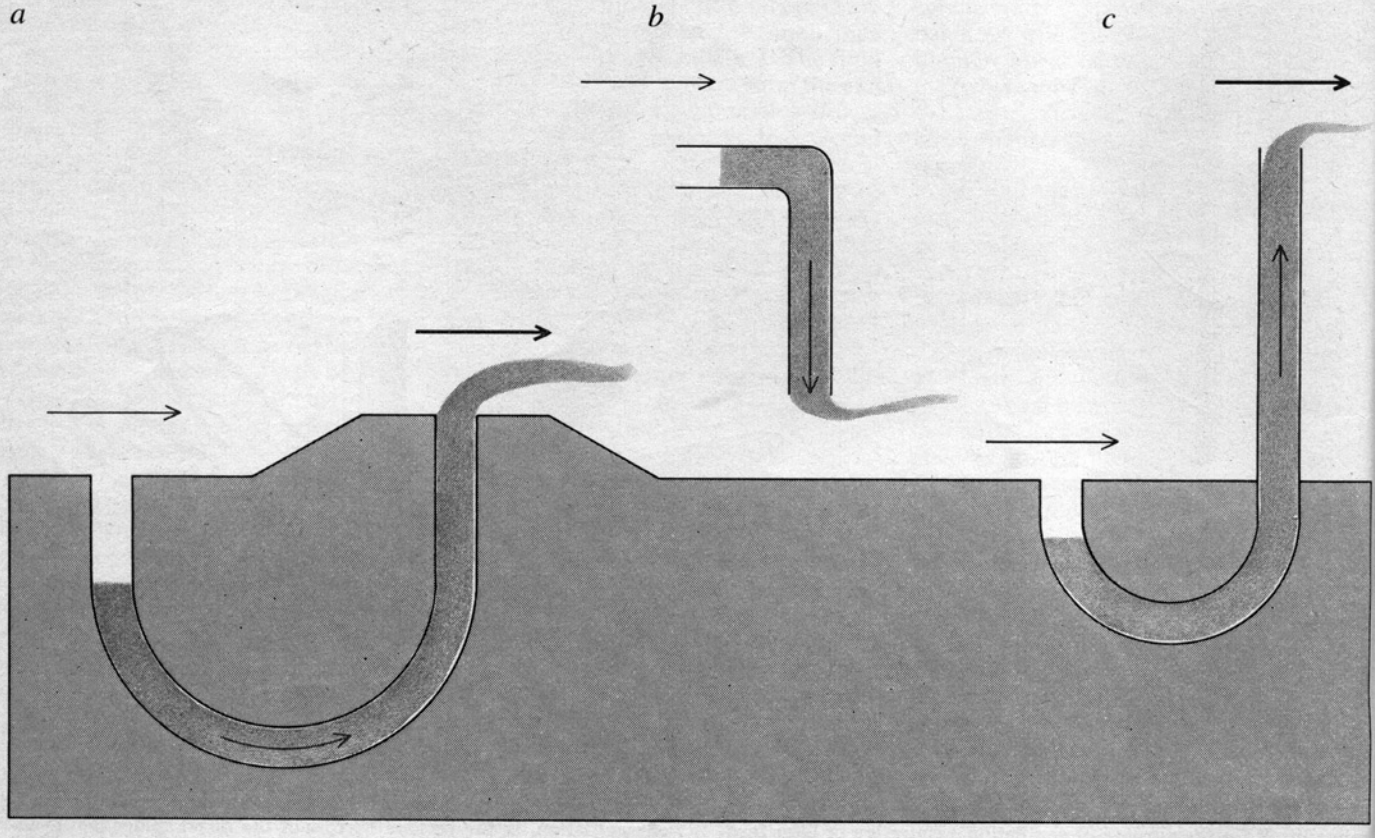
Each end of the prairie dog's burrow emerges in the center of a mound of dirt; such mounds are commonly regarded as lookouts or as protection from flash floods. Two types of mound are scattered through a town: a low, rounded "dome" mound and a higher, sharper-edged "crater" mound. The difference is clearly more than an accident of excavation, since after a rain the animals carefully rebuild the mounds, maintaining the distinction between them. Delbert L. Kilgore, Jr., of the University of Montana identified the openings of a given burrow by the simple expedient of forcing smoke down one hole and observing where it emerged. He found that a typical burrow has a crater mound at one end and a dome mound at the other.

The burrow of the prairie dog therefore meets the geometrical requirements of a Type I flow inducer. Does air actually flow through it? Kilgore dropped small smoke bombs into a few burrows and noted that whenever a breeze sprang up, a plume of smoke appeared above the end of the burrow with the higher crater mound. To test whether the Type I mechanism was involved Charles P. Ellington and I, working in my laboratory at Duke University, built a model burrow in which all the linear dimensions were reduced tenfold and tested the model in a wind tunnel at airspeeds 10 times higher than those expected in nature. (One change compensates for the other.) When scale models of the dome mound and the crater mound were added to the model burrow, it transmitted air in a manner indistinguishable from that of the real burrow. The effect was detectable in the wind tunnel at low wind speeds, indicating that even a barely perceptible breeze of about one mile per hour (.45 meter per second) over a real burrow should suffice to change the air inside about once every 10 minutes.

Measurements made with a series of different mound configurations on the model burrow demonstrated that flow could be induced by either a difference in height between the mounds or a difference in shape; in practice the two differences work in concert. The direction of the wind passing over the mounds did not alter the direction of induced airflow through the burrow. This finding makes "biological" sense: although wind is a dependable feature of the climate in Dodge City, Kans. (the closest Weather Bureau station to Kilgore's burrows), wind direction is notably variable.

Turret spiders (genus *Geolycosa*) construct single-opening vertical burrows in sand or porous soil on roadsides, in open fields and near ocean fronts. Over the entrance of the burrow is the "turret," a craterlike ring of sand, pebbles or bits of vegetation perhaps half an inch high, lined and laced together with silk. During the day the spider stays at the bottom of the burrow, a foot or so below the surface; at night it straddles the turret, poised to pounce on prey. This structure too is no mere accident of excavation: in addition to serving as a handy perch and as some insurance against inedible objects rolling into the burrow, the turret induces a flow of air through the tunnel. If a small flow-measuring device is inserted into the burrow and a second device is placed near the turret, recordings from the two are correlated: whenever a breeze crosses the turret, air moves upward in the burrow.

If the burrow has only one opening, where does the air come from? The an-



PHYSICAL EFFECTS are exploited by living organisms to induce the flow of fluid through some internal plumbing with a minimal expenditure of metabolic energy. According to the principle formulated by the mathematician Daniel Bernoulli, the pressure of a steadily moving fluid must decrease whenever its velocity increases so that its total energy remains constant. Thus in *a* flow will be induced in a *U*-shaped pipe if one end is elevated above the substratum because the velocity of the current there will be greater and the pressure accordingly lower. In *b*, a less direct consequence of Bernoulli's principle, flow is induced through the *L*-shaped pipe because the perpendicular opening is exposed only to the static pressure of the stream whereas the opening facing the current is also subjected to the dynamic pressure of the oncoming fluid. A third mechanism for inducing flow (*c*) is based on the viscosity (resistance to flow) of a fluid: the movement of a current past the opening of a pipe oriented perpendicularly to it will draw fluid out of the pipe, an effect known as viscous entrainment. In cases *a* and *c* the flow of air or water through pipe is induced in only one direction regardless of the direction of external current.

swer is that the surface of the sand or soil around the entrance serves as a second opening, because only very slight pressures easily generated by gentle winds are needed to draw air through the porous substratum in which the spiders live. Thus the turret-spider burrow matches the Type I model.

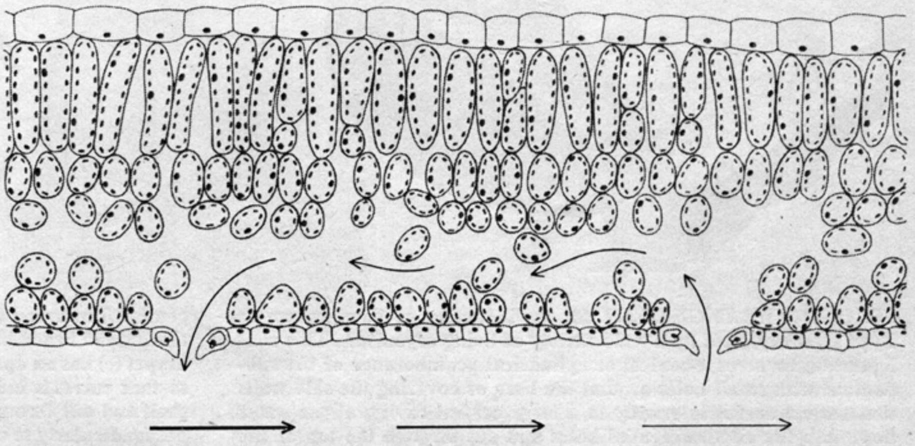
What is the functional significance of induced airflow for the spiders? Is it just a by-product of a turret built for another purpose or does it play a more direct role? Turret spiders live in what amount to local deserts, and since they have no regular access to standing water desiccation can be a serious problem. Even in a desert, however, the air between soil or sand particles is usually saturated with water only a few inches below the surface. A system for slowly drawing moist air into the burrow could enable the spider to spend its days in air of high humidity, thereby minimizing the loss of body fluid. In addition, as will not surprise anyone who has walked barefoot across sand on a relatively calm sunny day, the air in the upper part of the burrow can get very hot. A slow upward flow could prevent the penetration of hot surface air into the deeper part of the burrow.

On the ocean shore many intertidal mud flats are perforated with thousands of openings belonging to the double-ended burrows of marine invertebrates such as lugworms, clam worms and burrowing shrimps. Like the burrows of the prairie dog, these burrows have one opening elevated above the substratum, as can be demonstrated by injecting dye into one opening with a basting syringe and observing where the dye emerges. The worms, at least, will also excavate their burrow in buckets of mud in the laboratory. If they can then be persuaded to leave the burrow, the induction of flow through the burrow can easily be demonstrated; indeed, given the layout of the burrow, some special device would be needed to prevent the induction of flow when the water above the burrow is in motion.

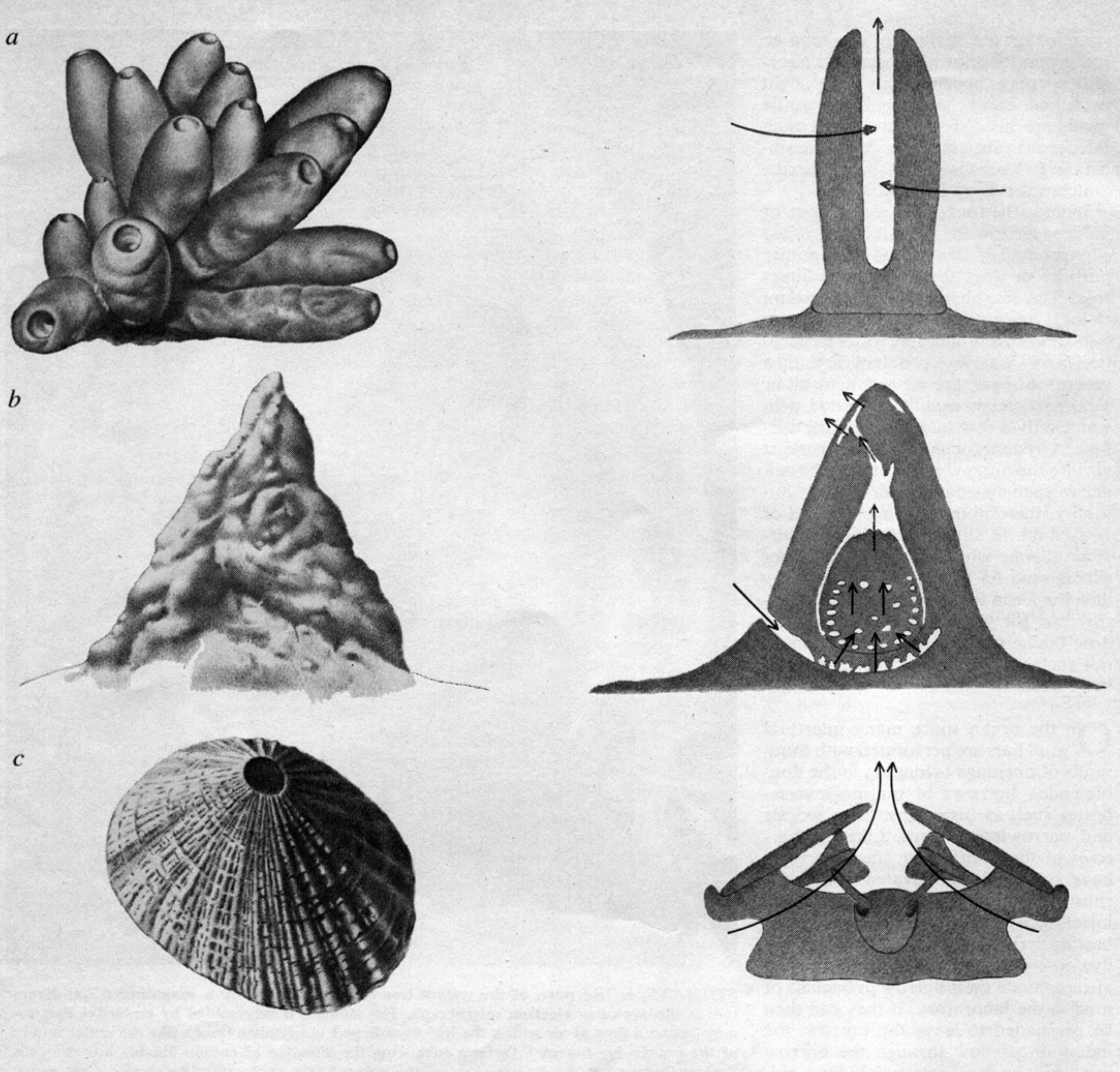
When a marine worm is in its burrow, however, its body plugs or nearly plugs the passage, and the worm displays a wide repertory of rhythmic pumping movements, raising the question of whether induced flow is significant under natural conditions. The worms can clearly sense external currents, but it is difficult to judge whether they are making use of the currents to augment their pumping. On the other hand, some of the burrowing shrimps are reported to leave the main tunnel of their burrow open, residing in a small side chamber after excavation is complete. Under such circumstances flow would certainly be induced and might serve to enhance the feeding and respiration of the animal.

An example of induced flow at the

STOMATE, or leaf pore, of the walnut tree *Pterocarya stenoptera* is magnified 6,700 diameters in this scanning electron micrograph. The stomate is surrounded by craterlike lips that may induce a flow of air within the leaf by a Type I mechanism (much like the crater mound of the prairie-dog burrow), thereby enhancing the diffusion of carbon dioxide into the cells. Perhaps because of the drying effect of the induced flow such craterlike stomates are generally limited to the leaves of hydrophytes (plant species that possess liberal supplies of water).



CROSS SECTION OF THE LEAF of a hydrophyte illustrates the induced flow of air through the continuous air passages that connect the stomates. Since the stomates near the upwind edge of the leaf are subjected to higher wind speeds than those farther from the edge, air should enter the stomates in the center of the leaf and exit through the stomates at the edge of the leaf.



SECOND ARRANGEMENT for the induction of flow, known as Type II, is exploited by a wide variety of living organisms. This configuration involves a conical or cylindrical protuberance of the substratum with small holes around the base or covering the side walls that are connected internally to a large central cavity; air or water flows into the circumferential holes and out through the top of the protuberance. Unlike the Type I system, the entire Type II system is located above the substratum. Marine sponges (*a*) exploit induced flow to increase the rate at which nutrient-rich ocean water passes through their filtration system. The giant mounds of African termites of the genus *Macrotermes* (*b*) induce the flow of air for the purpose of ventilating the brood chamber in the center of the mound. The keyhole limpet (*c*) has an opening, or "keyhole," at the apex of its conical shell so that currents induce a flow of water under the lower rim of the shell and out through the keyhole. The brachiopod (*d*) orients itself perpendicularly to a current so that water is forced into the sides of its gaping shells, passes through the filtration apparatus within and exits through the center of the gape. When the direction of the external current changes, brachiopod will rotate on its stalk in order to continue to benefit from the induced flow. This is its only known behavior.

microscopic level is provided by the stomates, or leaf pores, through which plants exchange gases. In certain hydrophytes (plants that have liberal supplies of water) the stomates are surrounded by craterlike lips and are interconnected within the leaf by continuous air passages. Ellington has proposed that the movement of wind across such a leaf might induce the flow of air into one stomate and out through another, since the stomates near the upwind edge of the leaf would be subjected to a higher wind speed than those farther from the edge. If the flow is induced by a mechanism of Type I, the stomates at the edge of the leaf should function as exit pores and those in the center as entrance pores. Observations of the flow of dye through leaves whose air passages have been filled with water indicate that such bulk flow does occur, although at rather low speeds.

A function for induced airflow within leaves is not hard to imagine. Green plants utilize carbon dioxide as their source of carbon for growth and energy storage, but this gas is only a minor constituent of the atmosphere, about one part in 3,000. In order for carbon dioxide to diffuse into a leaf there must be a still lower concentration of the gas inside it. A forced airflow, however, could circumvent this requirement. The fact that only the leaves of hydrophytes possess the crater-lipped stomates required for the induction of flow suggests that only plants with large supplies of water can tolerate the drying effect of induced airflow within their leaves. Reducing the phenomenon to quantitative terms has proved difficult, because the pores and passages of leaves are less than a tenth of a millimeter in diameter. For this reason the relative contribution of diffusion and induced flow to gas exchange in the leaves of hydrophytes remains to be determined.

What other biological applications of Type I flow induction might there be? Let me suggest a few possibilities. Insects in flight consume prodigious amounts of oxygen, which is supplied to their flight muscles through a set of tracheas, or air pipes, opening directly to the surface of the insect's body. In certain large flying beetles the wind generated by the beating of the wings and the forward motion of the insect has been shown to induce airflow through the thoracic tracheas. Flying birds also require rapid gas exchange and have evolved lungs through which air passes in only one direction. In the most advanced birds air capillaries loop off the fine passages of the lungs in such a way that induced flow enhances the diffusion of oxygen into the blood.

One species of kangaroo rat (*Dipodomys spectabilis*) of the American Southwest builds mounds several feet in diameter in the middle of cleared areas. Up to a dozen relatively large holes perforate the face of the mound; in passages radiating outward from the holes the rat stores supplies of seeds and other plant materials. The mound appears to function as a flow-inducing device to draw moist soil air into the passages and thereby increase the water content of the stored food, one of the kangaroo rat's few sources of water. Still other instances of induced flow may well be found in the diverse burrows of ants, wasps, rodents and moles and even (for water) in the nostrils of certain fishes. There is certainly no dearth of possibilities awaiting investigation.

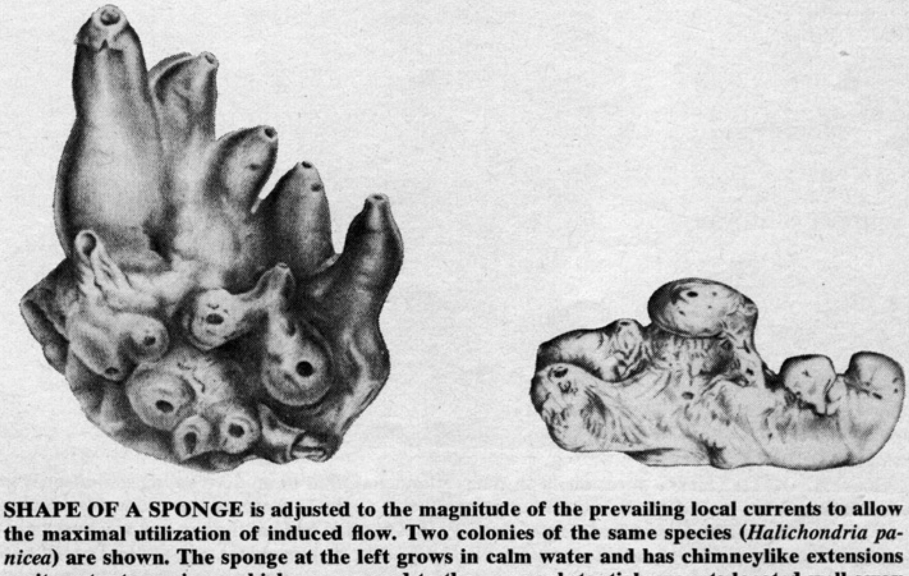
Another geometrical arrangement for inducing internal flow is called Type II. This configuration involves a conical or cylindrical protuberance of the substratum with small holes around the base or covering the side walls; the holes are connected internally to a large central cavity that opens to the outside at the top of the protuberance. Air or water flows into the circumferential holes and flows out at the top of the central cavity. Unlike the Type I system, the entire Type II system is above the substratum.

Marine sponges provide the best examples of the induction of flow by a Type II mechanism. Sponges make their living by passing enormous quantities of water through themselves (10,000 to 20,000 times their body volume per day) and filtering out microorganisms and other nutrient particles. Water enters through tiny holes in the animal's surface and is forcibly expelled through one or more large openings at the top of the animal. To the surprise of early investigators the flow is generated not by muscular action but by the uncoordinated beating of a very large number of tiny flagella.

According to many accounts, marine sponges prefer habitats in which the water is normally moving. Do they under certain circumstances derive benefit from induced flow while actively pumping with their flagella? To answer this question William L. Bretz of the Duke University Marine Laboratory and I built a cylindrical plastic model of a sponge with one large hole near the top and a ring of small holes near the base. When the water around the model was moving, water flowed into the small holes and out of the large hole just as if the "animal" were actively pumping.

At the Bermuda Biological Station I was able to record flow within and adjacent to eight species of sponges without removing them from their site of attachment or even touching them. In all cases any increase in the velocity of the current around the sponge was closely mirrored by an increase in the rate at which water passed through the sponge. Even local currents well below the pumping velocity of 10 to 20 centimeters per second were effective, and higher currents nearly doubled the flow rate. The advantage to a sponge of such augmentation of flow is obvious: filter feeding in most places is a marginal business, with the energy cost of processing water not far below the energy yield of the filtrate. Any device that increases the filtering rate without direct metabolic cost should therefore prove profitable.

Further investigation revealed that sponges, supposedly among the simplest of macroscopic animals, are exquisitely designed to take maximal advantage of induced flow. In most species



SHAPE OF A SPONGE is adjusted to the magnitude of the prevailing local currents to allow the maximal utilization of induced flow. Two colonies of the same species (*Halichondria panicea*) are shown. The sponge at the left grows in calm water and has chimneylike extensions on its output openings, which are exposed to the more substantial currents located well away from the substratum. The sponge at the right, on the other hand, grows on surfaces swept by fast-moving water and is therefore lower, more rounded and has smaller and less elaborate exit holes. The extreme plasticity of this sponge species increases its ecological versatility.

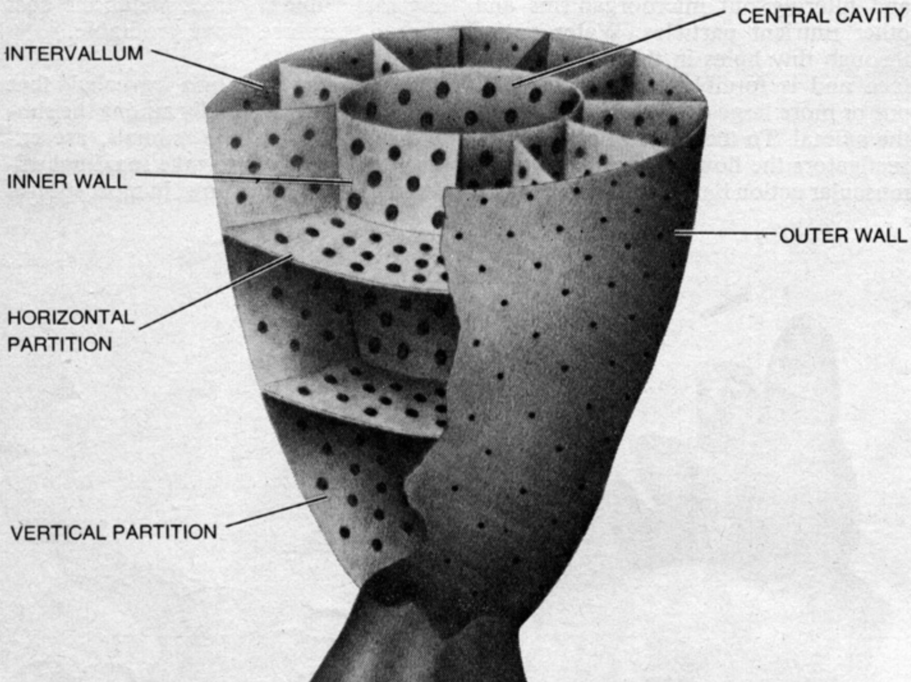
there is an open space just under the outer skin that allows water entering the upstream holes under the pressure of the current to enter the parts of the filtration system on the downstream side of the animal as well; a set of valves in the skin appears to prevent backflow where the pressure inside the animal is greater than that outside. As a result no matter what the direction of the current around a sponge is, the animal can take advantage of both the positive water pressure on its upstream entrance holes and the negative pressure at its exit holes.

Moreover, the very shape of sponges is adjusted to the magnitude of prevailing local currents in just the manner appropriate for maximal utilization of induced flow. Even within a single species individuals growing in relatively calm water are commonly taller and may have chimneylike extensions on their output openings; these arrangements expose the exit holes to the more substantial currents located well away from the substratum. In contrast, sponges of the same species that grow on surfaces swept by faster-moving water are lower, more rounded and have smaller and less elaborate exit holes. The extreme plasticity of the shape of sponges is therefore a remarkable strategy for increasing ecological versatility.

The archaeocyathids ("ancient cups") were a group of sessile animals that occupied a major portion of reefs during the Cambrian period, some 500 million years ago. Although nothing is known of their behavior or of the soft parts of their anatomy, the typical archaeocyathid was about four inches high, was shaped like a vase and had a central cavity that opened wide at the top and was surrounded by two concentric walls of calcified material. The outer wall was perforated by a large number of holes; the inner wall was also perforated, but the holes were larger. Archaeocyathids were probably filter feeders, and since their remains are found in coarse sediments they probably lived in moving water.

William L. Balsam of Brown University first pointed out that archaeocyathids were quite reasonably shaped to take advantage of induced flow, somewhat in the manner of their possible relatives the sponges. To test this hypothesis Balsam and I made an approximation of an archaeocyathid out of aluminum: a double-walled inverted cone with small holes in the outer wall and larger ones in the inner wall. When we tested the model in a flow tank, the model induced flow much more strongly than even the best sponge models. In effect it had a two-stage induction system: the external current not only drew water up out of the central cavity but also drove a large vortex in the cavity, which in turn drew more water through the holes in the inner wall.

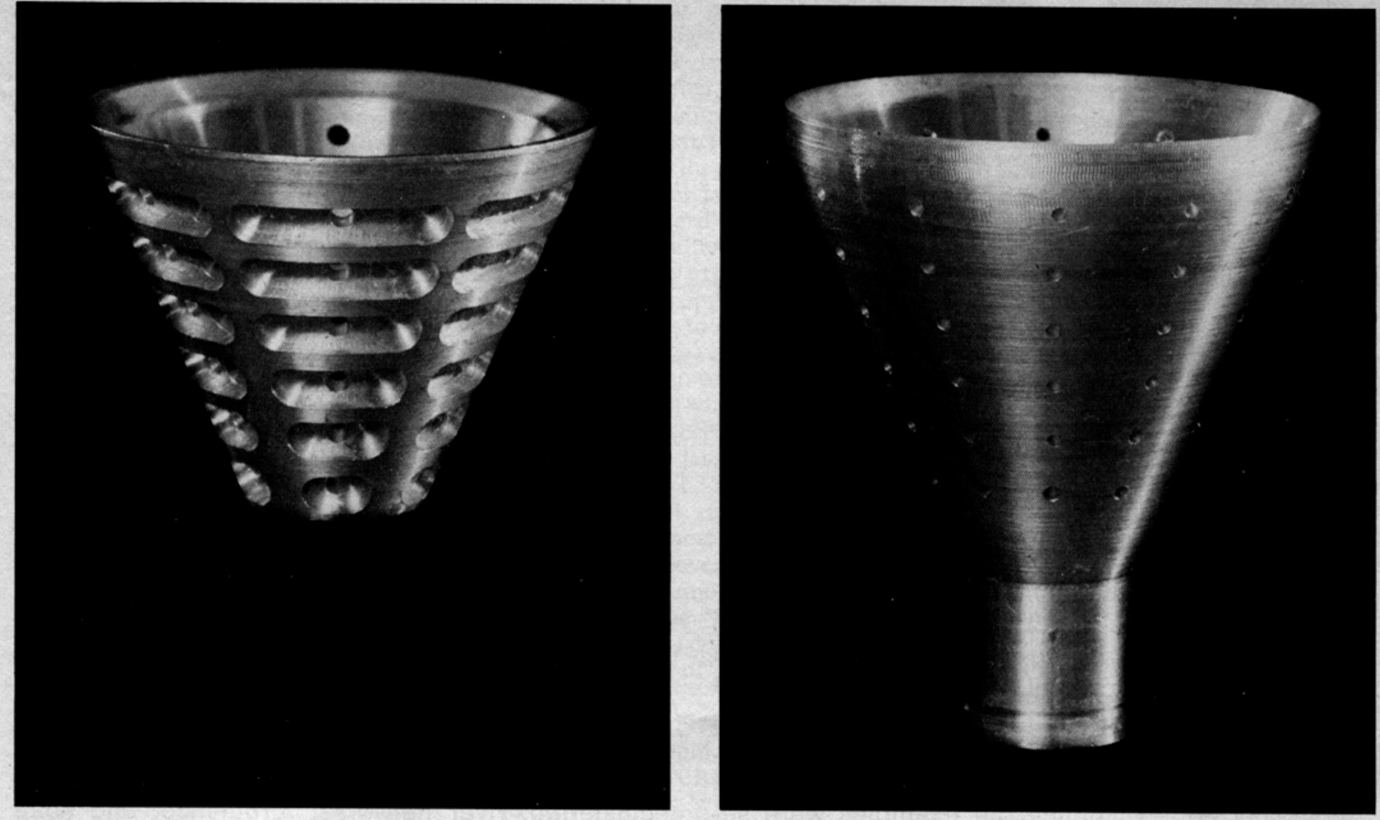
The contrast between sponges and archaeocyathids raises some interesting questions. Modern sponges that are the size of fossil archaeocyathids have a more constricted exit opening, a feature that reduces the efficiency of flow induction but acts as a nozzle to increase output speed and lessen the chance that when outside currents are slow, the sponge will simply be reingesting water it has already filtered. If the archaeocyathid lacked a metabolically powered pump, then it could filter feed only in the presence of an external current and thus would never have confronted the problem of reingesting already filtered water. Is the wide opening of the central cavity of the archaeocyathid evidence that it lacked an active pump? If it is, then perhaps these primitive animals were more completely dependent on currents than sponges are, a lack of behavioral flexibility that may ultimately have contributed to their extinction. A corollary of this hypothesis is that flow induction in macroscopic filter feeders may be a device more ancient than metabolically driven pumping.



ARCHAEOCYATHIDS were sessile animals, somewhat akin to modern sponges, that thrived in the Cambrian period some 500 million years ago. A typical specimen was about four inches high, was shaped like a vase, had a central cavity that opened wide at the top and was surrounded by concentric walls of calcified material held together by horizontal and vertical partitions. The walls were perforated by a large number of holes whose diameter increased from the outer wall to the inner one. Archaeocyathids were almost certainly filter feeders, and because their fossil remains are found in coarse sediments they appear to have lived in moving water. It seems likely that they used the Type II mechanism to enhance the flow of water through themselves.

The giant mounds of certain African termites (genus *Macrotermes*) combine the ventilation problem of the prairie-dog burrow with the geometry of the marine sponges. Millions of termites together with their associated fungi may live in a mound as much as 16 feet high; their substantial demand for oxygen makes some kind of ventilation system essential. In some mounds found in forests the heat generated in the central brood chamber drives a convective air current up through the middle of the mound and down through peripheral passages located just under the outer walls [see "Air-conditioned Termite Nests," by Martin Lüscher; SCIENTIFIC AMERICAN, July, 1961]. In other mounds found in more open country, however, the peripheral passages are replaced by porous-walled tunnels around the base of the mound and in a turret at the top. According to R. Loos of the National University of Zaire, in such mounds the convective flow of air is augmented by a wind-driven component, apparently another instance of the induction of flow by a Type II system.

A different species of African termite builds mounds equipped with large, funnel-shaped holes that are connected with the network of passages within and under the mound. John S. Weir of the University of New England in Australia found that air entered such mounds through holes without rims around the periphery of the mound and exited through holes with rims near the top. Some holes on the sides of the mound could act as either entrances or exits, depending on the direction of the wind, but on the whole the airflow inside the



MODEL OF AN ARCHAEOCYATHID was made out of aluminum by William L. Balsam and the author at Duke University to enable them to test whether the animal was the right shape to take advantage of induced flow. In the assembled model the cone at the left fits snugly into cone at the right when they are fastened with a screw through their apexes. Two small holes in the outer wall communicate with one larger hole in the inner wall through the grooves in the surface of smaller cone. Model is seven centimeters high and five wide.

INDUCED FLOW through the model archaeocyathid is demonstrated in a flow tank by injecting dye near the outside pores. The external current draws the dye into the upstream pores and out through the central cavity, as is shown in this photograph. A vortex in the central cavity is also created that draws more water through the holes in the inner wall. The efficiency of this two-stage flow induction suggests that the archaeocyathid exploited external currents for filter feeding. Indeed, the animal may have been totally dependent on induced flow.

mound was unidirectional, as it is in other Type II systems.

Keyhole limpets are a family of marine mollusks in the same class as snails, but instead of being coiled-up cones they are squat and uncoiled: they are two or three times as broad as they are high and an inch or two in overall length. They make their living by scraping algae from the rocks of the intertidal or subtidal zone. Keyhole limpets differ from other species of limpet in that they have an opening, or "keyhole," at the apex of their cone. John Markham of the Bermuda Biological Station first suggested that keyhole limpets might make use of flow induction, and Gordon R. Murdock of Duke later found that the flow of water through the mollusk, from the lower rim of the shell to the hole at the apex, was faster when the surrounding water was in motion. Moreover, some of the limpets oriented themselves to face an oncoming current and partly withdrew their gills to allow an even faster flow of water through themselves. The function of such induced flow in the keyhole limpet is unclear; the animals are not filter feeders and live in well-oxygenated water, so that little metabolic energy is required to satisfy their modest respiratory needs. Still, gills do take up space, and induced flow might confer a real selective advantage if, for example, it made it possible for the animal to have smaller gills and larger ovaries or testes.

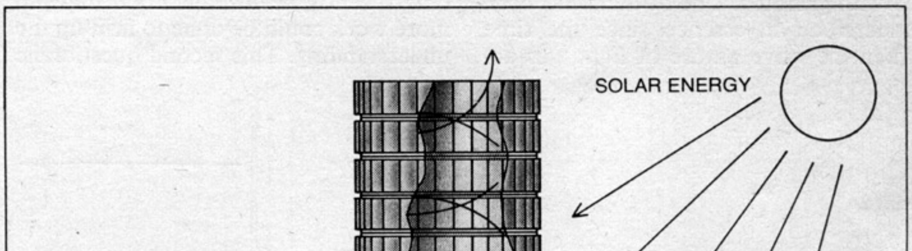
The brachiopods are another group of marine invertebrates. Although they were enormously abundant in Paleozoic seas, some 300 to 500 million years ago, only a few hundred species now remain. At first glance brachiopods resemble clams, but their hinged shells form the anatomical top and bottom of the animal rather than the left and right halves. The shells gape at one edge, revealing an elaborate filtration apparatus within. Water leaves the filter at the center of the gape and enters on each side.

Michael C. LaBarbera of the University of Chicago investigated several species of brachiopod that are attached by a stalk to subtidal rocks. He observed that the animals rotated on their stalk so that the widest central portion of the gape was oriented perpendicularly to the fastest flow of current, with the sides of the gape exposed to lower speeds. In this orientation the circulation of water through the filtration system was enhanced by flow induction. A change in the direction of the current resulted in a shift in the animal's orientation, so that it continued to benefit from the induced flow. These findings contradicted the widespread assumption that brachiopods possessed little in the way of sensory equipment or overt behavior, since current flow as an environmental stimulus had been overlooked by earlier investigators. Organisms care about flow, and biologists should too.

Undoubtedly the most elegant and sophisticated biological exploitation of an environmental velocity difference does not fit into either Type I or Type II but should not go unmentioned. Certain birds practice what is called dynamic soaring, in which they are able to stay aloft without either beating their wings or having an upward current of the air around them. By alternately diving and climbing they are exposed to different wind speeds and from the difference can extract the energy to remain aloft.

Human beings have also learned to extract energy from velocity differences. The operation of windmills, carburetors, chimneys and certain types of ventilators depends at least in part on flow induction. James T. Yen of the Grumman Corporation recently devised a wind-energy extractor that avoids the long blades of conventional windmills; his device bears some functional resemblance to a sponge. The traditional architecture of many cultures also exploits the induced flow of air for heating or cooling purposes. Sydney A. Baggs of the University of New South Wales has pointed out that opal miners in the Australian outback often ventilate their dugout dwellings with a wind-driven system resembling that of the prairie-dog burrow. The tepees of the American Indians of the Great Plains are conical structures with a porous lower edge and an opening near the top that induce flow by the Type II mechanism; such structures are naturally well ventilated and are both comfortable in the heat of summer and capable of containing a fire in winter without asphyxiating the inhabitants. The traditional architecture of the Middle East provides some even more sophisticated examples of cooling by flow induction [see "Passive Cooling Systems in Iranian Architecture," by Mehdi N. Bahadori; SCIENTIFIC AMERICAN, February].

What conclusions can be drawn from this excursion into what might be called experimental natural history? One important point is that careful and imaginative consideration of the physical world is imperative when investigating the adaptive strategies of living organisms. The particular physical opportunities as well as the constraints under which an organism lives must be appreciated. Moreover, the biologist should hesitate to invoke explanations of phenomena that require the expenditure of chemical energy until simpler physical mechanisms have been ruled out. In matters of energy nature seems to love a bargain.



WIND-ENERGY EXTRACTOR designed by James T. Yen of the Grumman Corporation avoids the long blades of conventional windmills; instead it exploits Type II flow induction much as a sponge does. Convective hot-air currents from solar heating or the burning of fuel, together with the currents induced by the wind, drive a central turbine to generate electricity.