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Patterns in Nature

The new focus on self-organizing processes links such diverse natural phenomena as a zebra's stripes and a mound of termites.

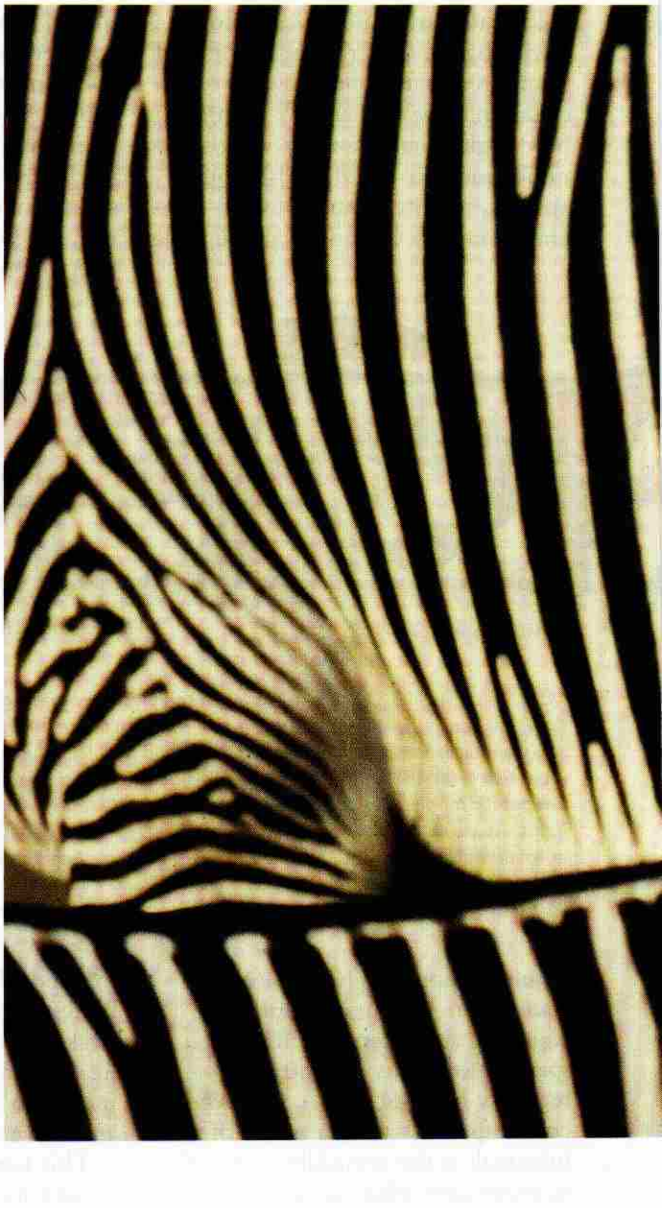
By Scott Camazine

The natural world abounds in eye-catching patterns. Consider the synchronized movements of a school of fish gliding through deep ocean waters; or the coordinated turns and swoops of a flock of starlings whirling among tall trees before coming to rest on a telephone wire. How do all the individuals in the school or the flock avoid collisions with their neighbors? How do they orchestrate their graceful movements?

Other patterns in nature are just as dynamic, but develop so slowly that they appear as snapshots to the human eye: a brief, static moment in a biological process. Think of the striking regularity of alternating light and dark stripes on a zebra's coat, or the reticulations on the surface of the fruiting body of a morel mushroom. Zooming in for a close-up of a slime mold, you can observe the branching network patterns that emerge as the mold grows. On a still smaller scale, magnified several hundred times, similar patterns emerge on the surface of a pollen grain. Intricate reticulated patterns appear in the passageways of the fungus gardens of African termite colonies, and in the crisscrossing trails of foraging army ants.

The living world is filled with striped and mottled patterns of contrasting colors; with sculptural equivalents of those patterns realized as surface crests and troughs; with patterns of organization and behavior even among individual organisms. People have long been tempted to find some obscure "intelligence" behind all these biological patterns. In the early twentieth century the Belgian Symbolist playwright Maurice Maeterlinck, pondering the efficient organization of bee and termite colonies, asked:

> What is it that governs here? What is it that issues orders, foresees the future, elaborates plans and preserves equilibrium, administers, and condemns to death?



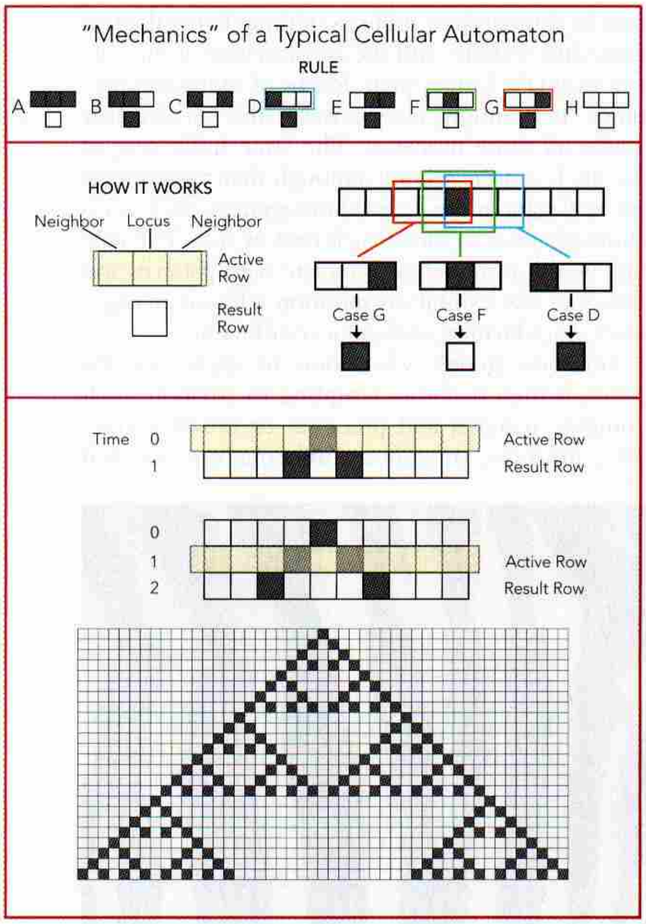
The biblical songwriter in Proverbs marvels at the same phenomenon among the ants, though, more wisely than Maeterlinck, resists the temptation to invoke an intelligent ant:

> Go to the ant thou sluggard; consider her ways, and be wise,
> Which having no guide, overseer, or ruler,
> Provideth her meat in the summer, and gathereth her food in the harvest. (*Prv.* 6: 6–8)

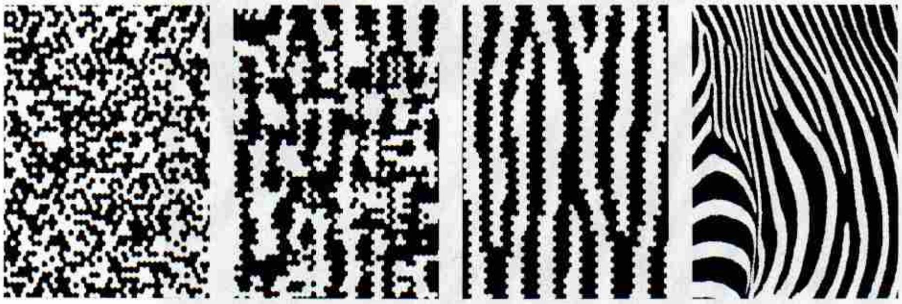
In this instance, science agrees with the Old Testament. Do ants or, for that matter, termite mounds, flocks of birds, or schools of fish have leaders that all the members of the group follow? The answer is, clearly, no. Imagine the kind of oversight that would be needed to build a termite mound. The mound may be thousands or millions of times larger than an individual termite, and the construction of the edifice may take longer than dozens of individual lifetimes. It is simply inconceivable that an overseer guides all those processes. The same holds true of the flock and the school: although their movements are as elegant as the finest choreography, there is no choreographer to direct each bird or fish. The natural world, it turns out, is replete with patterns and processes that exhibit organization without an organizer, coordination without a coordinator.

For some people who come to appreciate this point, it then becomes tempting to attribute such complex patterns and processes to innate behaviors, instincts, or genetic information encoded

Striped markings on the coats of zebras exhibit the kinds of patterns that occur throughout nature, which can be described by simple mathematical tools.



Operation of a cellular automaton is easiest to demonstrate in its one-dimensional form. From a given initial state (row of white or black squares at time 0), a rule specifies how the color of each cell for each of an indefinite number of subsequent ticks of a clock depends only on the colors of a fixed group of neighboring cells; the rule simply itemizes the possibilities. If each step in the evolution is portrayed as a new row of cells, the result, which depends both on the rule and the initial state of the line of cells, is a two-dimensional grid that can simulate a wide range of patterns in nature. The intricate, nested pattern at the bottom of the diagram is the result of applying the rule over the course of twenty-three steps.



Zebra skin markings are simulated here by a two-dimensional cellular automaton, from an initial, random distribution of black and white cells (far left). Even with the first tick of the clock a pattern begins to appear (second from left). At the tenth tick of the clock, a stable pattern emerges (third from left), which is quite similar to an actual zebra coat (far right).

deep within the chromosomes of the organism. But such "simple explanations" are not likely and, in the best of cases, they merely sweep the question under the carpet. What then is the origin of all this stunning complexity?

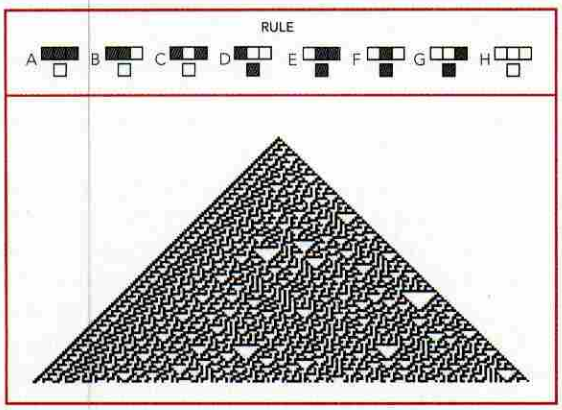
I have always been fascinated by the natural world, by the strange and complex creatures that inhabit it. As a child, I was drawn to small animals and insects and delighted in their diversity and behaviors. My curiosity took the form of carefully labeled collections of minerals, pressed flowers, feathers, and pinned insects, each specimen with a shape and pattern all its own. I often wondered how such patterns arose, but never found an explanation. Looking back, I think part of the difficulty was that people didn't have the tools needed to explore the question.

In the past several decades, however, a rich convergence of insight has come from a wide range of scientific disciplines, including biology, chemistry, computer science, mathematics, and physics. Out of that mix the field of complex systems emerged. I have followed the exciting developments in this field as a research biologist, physician and photographer.

In the years since my childhood, those who study complex systems have learned that many natural patterns share a similar mechanism of formation called self-organization. Self-organization refers to a wide range of processes in both living and nonliving systems. Those processes are characterized by simple "rules" that depend solely on local interactions among the subunits of the system. Yet despite their simplicity and the local range of their immediate effects, the rules and their actions on the subunits give rise to the spontaneous emergence of pattern, order, and structure on a global, system-wide scale.

To put the matter a slightly different way, in a self-organizing system order is not imposed from the outside, by external influences. No architect or foreman holds the blueprint or has a preconceived idea about what patterns will evolve. The patterns that arise are emergent properties, properties that cannot be predicted simply by examining the subunits in isolation. To understand them, the dynamic and often remarkably complex interactions among the subunits must be taken into account.

Think about the concentric pattern of honey, pollen, and brood that arises on the honey combs of a beehive. Thousands of bees contin-



Entirely different and unpredictable pattern arises as a result of applying a different rule (top of diagram) to the same initial state used in the upper illustration on the opposite page.

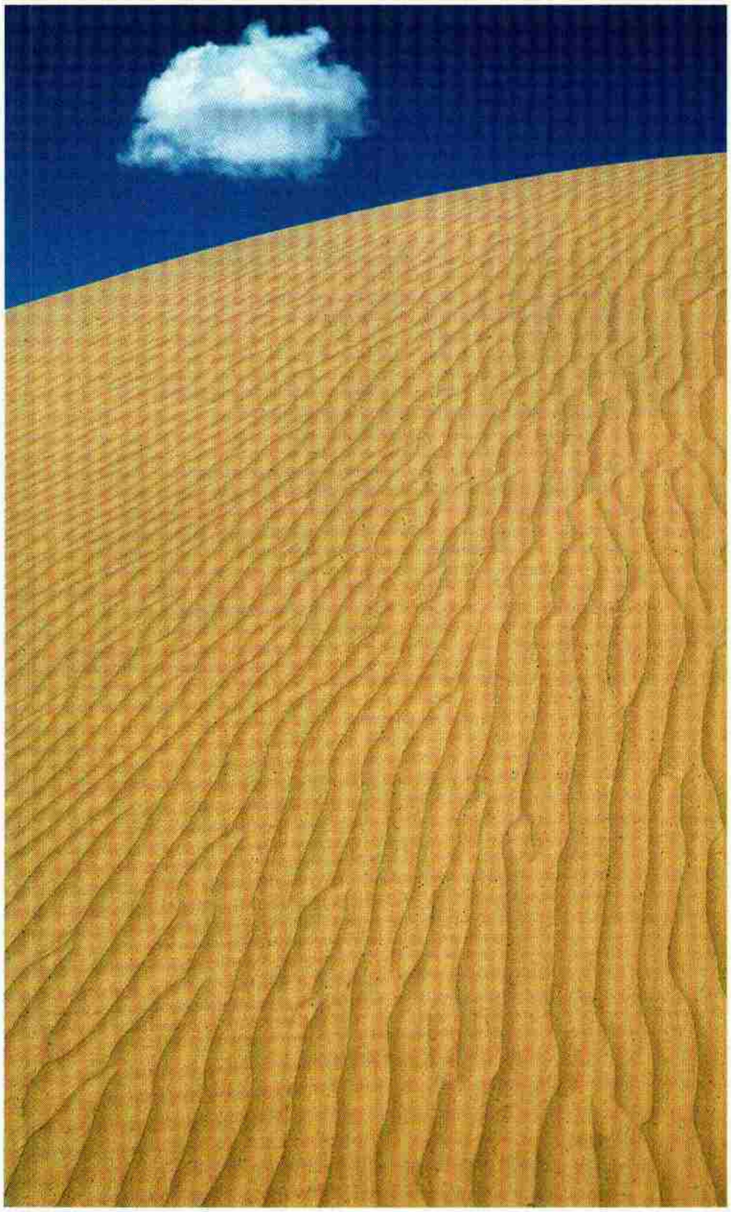
ually and simultaneously contribute to the emerging pattern: workers from the field bring in honey and pollen throughout the day; other workers consume the honey and pollen and feed it to the brood; the queen wanders over the combs looking for cells in which to place her eggs; the eggs hatch, become larvae, and finally vacate the cells when they pupate and develop into adults. My research has shown that the bees do not have special "designated" places to put the honey, pollen, and eggs. Instead, they conform to a simple set of what we call rules that guide their behaviors. Nevertheless, the dynamic interactions among all the bees result in the spontaneous emergence of a consistent, stable pattern.

Unfortunately the human mind is poor at predicting what happens when hundreds or thousands of "things" interact with one another, even if the interactions themselves are quite simple. Computers, however, are ideally suited to such a task. One tool for simulating self-organized pattern formation is readily implemented with computer software; the tool is called a cellular automaton, and the patterns that emerge, even from what seem to be the most trivial rules, make a highly convincing rationale for exploring the properties of automata.

One of the first cellular automata to be studied in any depth was the so-called game of life, devised by the mathematician John Horton Conway, now of Princeton University, and popularized by the writer Martin Gardner is his "Mathematical Games" column for *Scientific American* magazine in October 1970.

To understand how the game of life works, imagine a huge grid of squares, entirely covered by checkers, or cells, that are either black or white, "alive" or "dead." Each cell is surrounded by eight neighboring cells whose squares share an edge or a corner with the square occupied by the original cell. A clock ticks the time, and with each tick, the state of each cell on the entire grid evolves to its next state in accord with four simple rules:

1. A live cell surrounded by two or three live cells at time t will also be alive at the next clock tick, time $t + 1$ (it survives).
2. A live cell with no live neighbors or only one live neighbor at time t will be dead at time $t + 1$ (it dies of loneliness).
3. A live cell with four or more live neighbors at time t



Wide range of patterns in nature can be simulated by surprisingly simple rules. Here and on succeeding pages is a gallery of photographs suggesting the variety. Above, wind-blown ripples develop on the surface of the sand in the Gobi desert, in Mongolia.

will be dead at time $t + 1$ (it dies of overcrowding).

4. A dead cell surrounded by three live cells at time t will be alive at time $t + 1$ (it will be born); otherwise, a dead cell remains dead.

When the rules are applied to some initial configuration of live and dead cells (at, say, time $t = 0$), the pattern that arises at time $t = 1$ can be quite unexpected. Moreover, if the same rules are applied to the new patterns of live and dead cells that result at times $t = 1$, $t = 2$, $t = 3$, and so forth, the patterns that evolve over time can be entirely unpredictable. In other words, for some initial patterns, the only way to determine how they evolve under the rules is to watch them.

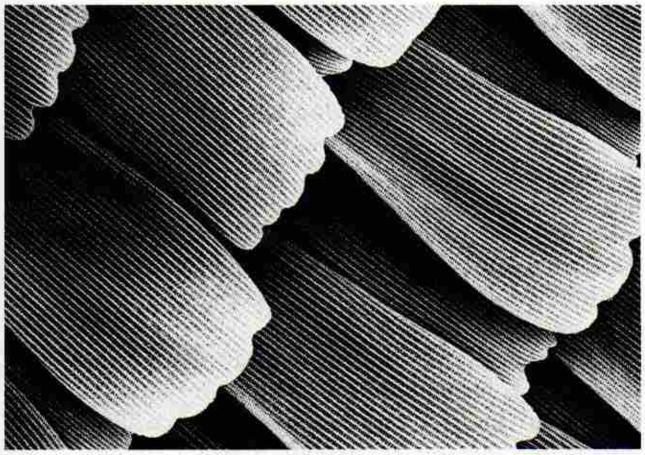
To better understand how such a program works, consider an even simpler version of a cellular automaton. This one begins not with an entire checkerboard of cells (a "two-dimensional" cellular automaton), but instead with just a single row (a "one-dimensional" automaton). In other words, start with a horizontal row of square cells that extends indefinitely far to the left and right. As in the game of life, each cell is colored either black or white. The neighborhood of each cell in the row includes just the two adjoining cells, one to its left and one to its right. And again, as in the game of life, with each tick of a clock, the color, or state, of each cell in the row changes according to some simple rule.

For example, one rule might be the following: a cell becomes black on the next tick of the clock whenever one or the other, but not both, of its neighbors are black; otherwise it remains (or becomes) white [*see upper illustration on page 36*]. A one-dimensional cellular automaton has the advantage that successive patterns can be represented as successive horizontal rows, the "successor" pattern just under its predecessor. The pattern that results is a two-dimensional grid of cells that portrays the evolution of the top row throughout all the ticks of the clock.

Suppose the initial row of cells has a single black cell in the center. When the rule I just defined is applied to that row—the active row—and then to the subsequent rows, a complex pattern develops that is shown at the bottom of the illustration. Applying another rule to the same initial pattern would give rise to an entirely different set of successive rows [*see upper illustration on preceding page*].

It is difficult to convey the intricacy and dynamism of even the simplest cellular automaton with a verbal description or even with static diagrams. Curious readers can visit Web sites where they will be able to watch "home movies" of cellular automata as they evolve:

Yellow morel, black morel, and half-free morel



Scales on the wing of a painted lady butterfly, x400

www.radicaleye.com/lifepage
www.math.com/students/wonders/life/life.html

To see bird flocking simulations visit
www.red3d.com/cwr/boids/

Also visit StarLogo at these three sites:
education.mit.edu/starlogo/
www.kasprzyk.demon.co.uk/www/ALHome.html
lachlan.bluehaze.com.au/alife.html

As with all self-organizing patterns, the main feature of cellular automata is that they are based on a simple set of rules, and they use only local information to determine how a particular subunit evolves. But programs such as the game of life or the one-dimensional cellular automaton just described, while suggestive, lack direct biological relevance. If rules are to be useful for understanding the patterns in real life, such as the stripes of a zebra's coat, they must be different rules.

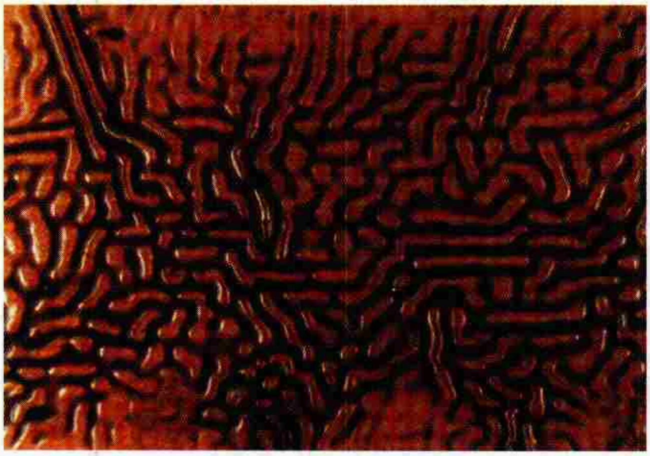
The zebra's coat alternates in contrasting areas of light and dark pigmentation. In technical jargon, the pigmentation reflects patterns of activation and inhibition—apt terms because of the dynamic process that generates the pattern. Cells in the skin called melanocytes produce melanin pigments, which are passed into the growing hairs of the zebra. Whether or not a melanocyte produces its pigment appears to be determined by the presence or absence of certain chemical activators in the skin during early embryonic development. Hence the pattern of the zebra's coat reflects the early interaction of those chemicals as they diffused through the embryonic skin.

With a new set of rules, a two-dimensional cellular automaton can readily simulate the pattern of the coat and so shed light on the mechanism of pattern formation in the zebra. Return to the square grid and randomly place a black cell or a white cell on each square. The grid will look something like the leftmost frame of the lower illustration on page 36. Assume that each black cell represents a certain minimum level of pigment activator. Such a random array of activator or its absence is thought to be the starting point for the early development of coat patterns.

Now apply another simple rule, based on the following underlying physical effect: activator molecules that are near each other strengthen and mutually reinforce their effect. At the same time, they diminish the effect of activators that are farther away, inhibiting their ability to activate their own nearby neighbors.

In this example, as in the game of life, each cell can be either on or off, black or white. And again, with each tick of the clock, the cells interact with one another according to a rule that reflects the underlying physical reinforcements and inhibitions, and switch their states appropriately. As the regions of activator compete with one another through their local interactions, a regular pattern develops. What emerges is a self-organizing pattern that looks very much like the skin of the zebra [*see the remaining three frames of the lower illustration on page 36*].

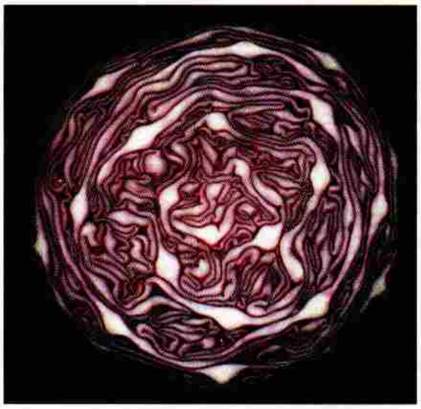
Similar patterns occur in the brain. As the embryonic brain develops, competing influences from the right and left eye determine where connections are made in the back of the brain, the visual cortex. Clusters of neurons from one eye or the other dominate portions of the cortex in a distinct pattern. The pattern is thought to develop because the neurons from each eye compete with one another for space. Initially, the neuronal projections coming from the left or right eye are slightly different, a difference that presumably arises at random. The rules of the competition have the same general form as the rules of activation and inhibition of zebra coat pigment. Projections of the neurons from one eye stimulate and encourage additional projections from the same eye. At the same time, those projections inhibit the development of projections to that area from the other eye. This local competition for real estate in the brain results in a pattern of stripes reminiscent of those of the zebra.



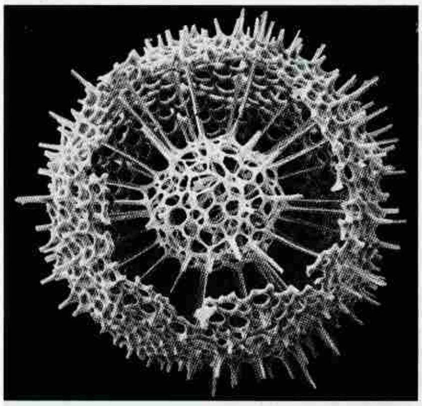
Wrinkle pattern formed by a coat of varnish on a wooden surface

Plasmodial slime mold (Physarum polycephalum) *growing on a leaf.*

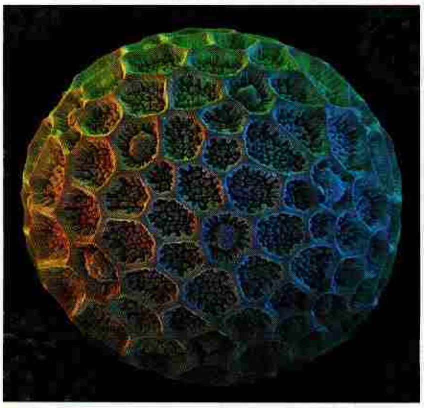
Self-organizing patterns extend to the nonliving world as well. They appear in mineral deposits between layers of sedimentary rock, in the path of a lightning bolt as it crashes to the ground, in the undulating ripples of windblown sand on a desert dune. When the forces of wind, gravity, and friction act on sand dunes, the innumerable grains of sand ricochet and tumble. As one grain lands, it affects the position of other grains, blocking the wind or occupying a site where another grain might have landed. Depending on the speed of the wind and the sizes and shapes of the grains of sand, this dynamic process creates a regular pattern of stripes or ripples.



Cabbage



Radiolarian, x120



Polygonum pollen grain, x900

Similar patterns arise accidentally on painted surfaces exposed to harsh weather. Paints and varnishes are designed, of course, to adhere permanently and evenly to a surface. Nevertheless, heat, moisture, and sunlight often combine to lift the paint off the underlying surface, causing the paint to crack or buckle. As a patch of paint begins to pull away from the surface, a dynamic tension—between the forces causing the paint to buckle and wrinkle and the adhesive force between the paint and the surface—develops at that spot. The more paint that pulls away, the weaker the adhesive force exerted by the paint nearby that is still sticking to the surface.

The result is a runaway situation but with a countervailing effect. At some point, the dynamic tensions begin to split the paint that has already pulled away. Once that happens, the tensions on the paint far from the split, still adhering to the surface, are reduced. The result is a pattern of buckling ridges.

The runaway process and its countervailing effect, so prominent in the example of the paint, are also key parts of the way patterns form in zebra fur and in sand. The runaway process is also called positive feedback: just as in a snowball rolling down a hill, more leads to even more. In the zebra, an elevated level of activator in the skin leads to more activation nearby, and so to the production of even more melanin pigment. Sand dunes develop ridges when the wind deposits a chance accumulation of sand grains. One small, almost insignificant ridge becomes amplified because it acts as a barrier, promoting the accumulation of even more grains of sand on the windward side of the ridge.

But if positive feedback operated alone and unchecked, there would be no pattern. The zebra would be entirely black; the sand dune would have no ridges. What comes into play is a second kind of process called negative feedback, in which more leads to less. Negative feedback puts the brakes on processes with positive feedback, shaping them so as to create a pattern. The presence of an activator in the zebra skin inhibits pigment production in nonadjacent skin patches and the zebra ends up as a mixture of black and white. (A similar mechanism may also explain the uniform coat of spots in a leopard, formed from islands of high activation.)

Self-organized patterns often arise in living systems because evolutionary processes can build the patterns so economically. The location and branching of each and every marking of a zebra need not be explicitly specified by the limited genetic information carried by DNA. Instead, all that needs to be genetically coded are the characteristics of the interacting molecules. Those characteristics determine just how the molecules act upon one another—what we interpreted as the "rules" that govern the positive and negative feedback processes of the underlying activators that are distributed across the embryonic zebra's skin.

A second economy is an explanatory one: there is no need to invoke a different process to explain each of the many different striped and spotted patterns that occur on the surfaces of mammals, fish, and insects. All such patterns arise through similar developmental pathways. A particular pattern simply emerges from the ways in which certain substances activate or inhibit one another's effects on the formation of pigment.

In nonbiological physical systems, self-organized patterns are epiphenomena that have no adaptive significance. There is no driving force that pushes cloud formations, mud cracks, irregularities in painted surfaces, or spiral waves in certain chemical reactions into developing the striking patterns they exhibit.

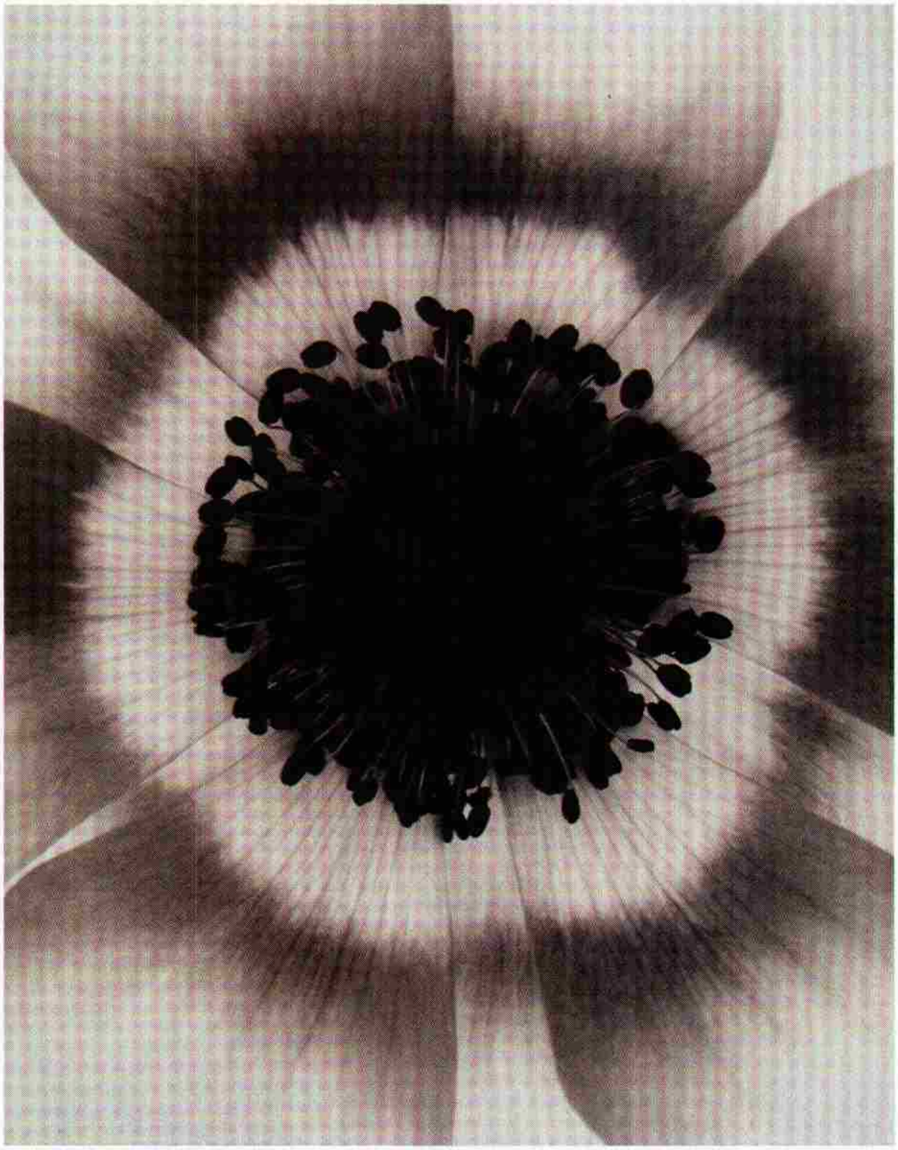
In biological systems, however, natural selection can act to favor certain patterns. The particular chemicals within the skin of the developing zebra diffuse and react in such a way as to consistently produce stripes. If the properties of the zebra skin, or the composition of the chemical activators, were even slightly different from what they are, a pattern would not develop. But in the course of evolution, the specific properties that result in precisely the kind of stripes that zebras possess were selected for and have persisted. One advantage of this pattern of disruptive coloration seems to be an effective adaptation to the presence of biting flies. The visual system of the tsetse fly is particularly sensitive to large blocks of contrasting color. A large black animal on a background of uniformly light-brown savannah is more easily recognized as a potential meal than is a pattern of fine black-and-white stripes.

Zebras' coats are just one example of the adaptive advantage of self-organized patterns. Such patterns also come into play on the folded, reticulated surface of the morel mushroom or on the lining of the stomach. In both those cases, the large surface area, a consequence of the folding, is an advantage: for producing spores in the first case, or for absorbing nutrients in the second.

Yet not all patterns that occur in nature arise through self-organization. A weaver bird uses its own body as a template as it builds the hemispherical egg chamber of its nest. A spider creates its sticky orb following a genetically determined recipe for laying out the various radii and spirals of the web. A caddisfly larva builds an intricate hideaway from grains of sand or other debris carefully fastened together with silk. In those cases, the building of structures does indeed involve a little architect that oversees and imposes order and pattern. There are no "subunits" that interact with one another to generate a pattern; instead, each of the animals acts like a stonemason, measuring, fitting, and moving pieces into place.

Finally, what about the graceful movements of birds and fish? Do they depend on leaders, or are they, too, system subunits that "follow rules" and that move gracefully despite the absence of any leaders to guide the group. Coordinated flocking appears to rely on three behavioral rules for maintaining separation, alignment, and cohesion of flock-mates: steer to avoid crowding or colliding with nearby birds; maintain the average heading of nearby birds; and move toward the average position of nearby birds. Fishes' rules are similar, and they suffice to describe the phenomenon.

It is not easy for human beings to intuit how such a decentralized mode of operation can function so efficiently, because human groups rely so heavily on hierarchical organization. Executive functioning, planning, and decision-making exist at many levels of the hierarchy. Imagine a world without supervisors, administrators, and managers, and many people would imagine sheer chaos. Nevertheless, self-organization in nature is efficient, economical, and ubiquitous. It is one of the least known, yet most powerful, devices for achieving pattern and order in the world. ☐



Windflower, Anemone coronaria

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