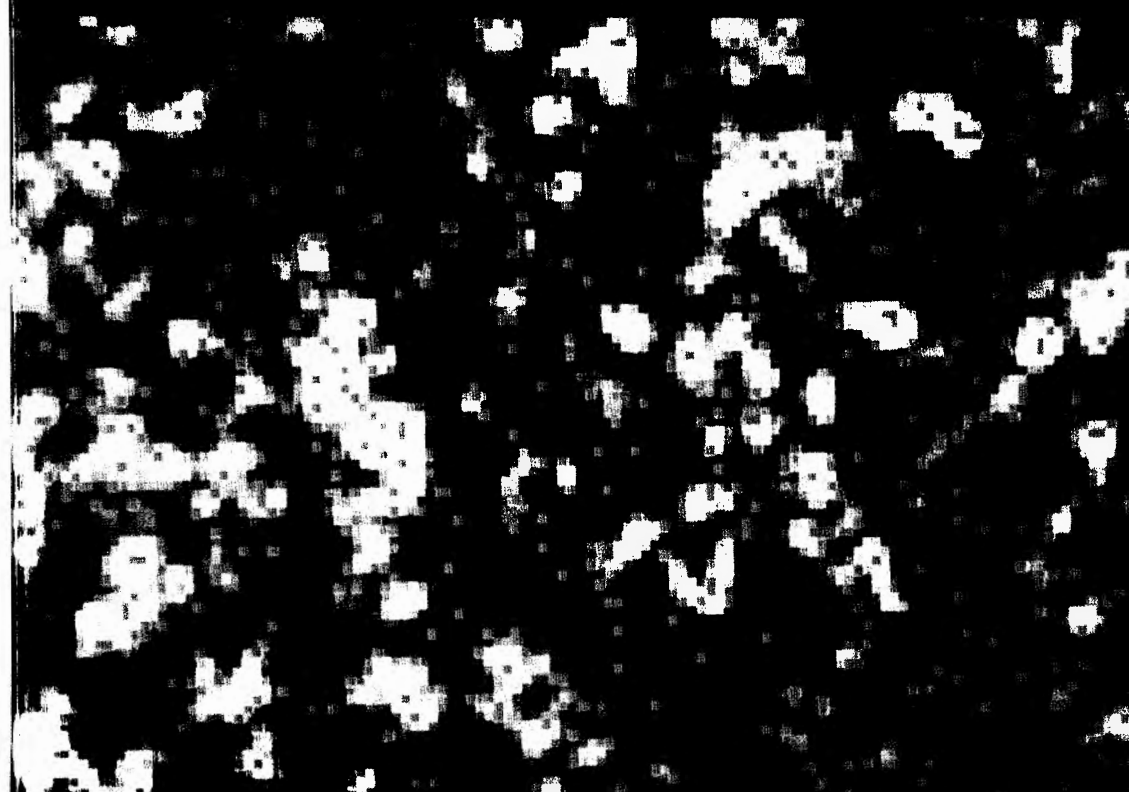
TURTLES, TERMITES, AND TRAFFIC JAMS



EXPLORATIONS IN

MASSIVELY PARALLEL

MICROWORLDS

1 Foundations

> Any study which throws light upon the nature of "order" or "pattern" in the universe is surely nontrivial.
>
> —Gregory Bateson, *Steps to an Ecology of Mind*

Introduction

A flock of birds sweeps across the sky. Like a well-choreographed dance troupe, the birds veer to the left in unison. Then, suddenly, they all dart to the right and swoop down toward the ground. Each movement seems perfectly coordinated. The flock as a whole is as graceful—maybe more graceful—than any of the birds within it.

How do birds keep their movements so orderly, so synchronized? Most people assume that birds play a game of follow-the-leader: the bird at the front of the flock leads, and the others follow. But that's not so. In fact, most bird flocks don't have leaders at all. There is no special "leader bird." Rather, the flock is an example of what some people call "self-organization." Each bird in the flock follows a set of simple rules, reacting to the movements of the birds nearby it. Orderly flock patterns arise from these simple, local interactions. None of the birds has a sense of the overall flock pattern. The bird in front is not a leader in any meaningful sense—it just happens to end up there. The flock is organized without an organizer, coordinated without a coordinator.

Bird flocks are not the only things that work that way. Ant colonies, highway traffic, market economies, immune systems—in all of these systems, patterns are determined not by some centralized authority but by local interactions among decentralized components. As ants forage for food, their trail patterns are determined not by the dictates of the queen ant but by local interactions among thousands of worker ants. Patterns of traffic arise from local interactions among individual cars. Macroeconomic patterns arise from local interactions among millions of buyers and sellers. In immune systems, armies of antibodies seek out bacteria in a systematic, coordinated attack—without any "generals" organizing the overall battle plan.

In recent years, there has been a growing fascination with these types of systems. Ideas about decentralization and self-organization are spreading through the culture like a virus, infecting almost all domains of life. Increasingly, people are choosing decentralized models for the organizations and technologies that they construct in the world—and for the theories that they construct about the world.

Almost everywhere you look these days, there is evidence of decentralization. You can see it every time you pick up a newspaper. On the front page, you might see an article about the failure of centrally planned economies in Eastern Europe. Turn to the business page, and you might find an article about the shift in corporate organizations away from top-down hierarchies toward decentralized management structures. The science section might carry an article about decentralized models of the mind, or maybe an article about distributed approaches to computing. And in the book review you might read an article suggesting that literary meaning itself is decentralized, always constucted by readers, not imposed by a centralized author.

But even as the influence of decentralized ideas grows, there is a deep-seated resistance to such ideas. At some deep level, people seem to have strong attachments to centralized ways of thinking. When people see patterns in the world (like a flock of birds), they often assume that there is some type of centralized control (a leader of the flock). According to this way of thinking, a pattern can exist only if someone (or something) creates and orchestrates the pattern. Everything must have a single cause, an ultimate controlling factor. The continuing resistance to evolutionary theories is an example: many people still insist that someone or something must have explicitly designed the complex, orderly structures that we call Life.

This assumption of centralized control, a phenomenon I call the *centralized mindset,* is not just a misconception of the scientifically naive. It seems to affect the thinking of nearly everyone. Until recently, even scientists assumed that bird flocks must have leaders. It is only in recent years that scientists have revised their theories, asserting that bird flocks are leaderless and self-organized. A similar bias toward centralized theories can be seen throughout the history of science.

Of course, centralized ideas are not always bad or wrong. Some phenomena are described quite well by centralized theories. In some systems, there *are* leaders. And when people try to construct new technologies and new organizations, centralized strategies are often very useful. Sometimes it is a good idea to put someone or something in charge. The problem is that people have, too often, relied almost entirely on centralized strategies. Decentralized approaches have been ignored, undervalued, and overlooked. Centralized solutions have been seen as *the* solution.

That is starting to change, but only slowly. There is a powerful tension. On one side is the growing fascination with decentralized systems and self-organizing behaviors. On the other side is the deep commitment to centralized ways of thinking.

In this book I explore both the allure of decentralization and the centralized mindset that resists it. I examine how people think about decentralized systems and how they might learn to think about them in new ways. I describe new tools and activities that I designed to encourage people to experiment with new types of systems—and to engage in (and reflect upon) new types of thinking.

My investigation consists of several interwoven threads, each of which reinforces and enriches the others:

- *Probing people's thinking.* How do people think about self-organizing behaviors? To what extent do they assume centralized causes and centralized control, even when none exists? Are people even aware of such assumptions? In the cognitive science community, there has been a great deal of research into "folk physics," examining how people think about concepts from Newtonian physics. Here, I am interested in "folk systems science," aiming to understand how people think about systems.

- *Developing new conceptual tools.* In recent years, there has been considerable research into analytic techniques for describing and "solving" decentralized problems, and making accurate predictions about decentralized systems. But that is not my primary interest. Rather, I am interested in developing heuristics and qualitative tools to help people think about decentralized systems in new ways. My hope is that these conceptual tools will help people move beyond the centralized mindset.

- *Developing new computational tools.* Probably the best way to develop better intuitions about decentralized systems is to construct and "play with" such systems. To make that possible, I developed a massively parallel programming language that lets people control the actions of (and interactions among) thousands of computational objects. The language, called StarLogo, is an extension of Logo, a programming language commonly used in precollege education. Whereas traditional versions of Logo allow users to control a single graphic "turtle" (or maybe a few graphic turtles), StarLogo gives users control over thousands of graphic turtles. With StarLogo, people can create and explore a wide variety of decentralized systems. For example, a user might write simple programs for thousands of "artificial ants," then watch the colony-level behaviors that arise from all of the interactions.

High-school students have used StarLogo to create and explore a variety of decentralized microworlds. One pair of students programmed the motion of cars on a highway, exploring how and why traffic jams form. Another student used StarLogo to construct and explore an ecological system with turtles and grass. My observations of the students, along with self-observations of my own StarLogo projects, provided me with ideas for improving StarLogo as a language—and, more important, insights into how péople think (and how, given new tools, they *might* think) about decentralized systems.

This research might seem like a strange mixture. What field is it in? Is it education? Computer science? Psychology? Epistemology? Biology? In my view, it is all of these—and necessarily so. It would be counterproductive to separate one from the others. Only by drawing on all of these domains is it possible to do justice to any of them.

The Era of Decentralization

On December 7, 1991, Russian president Boris Yeltsin met with the leaders of Ukraine and Belarus in a forest dacha outside the city of Brest. After two days of secret meetings, the leaders issued a declaration: "The Union of Soviet Socialist Republics, as a subject of international law and a geopolitical reality, is ceasing its existence." With that announcement, Yeltsin and his colleagues sounded the final death knell for a centralized power structure that had ruled for nearly 75 years. In its place, the leaders established a coalition of independent republics, and they promised a radical decentralization of economic and political institutions.

The next day, halfway around the world, another powerful institution announced its own decentralization plans. IBM chairman John Akers publicly announced a sweeping reorganization of the computer giant, dividing the company into more than a dozen semiautonomous business units, each with its own financial authority and its own board of directors. The goal was to make IBM more flexible and responsive to the needs of rapidly changing markets. As *Business Week* magazine put it, "The reorganization could amount to no less than a revolution in the way IBM does business."

Thus, within days, two of the world's most powerful institutions announced radical transformations, abandoning centralized hierarchies in favor of more decentralized structures. Of course, the reorganizations of the Soviet Union and IBM were not directly related to one another. But the two reorganizations are both part of a broad trend that is sweeping through our culture. Throughout the world, there is an unprecedented shift toward decentralization.

The decentralization trend is evident in the ways that people organize countries and corporations, and in the ways people design new technologies. But more important, it is evident in the ways people *think about* the world. More so than ever before, scientists are using decentralized models and metaphors to describe the phenomena they observe in the world. Increasingly, scientists (and others) are seeing decentralization wherever they look. It seems fair to say that we have entered an Era of Decentralization.

Of course, interest in decentralization is not entirely new. More than two hundred years ago, Adam Smith made a forceful argument against centralized government control of the economy. In *The Wealth of Nations,* published in 1776, Smith advocated decentralized markets as a more orderly and more efficient alternative to centralized control. He used the image of an "invisible hand" to drive home the radical idea that economic order and justice can be achieved (and, in fact, are more likely to be achieved) without centralized control of the economy. Each individual in a society, wrote Smith, "neither intends to promote the public interest, nor knows how much he is promoting it . . . he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of his invention." This faith in the decentralized actions of individuals can also be seen in other political and philosophical writings of Smith's era—including the United States Declaration of Independence, written just a few months after the publication of *The Wealth of Nations.*

Nearly a century after Adam Smith, Charles Darwin brought the idea of the invisible hand to biology. Darwin's challenge was to explain the organized complexity of living systems. Even the simplest creatures of the living world are more complex than the most complex machines of the technological world. Who or what is responsible for this organized complexity of living systems? Before Darwin, nearly everyone accepted a centralized explanation: God designed the complexity of creatures. In *Origin of Species,* Darwin offered the first serious alternative: his (decentralized) theory of natural selection. Just as Adam Smith asserted that centralized government control is not needed to create order in the economy, Darwin asserted that a centralized designer of life is not needed to create order in the living world. Instead, order and complexity arise from the decentralized processes of variation and selection.

So interest in decentralization is not a new phenomenon. But there *is* something new and different today. Ideas about decentralization are now spreading more widely, and penetrating more deeply, than ever before. More people are open to the idea of decentralization. Decentralized phenomena have a high salience in today's culture: they are attracting more attention, generating more interest. As a result decentralization has emerged as a theme in almost every domain of human activity. We seem to be undergoing a revolutionary change—what Thomas Kuhn would call a "paradigm shift"—in the way we see and construct the world.

This section examines the trend toward decentralization in five different domains:

- Decentralization in organizations
- Decentralization in technologies
- Decentralization in scientific models
- Decentralization in theories of self and mind
- Decentralization in theories of knowledge

As I investigated the growing interest in decentralized ideas in so many varied domains, my first inclination was to try to figure out which domain is the most influential. Does one of these domains act as the primary catalyst of decentralization, sparking decentralization in other domains? Perhaps new decentralized scientific models are influencing the ways we design our organizations and technologies? Or maybe it is the decentralization of technology that is provoking us to view the natural world in more decentralized ways?

But as I thought about it, I realized that my inquiry was violating the spirit of the very trend that I was trying to study. Why should there be a single, central, underlying cause for all of this decentralization? It seems better to view these domains as a type of auto-catalytic system: the decentralization of each domain reinforces and catalyzes the decentralization of the others. Most likely, there is no single, ultimate cause. Each domain provides new models and new metaphors that influence the others, refining and accelerating the decentralization trend.

The following overview is necessarily superficial, ignoring many of the subtleties and exceptions to the decentralization trend. It paints in broad

strokes, not fine detail. Its goal is to provide the big picture of how decentralized ideas are spreading through the culture, affecting nearly all domains of life.

Decentralization in Organizations

The spread of decentralized ideas can be seen in organizations of all sizes and types—countries, companies, schools, clubs. Although details are different in each case, the basic idea is always the same: pushing authority and power down from the top, distributing rights and responsibilities more widely.

For some countries (such as the Soviet Union) decentralization has meant breaking apart into separate pieces. But changes in national boundaries are not nearly as important as changes in political and economic structures. Politically, countries throughout the world are shifting away from totalitarianism toward democracy. Economically, countries are shifting away from centrally controlled economies toward market-oriented economies. As a result, decision making (both political and economic) is becoming more decentralized than ever before.

Of course, there are exceptions to the trend. In China, the government reasserted its centralized power with the brutal crackdown in Tiananmen Square. And in many of the former Soviet republics, democracy is very fragile. But the overall trend is clear. Between 1989 and 1991, countries with a combined population of 1.5 billion people, more than one-quarter of the world's population, moved away from autocratic toward more democratic forms of government, according to Freedom House, an American human-rights group. Now, for the first time ever, more than half of all countries are democracies.

A growing faith in market mechanisms is an important component of the decentralization trend. Many countries that previously relied on centrally planned economies are now switching to market-oriented approaches. And countries where market-based economics are already firmly entrenched are starting to use market mechanisms even more than before. In the United States, the government is increasingly using market mechanisms as part of the regulatory process. In the past, the Federal Communications Commission decided how to allocate frequencies on the radio spectrum. But the commission recently proposed a new approach: let new spectrum users (for example, wireless telephones) buy frequencies from existing users (for example, microwave communications by railroads). Similarly, the government is now allowing companies to buy and sell "rights to pollute." Each factory has pollution guidelines. But it can exceed those guidelines if it buys "pollution credits" from another factory that keeps its own pollution levels sufficiently below the guidelines.

In American education, decentralization is playing a role on several levels. The school-choice movement brings market-oriented thinking to the world of education, asserting that individual families—not the government—should decide where children go to school. Meanwhile, another movement called school-based management is pushing for a different type of decentralization: shifting decision-making authority from district (and state) offices to individual schools. Inside the classroom, a growing number of educators are recognizing the value of child-centered approaches to learning, transforming the teacher from a central authority figure into a catalyst, coach, and collaborator.

In the corporate world, too, there is decentralization on several levels. The rise of entrepreneurship in the 1980s led to a proliferation of small companies and independent consultants. That trend is likely to continue. Economic activity can be coordinated in two different ways: either a company makes the parts it needs internally (via vertical integration), or it buys parts from outside suppliers (via the market). For example, General Motors can make its own tires, or buy them from Goodyear. In the past, the high "coordination costs" of external purchases led many companies to make parts internally. But improvements in information technology are decreasing coordination costs, shifting the balance toward greater use of outside markets—and, thus, a proliferation of smaller firms (Malone, Yates, and Benjamin 1987).

At the same time, management structures within companies are also becoming decentralized. Since the beginning of the Industrial Revolution (and even before), companies have organized themselves as pyramid-like hierarchies. Information flowed up the hierarchy to the top, where decisions were made and passed back down the hierarchy. Thus, power, authority, and decision making were centralized at the top in most corporations—and in many other organizations that followed the corporate model.

That is now changing. A 1989 *Harvard Business Review* article called "Managing without Managers" explains: "The organizational pyramid is the cause of much corporate evil, because the tip is too far from the base. Pyramids emphasize power, promote insecurity, distort communications, hobble interaction, and make it difficult for the people who plan and the people who execute to move in the same direction" (Semler 1989). In place of the traditional pyramid, companies are "flattening" their organizational structures by getting rid of middle managers and distributing decision-making responsibility more evenly through the organization. The movement started with employee participation in "quality circles" in the 1970s. Now companies are giving workers more responsibilities over production decisions. Some are even experimenting with "self-management teams"—that is, teams without bosses (Dumaine 1990). Someday, companies could end up with what MIT sociologist Charles Sabel calls a "Mobius strip organization"—an organization without a top or bottom.

Decentralization in Technologies

The decentralization in organizational structures is linked, in part, to decentralization of technologies. This connection was particularly apparent during the attempted Soviet coup in 1991, when hard-liners tried to reassert centralized control. As John Barlow (1992) wrote, "Because of the decentralized and redundant nature of digital media, it was impossible for the geriatric plotters in the Kremlin to suppress the delivery of truth. Faxes and email messages kept the opposition more current with developments than the KGB, with its hierarchical information systems, could possibly be."

Computer technologies have not always been viewed as a decentralizing force. Just 30 years ago, computers were synonymous with centralized power. Only the largest institutions could afford computers. And within those institutions only a few privileged people had direct access to the machines. To run a program, you had to deliver a stack of cards (or tape) to a member of the "computer priesthood" that guarded and cared for the machine. Not surprisingly, college students in the 1960s saw computers as impersonal tools used by the Establishment to keep control over the masses.

But as the cost and size of electronics continued to decline, the uses (and perceptions) of computers changed radically. In the 1970s time-sharing technology gave more people access to computers. To run a computer program, you could sit at a terminal (maybe on your own desk) and interact with the computer in real time. But the computer itself was still centralized and shared. The real breakthrough came with the personal computers of the 1980s. Suddenly computers began to appear on desks everywhere. In 1972 there were only 150,000 computers. A decade later there were several million computers. Today there are more than 100 million computers.

The decentralization trend continues today with the proliferation of notebook computers and even palmtop computers. Computers are becoming part of the environment itself, invisibly buried within all types of objects (such as televisions, fax machines, and telephones). Ultimately all of these objects will be linked together, in a decentralized computational web.

Even as computers spread through offices, factories, and homes, most computers remain quite centralized in their internal architecture. Most of today's computers continue to use an architecture developed by John von Neumann nearly half a century ago. This von Neumann architecture is based on a single "central processing unit" that performs and organizes most of the computational work. All information must flow through that single processor.

But that too is changing. A growing number of companies are developing parallel computers—computers with more than one processor inside. Some "massively parallel" computers have tens of thousands of processors, and there are plans for computers with more than a million processors. With a parallel computer, a user can divide a problem into many separate parts, then assign different processors to work on different parts of the problem at the same time. The challenge is to find ways for all of the processors to remain coordinated—just as birds remain coordinated within a flock.

Thus the decentralization of computation proceeds at multiple levels, in an almost fractal-like fashion. As computational power becomes decentralized throughout society, it is also becoming decentralized within the computers themselves.

Decentralization in Scientific Models

For three hundred years, the models and metaphors of Newtonian physics have dominated the world of science—and, even more so, people's perceptions of science. Newton offered an image of the universe as a machine, a clockwork mechanism. Newton's universe is ruled by linear cause and effect—one gear turns, which makes a second gear turn, which makes a third gear turn, and so on. This cause-effect relationship is captured in Newton's famous $F=ma$ formula: force gives rise to acceleration; cause gives rise to effect.

In the common perception of the Newtonian universe, the idea of "mutual interaction" is de-emphasized. When people think of interactions in the Newtonian universe, they think of one object acting on

another. One object acts as the cause, the other object receives or suffers the effect. One object is in control, the other is acted upon. Most of the attention goes to Newton's first two laws of motion, which focus on how a force influences the motion of an object. Much less attention goes to Newton's third law, which focuses on the reaction that accompanies every action.

During the twentieth century, the Newtonian view of the world has been challenged on many different fronts. One of the most serious challenges comes from the growing interest in so-called complex systems. In an increasing number of fields, scientists have shifted metaphors, viewing things less as clocklike mechanisms and more as complex ecosystems. Rather than viewing the world in terms of one individual object acting on another in a neat causal chain, researchers are viewing the world in terms of decentralized interactions and feedback loops. They are studying how complex behaviors can emerge from interactions among simple rules, and how complex patterns can emerge from interactions among simple components.

This growing interest in "emergent" phenomena has been accompanied by confusion and controversy, since different people use the term *emergent* in different ways. Many popular descriptions of emergence (and even some scientific ones) are tinged with mysticism, as if something magical is going on. But no magic is needed. As I am using the term, emergence is fully consistent with most traditional scientific ideas—including Newtonian physics. The point is not that Newtonian models are *wrong*. It is that Newtonian models are *inappropriate* for trying to make sense of certain types of phenomena. New types of models are needed, operating at a different "level" from Newtonian models, focusing on the behaviors of systems, not the actions of individuals.

Many ideas about emergence and complexity have been inspired by research in the biological fields of ecology, ethology, and evolution. In one classic study, ethologist Niko Tinbergen described how the behavior of a stickleback fish emerges from interactions among several simple rules. And much ecological research looks at how large-scale patterns emerge from local interactions among living organisms. But interest in complex systems has spread far beyond biology. In the 1940s and 1950s the field of cybernetics attempted to create a new unifying framework for understanding all types of systems in the world—be they biological, social, or technological. The field attracted engineers, biologists, psychologists, anthropologists, and others. Working together, researchers tried to find and forge connections among their disciplines, looking for similarities in the behaviors of minds, machines, animals, and societies.

While cybernetics never developed into a mainstream discipline, many of its core ideas (such as feedback and self-organization) are alive and increasingly influential in scientific thinking. Nobel Laureate Ilya Prigogine and his associates have shown how physical and chemical systems can exhibit the same types of self-organizing behaviors that are typical of biological systems. Under the right conditions, for example, a heated liquid will form rotating "convection cells," where the rotating patterns are millions of times larger than the range of the intermolecular forces that cause them. Similarly, certain chemical reactions (such as the Belousov-Zhabotinski reaction) can exhibit either spatial patterns (large-scale spirals) or temporal patterns (periodically changing color). Self-organizing patterns can also arise in technological systems. Computers interconnected on networks can sometimes behave as "computational ecologies": interactions among individual machines can give rise to surprising network-wide patterns (Huberman 1988).

The study of self-organizing systems is one strand in the study of nonlinear dynamical systems, the rapidly growing research effort that aims to find common mathematical foundations for all types of complex behavior. Dynamical systems that exhibit *chaotic* behavior have received a particularly high level of attention and publicity in recent years. As noted by Farmer and Packard (1986), the study of self-organizing systems is, in some ways, the "related opposite" of the study of chaos: in self-organizing systems, orderly patterns emerge out of lower-level randomness; in chaotic systems, unpredictable behavior emerges out of lower-level deterministic rules.

The new field of artificial life is a striking example of the growing interest in self-organization and decentralized scientific models. Artificial life researchers aim to gain a better understanding of living systems by creating computational versions of them—for example, creating artificial versions of ant colonies or bird flocks. In their efforts, artificial life researchers are guided by an abiding faith in decentralized approaches. As Chris Langton (1989) wrote in the founding article of the new field,

> The most promising approaches to modeling complex systems like life or intelligence are those which have dispensed with the notion of a centralized global controller, and have focused instead on mechanisms for the *distributed* control of behavior. . . . Artificial Life studies natural life by attempting to capture the behavioral essence of the constituent components of a living system, and endowing a collection of artificial components with similar behavioral repertories. If organized correctly, the aggregate of artificial parts should exhibit the same dynamic behavior as the natural system. This bottom-up modeling technique can be applied at any level of the hierarchy of living systems in the natural world—from modeling molecular dynamics on millisecond time-scales to modeling evolution in populations over millenia.

Decentralization in Theories of Self and Mind

Few things seem more obvious than the singular nature of the mind and self. Each of us experiences life as a single thread of consciousness. Each of us feels as if we have a single, unified presence in the world. In the words of Francisco Varela and his associates, each of us has "a stable and constant vantage point from which to think, perceive, and act" (Varela, Thompson, and Rosch 1991). Each of us imagines our own mind as "I," not "we."

But the idea of the unified, centralized mind has eroded during the past century—and the erosion has accelerated in the past decade. The beginnings of the "decentering" of self and mind can be seen in the nineteenth-century writings of Sigmund Freud. Freud's "unconscious" was a direct attack on the idea of a single executive in charge of the mind. Freud saw the unconscious as an equal participant (with the conscious) in the workings of mind. The unconscious, according to Freud, is not a passive repository of forgotten ideas but a lively agent actively repressing thoughts. Freud further fragmented the mind with his formulation of the ego, the superego, and the id—with the superego and id pulling the ego in different directions.

The decentralized nature of Freud's theories met with resistance, even among Freud's followers in psychoanalytic research. So-called ego psychologists focused their attention on the ego, viewing the ego as a type of leader or chief executive within the mind. Ego psychology, writes Sherry Turkle (1988), "takes what is most subversive [in Freud's theories]—the decentered self—and softens it."

In recent years, however, psychoanalytic research has swung back toward decentralized models, particularly with the rise of object relations theory. This theory, exemplified by the work of Melanie Klein, describes psychological development in terms of the "internalization" of objects. Relationships with people in the world are internalized as agents or objects within the mind. Freud took a step in this direction, describing the superego as the internalization of the ideal parent. But object relations theory goes much further, proposing an entire society of inner agents within the mind. The self emerges from the interactions among the internalized objects.

3
Explorations

Go to the ant, thou sluggard;
consider her ways, and be wise.

—The Bible (Proverbs 6.6)

Simulations and Stimulations

I'm not quite sure what to call the type of projects that I've worked on with StarLogo. Most people would call them *simulations*. But that doesn't feel quite right. A simulation is, according to *Webster's New Collegiate Dictionary,* "the imitative representation of the functioning of one system or process by means of the functioning of another." Many computer simulations fit this description. They try to imitate some real-world system or process as accurately as possible. In many cases computer simulations are used to make predictions about real-world processes. Computer simulations of nuclear reactors are used to predict when the reactors might fail. Computer simulations of meteorological patterns are used to predict tomorrow's weather. In these cases, the more accurate the simulation, the better.

In working with StarLogo, I have different goals. To be sure, many StarLogo projects are inspired by real-world systems: ant colonies, forest fires, traffic jams. But I'm not interested in developing accurate imitations of these real-world systems, or even in making accurate predictions about them. The real world serves only as an inspiration, a departure point for thinking about decentralized systems. When I write a StarLogo program with artificial ants, for instance, I am more interested in investigating antlike behaviors than the behaviors of real ants. Even more, I am interested in how people *think about* antlike behaviors.

In short, I am more interested in *stimulation* than in *simulation*. My work with StarLogo is aimed more at what's *in here* (in the mind) than what's *out there* (in the world). The goal is not to simulate particular systems and processes in the world. The goal is to probe, challenge, and disrupt the way people think about systems and processes in general.

I prefer to think of StarLogo projects as *explorations of microworlds*, not simulations of reality. Microworlds are simplified worlds, specially designed to highlight (and make accessible) particular concepts and particular ways of thinking. Microworlds are always manipulable: they encourage users to explore, experiment, invent, and revise. Seymour Papert (1980) describes microworlds as "incubators for knowledge." The standard Logo-turtle microworld, he writes, is a place where "certain kinds of mathematical thinking [can] hatch and grow with particular ease." StarLogo, with its sensory-enhanced turtles and patch-reified environment, is pärticularly well suited for developing "systems science" microworlds—that is, worlds where systems thinking can hatch and grow.

In the rest of this chapter I describe and discuss explorations of some StarLogo microworlds. In some of the explorations I worked by myself. In others I worked with students from Boston-area high schools. (For more information on the high-school students, see appendix A.)

When I worked with high-school students, I played several (simultaneous and intertwined) roles:

Observer. I observed how the students thought about decentralized systems, and how their thinking evolved during their interactions with StarLogo.

Catalyst. I proposed experiments, asked questions, challenged assumptions, and encouraged students to reflect on their experiences as they worked with StarLogo.

Collaborator. I helped students write their StarLogo programs, since I was not particularly interested in studying how well students learned to program in StarLogo. More important, I worked together with students in trying to make sense of unfamiliar phenomena. Often, working with students helped clarify my own thinking about decentralized systems.

Slime Mold

Slime mold is hardly the most glamorous of creatures. But it is surely one of the most strange and intriguing. As long as food is plentiful, slime-mold cells exist independently as tiny amoebas. They move around, feed on bacteria in the environment, and reproduce simply by dividing into two. But when food becomes scarce, the slime-mold behavior changes dramatically. The slime-mold cells stop reproducing

and move toward one another, forming a cluster (called a "pseudoplasmodium") with tens of thousands of cells.

At this point, the slime-mold cells start acting as a unified whole. Rather than behaving like lots of unicellular creatures, they act as a single multicellular creature. In short, "they" start acting like "it." It changes shape and begins crawling, seeking a more favorable environment. When it finds a spot to its liking, it differentiates into a stalk supporting a round mass of spores. These spores ultimately detach and spread throughout the new environment, starting a new cycle as a collection of slime-mold amoebas.

The process through which slime-mold cells aggregate into a single multicellular creature has been a subject of scientific debate. Until 1980 or so, most biologists believed that specialized "pacemaker" cells coordinated the aggregation. But scientists now view slime-mold aggregation as a very decentralized process. According to the current theories, slime-mold cells are homogeneous: none is distinguished by any special features or behaviors. The clustering of slime-mold cells arises not from the commands of a leader but through local interactions among thousands of identical cells. In fact, the process of slime-mold aggregation is now viewed as one of the classic examples of self-organizing behavior.

How do the slime-mold cells aggregate? The mechanism involves a chemical called "cyclic AMP" or cAMP (Goldbeter and Segal 1977). When the slime-mold cells move into their aggregation phase, they pro-

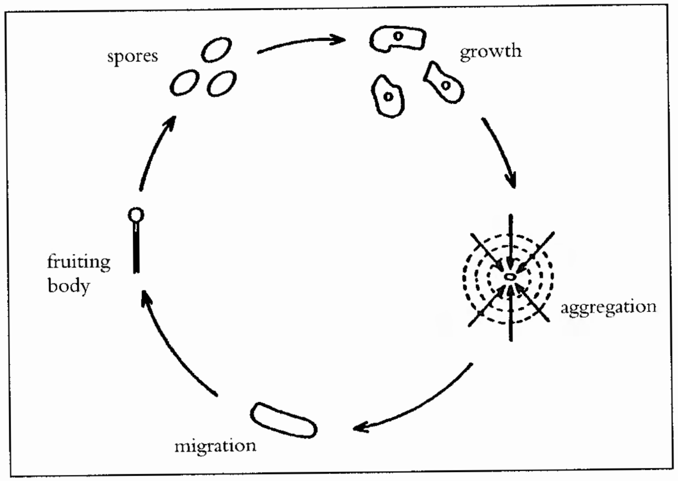


Figure 3.1
Life cycle of slime mold, reproduced from Prigogine and Stengers 1984

duce and emit cAMP into the environment. They are also attracted to the very same chemical. As the cells move, they follow the gradient of cAMP. That is, they test around themselves, and they move in the direction where the concentration of cAMP is highest. Note that this process is very *local*. Each cell can sense cAMP only in its immediate vicinity; it cannot tell how much cAMP there might be a few centimeters away.

I wrote a StarLogo program to explore the workings of this decentralized aggregation process. I was not interested in simulating every detail of the actual slime-mold mechanism. In the actual mechanism, slime-mold cells produce the cAMP in periodic pulses. As a result, slime-mold cells tend to come together in concentric waves. But this periodicity does not seem essential to the aggregation process. In fact, Prigogine and Stengers (1984) describe how the larvae of certain beetles (*Dendroctonus micans*) aggregate into clusters using a mechanism similar to that used by slime-mold cells, but without the periodicity.

My goal was to capture the essence of the aggregation process with the simplest mechanism possible. My StarLogo program was based on a set of simple rules. Each turtle was controlled by four demons: one demon made the turtle move, a second added a little randomness to the turtle's movements, a third made the turtle emit a chemical pheromone, and a fourth made the turtle "sniff" for the pheromone and turn in the direction where the chemical was strongest (that is, follow the gradient of the pheromone).

Meanwhile, each patch was controlled by two primary demons: one to make the pheromone in the patch evaporate, and another to diffuse the pheromone to neighboring patches. (A third demon controlled the color of the patches. Each patch was displayed as a shade of green: the more pheromone in the patch, the brighter the intensity of green.) All of the demons (for the turtles and patches) were very simple; each required at most two lines of StarLogo code.

Observer Procedures

```
to setup number
clear-all
create-turtle number
turtle-setup
patch-setup
end
```


Turtle Procedures

```
to turtle-setup
activate-demon [walk-demon wiggle-demon
                drop-pheromone-demon sniff-demon]
end

to walk-demon
forward 1
end

to wiggle-demon
right random 40
left random 40
end

to drop-pheromone-demon
ask patch-here [set-pheromone pheromone + 1]
end

to sniff-demon
if ask patch-here [pheromone > 2]
   [follow-gradient pheromone]
end
```

Patch Procedures

```
to patch-setup
patches-have pheromone
activate-demon [evaporation-demon
                diffusion-demon display-demon]
end

to evaporation-demon
set-pheromone pheromone * 0.9
end

to diffusion-demon
diffuse pheromone
end

to display-demon
scale-patchcolor green pheromone 0 3
end
```

depends on many other factors. If the evaporation rate of the pheromone is increased, more turtles are needed to start a cluster (so the critical density is higher). If the turtles emit larger drops of pheromone on each step, fewer turtles are needed to start a cluster (so the critical density is lower).

What if we change the turtles' sense of smell? There are several ways to do that. One way is to change the range of directions that the turtles sniff. By default, each turtle takes three sniffs in trying to follow the gradient of a scent: one sniff straight ahead, one sniff 45 degrees to the left of its heading, one sniff 45 degrees to the right of its heading. (On each sniff the turtle senses one unit-distance away from its current position.) What if we make the turtles take more sniffs? Say each turtle takes five sniffs: 90 degrees to the left, 45 degrees to the left, straight ahead, 45 degrees to the right, and 90 degrees to the right. Equivalently, we could think of this as increasing the number of noses on each turtle, so that each turtle has five noses instead of three noses, equally spaced at 45-degree intervals. (We can make this change with the StarLogo command `set-number-of-sniffs 5`.) With five noses/sniffs rather than three, the turtles clearly have a better sense of smell. How will this improved sense of smell change the dynamics of the program? Will there be more clusters or fewer? Will the clusters be larger or smaller? Think about it a minute before reading on.

I posed this scenario to about two dozen people (including high-school students and MIT researchers). More than three-quarters of the people predicted the result incorrectly. Most people expected fewer and bigger clusters. In fact, the turtles gather into more and smaller clusters. It isn't too surprising that many people had difficulty predicting what would happen. After all, the slime-mold program involves thousands of interacting objects. It is very difficult to make predictions about such complex systems. So it wouldn't be too surprising if half of the people predicted the result incorrectly. But it seems strange that *most* people predicted incorrectly. What underlies this false intuition?

I asked people to explain their reasoning. Many people reasoned something like this: "The creatures are trying to get together, to combine into one big thing. If the creatures have a better sense of smell, they will do a better job of that. So you'll end up with larger clusters." What's the flaw? This reasoning confuses levels by attributing inappropriate intentionality to the creatures. Creatures are not really trying to form large clusters; they are simply following a pheromone gradient. The creatures *do* follow the gradient more effectively when they have more noses. But as a result they form smaller (not larger) clusters. By following the gradient effectively, the many-nosed creatures more quickly "find"

other creatures to interact with. Giving more noses to the creatures is like giving a larger cross-section to particles in a physics simulation: collisions are more likely. And once the creatures find some others to interact with, they can form stable clusters with fewer partners, since each creature in the cluster stays closer to the others. The result is that clusters are smaller, there are more of them, and they form more quickly.

Artificial Ants

Myrmecology, the study of ants, might seem like a rather narrow and specialized scientific domain. But a growing number of researchers from outside the tight-knit myrmecology community have begun to take an interest in ants.

References to ants show up in unlikely places, from unlikely sources. In *Gödel, Escher, Bach,* Douglas Hofstadter (1979) describes a fictitious ant colony that he punningly calls Aunt Hillary. Hofstadter uses Aunt Hillary to explore differences between levels—in particular, differences between an ant colony as a whole and the individual ants that compose it. According to Hofstadter the workings of an ant colony can serve as a rough metaphor for the workings of the human brain: in each case, the behavior of the whole (colony or brain) is far more sophisticated (and of a very different character) than the behaviors of the component parts (ants or neurons).

In the nascent artificial life (ALife) community, dozens of researchers are creating simulations of artificial ants (for example, Collins and Jefferson 1991; Deneubourg and Goss 1989; Steels, 1990; Travers 1989). Indeed, ants have become the unofficial mascots of the ALife community. Artificial life posters are frequently illustrated with drawings of ants, and participants at ALife conferences adorn their name badges with plastic ants.

Interest in ants has even spread to the popular culture. Although not yet as popular as fish aquariums, ant farms are now becoming increasingly common in American homes. Uncle Milton Industries has sold more than 13 million of its Uncle Milton's Ant Farms, populated with 200 million *Pogonomyrmex californicus* ants (Miller 1991). Thousands of other households play with ants on their computer screens, using SimAnt software from Maxis. And *The Ants,* the definitive ant reference book by Harvard myrmecologists Bert Holldobler and E. O. Wilson (1990), has become a sort of cult classic, attracting attention far outside the myrmecology community.

Why the growing interest in ants? Many people, it seems, are intrigued with the collective nature of ant behavior. Each individual ant is quite simple. But an ant colony as a whole is capable of rather sophisticated behavior. Thus ant colonies have come to be viewed as a prototypical example of how complex-group behavior can arise from simple-individual behavior. As such, many people see the colony/ant relationship as an illuminating model (or, at least, an inspiring metaphor) for thinking about other group/individual relationships—such as the relationship between an organ and its cells, a cell and its macromolecules, a corporation and its employees, or a country and its citizens.

Compared with these other collective systems, ant colonies have the advantage of being more easily studied. As ant researchers Jean-Louis Deneubourg and Simon Goss (1989) note, "We can experiment on these [ant] societies in a way impossible in any other kind of collective decision-making organization. Unlike molecules or cells, [ant] workers are easily visible, and we can manipulate insect societies and place them in experimentally controllable situations with relative ease." Artificial ants, simulated on the computer screen, are even more easily manipulated and controlled (though at a risk of violating biological or physical realism). In particular, artificial ant simulations can help researchers probe the *mechanisms* that underlie collective behaviors. By experimenting with artificial ants, researchers can explore which individual-ant behaviors give rise to which colony-level behaviors.

Research on collective behavior in ant colonies has focused primarily on foraging activity (that is, how ants find and collect their food). Different species of ants search for food in different ways. In some species ants forage individually and adjust their strategies based on experience. But most species forage collectively, helping one another find and gather food. Typically, ants use *recruitment* strategies. When an ant finds some food, it recruits other ants to the food, who in turn recruit other ants to the food, and so on. The process slows down when there are fewer ants left to be recruited (or when there are other forces competing for the ants' attention).

Recruitment can take several different forms. In some species ants communicate directly with other ants. After an ant finds some food, it returns to the nest and leads one or more nestmates back to the food source. In other species ants communicate indirectly, through a chemical pheromone—a process known as *mass recruitment*. After an ant finds some food, it returns to the nest, dropping a chemical pheromone as it walks.

(Different types of ants find their way back to the nest in different ways: some by memory, some by smell, some by visual cues.) When other ants detect the pheromone trail, they follow it to the food source. Then they, too, return to the nest, reinforcing the pheromone trail. Before long, there is a strong trail between the food and nest, with hundreds of ants walking back and forth.

What happens when the ants finish exploiting the entire food source? Ants drop the chemical pheromone only when they are carrying food. So when the food source is fully depleted, the ants no longer drop pheromone. The pheromone trail becomes weaker and weaker through evaporation. As the trail becomes weaker, the ants become less likely to follow it. Instead they wander off in search of a new food source.

This mass recruitment process is implemented in the following StarLogo program. Each ant's actions are controlled by four demons. One demon tells the ant how to look for food (follow the pheromone if you sense it, wander randomly if you don't). A second demon tells the ant what to do when it finally bumps into the food (pick up a piece of food and turn around). A third demon tells the ant how to return to the nest (follow the scent of the nest, dropping pheromone as you go). And the fourth demon tells the ant what to do when it gets back to the nest (drop the food, and turn around to go get more). Meanwhile, the patches indicate where the nest and food are, and they cause the pheromone to evaporate and diffuse. (See the programming notes, following the program, for more details.)

Observer Procedures

```
to setup
clear-all
create-turtle 100
turtle-setup
patch-setup
end
```

likely to lose the ants that are already on the trail. On the weaker trail, ants are slightly more likely to wander off the trail. So the stronger trail is likely to get stronger still, and the weaker trail, weaker. In this way, small differences can grow quickly, leading to a "symmetry breaking" in which one trail becomes dominant. Deneubourg et al. (1986) speculate that such symmetry breaking could have evolutionary advantages for ants, "as it allows the society to concentrate the exploitation on one source which is then better defended than if the foragers were divided around several sources."

Traffic Jams

At the time Ari and Fadhil started working with StarLogo, they were also taking a driver's education class. Each had turned 16 years old a short time before, and they were excited about getting their driver's licenses. Much of their conversation focused on cars. So when I gave Ari and Fadhil a collection of articles to read, it is not surprising that a *Scientific American* article titled "Vehicular Traffic Flow" (Herman and Gardels 1963) captured their attention.

Traffic flow is rich domain for studying collective behavior. Interactions among cars in a traffic flow can lead to surprising group phenomena. Consider a long road with no cross streets or intersections. What if we added some traffic lights along the road? The traffic lights would seem to serve no constructive purpose. It would be natural to assume that the traffic lights would reduce the overall traffic throughput (number of cars per unit time). But in some situations, additional traffic lights actually *improve* overall traffic throughput. The New York City Port Authority, for example, found that it could increase traffic throughput in the Holland Tunnel by 6 percent by deliberately stopping some cars before they entered the tunnel (Herman and Gardels 1963).

Or imagine what would happen if a street were temporarily closed in a congested downtown area. With one less street, it would be natural to assume that traffic conditions would worsen. But assumptions would be wrong again. The New York City Transportation Commissioner found that closing 42nd Street actually improved traffic flow in the area (Cohen and Kelly 1990).

Ari and Fadhil, based on their membership in the teenage-driver culture, were familiar with a variety of interesting traffic behaviors. They told me about a phenomenon called "snaking," which I had never heard of.

Mitchel: *What's snaking?*

Fadhil: *First one lane slows down. Then the other lane slows down, and the first one starts moving. Then the first one slows down again, and the other one starts moving. So it's like a snake.*

Mitchel: *Why does it happen?*

Fadhil: *A lot of people switch from the first lane to the other lane. Once they get to the other lane, the first lane starts going again. It keeps going back and forth.*

Mitchel: *Because people keep switching?*

Fadhil: *You know how when you're in a lane. Then you switch to the next lane since you see it's going faster. Then that one stops. And you say, "Gee, I have no luck. All the lanes I go to slow down."*

Mitchel: *If you were the only car to switch, it would work, right?*

Fadhil: *Yeah. But since you're not, it would be best to stay in your lane.*

Traditional studies of traffic flow rely on sophisticated analytic techniques (from fields like queuing theory). But many of the same traffic phenomena can be explored with simple StarLogo programs. To get started, Ari and Fadhil decided to create a one-lane highway. (Later, they experimented with multiple lanes, to explore the snaking phenomenon.) Ari suggested adding a police radar trap somewhere along the road, to catch cars going above the speed limit. But he also wanted each car to have its own radar detector, so cars would know to slow down when they approached the radar trap. (Ari noted that his mother's car had a sophisticated radar detector, with "three levels of warnings.")

After some discussion, Ari and Fadhil decided that each StarLogo turtle/car should follow three basic rules:

- If there is a car close ahead of you, slow down.
- If there aren't any cars close ahead of you, speed up (unless you are already moving at the speed limit).
- If you detect a radar trap, slow down.

These rules can be implemented with three StarLogo demons: one to make the car move, one to check if another car is close ahead (and adjust the car's speed accordingly), and one to check for the radar trap (and adjust the car's speed if necessary).

random positions on the road. Random positioning led to uneven spacing between the cars, and uneven spacing could also provide the seed for a traffic jam to form. Fadhil explained, "Some of the cars start closer to other cars. Like, four spaces between two of them, and two spaces between others. A car that's only two spaces behind another car slows down, then the one behind it slows down."

Next, we changed the program so that the cars were evenly spaced. Sure enough, no traffic jams formed. All of the cars uniformly accelerated up to the speed limit. But Ari and Fadhil recognized that such a situation would be difficult to set up in the real world. The distances between the cars had to be just right, and the cars had to start at exactly the same time—like a platoon of soldiers starting to march in unison.

We reintroduced some randomness in the initial conditions of the StarLogo program, and the traffic jams returned. Watching the traffic jams more closely, Ari and Fadhil noticed that the jams did not stay in one place but tended to move with time. In fact, the traffic jams tended to move *backward,* even though all of the cars within them were moving forward. Fadhil described it: "The jam itself moves backward. If you keep your eye on one car, it leaves the traffic jam, but the jam itself, I mean where you see the cars piling up, moves backward."

The backward movement of the traffic jam highlights an important idea: collective structures (like traffic jams) often behave very differently from the elements that compose them. This idea is true not only for traffic jams but for a much wider range of phenomena, including waves. Ideas about waves are very difficult for students to grasp. One reason is that waves are often presented in unmotivated contexts (for example, perturbations moving along a string) and through difficult mathematical formalisms (such as differential equations).

StarLogo seems to provide a more accessible introduction to wavelike phenomena. Like differential equations, StarLogo can be used as a formal system for expressing ideas about wave behavior. But the StarLogo representation is different in several important ways. For one thing, StarLogo programs seem easier to understand and manipulate. In addition, StarLogo programs are executable, so that students can watch their programs run and revise their ideas based on what they see. Perhaps most important, StarLogo offers students a chance to explore wave phenomena in personally meaningful contexts. The fact that Ari and Fadhil developed strong intuitions about traffic flow while working on their StarLogo project was due, in no small part, to their deep interests in and experiences with cars.

Termites

Philip Morrison, the MIT physicist and science educator, once told me a story about his childhood. When Morrison was in elementary school, one of his teachers described the invention of the arch as one of the central, defining milestones of human civilization. Arches took on a special meaning for the young Morrison. He felt a certain type of pride whenever he saw an arch. Many years later, when Morrison learned that lowly termites also build arches, he was quite surprised (and amused). He gained a new skepticism about everything that he was taught in school, and a new respect for the capabilities of termites. Ever since, Morrison has wondered about the limits of what termites might be able to do. If they can build arches, why not more complex structures? Given enough time, Morrison wondered, might termites build a radio telescope?

Probably not. But termites *are* among the master architects of the animal world. On the plains of Africa, termites construct giant moundlike nests rising more than ten feet tall, thousands of times taller than the termites themselves. Inside the mounds are intricate networks of tunnels and chambers. Certain species of termites even use architectural tricks to regulate the temperature inside their nests, in effect turning their nests into elaborate air-conditioning systems. As E. O. Wilson (1971) notes, "The entire history of the termites . . . can be viewed as a slow escape by means of architectural innovation from a dependence on rotting wood for shelter" (p. 315).

Each termite colony has a queen. But, as in ant colonies, the termite queen does not "tell" the termite workers what to do. (In fact, it seems fair to wonder if the designation "queen" is a reflection of human biases. "Queen" seems to imply "leader." But the queen is more of a mother to the colony than a leader.) On the termite construction site there is no construction foreman, no one in charge of the master plan. Rather, each termite carries out a relatively simple task. Termites are practically blind, so they must interact with each other (and with the world around them) primarily through their senses of touch and smell. But from local interactions among thousands of termites, impressive structures emerge.

The global-from-local nature of termite constructions makes them well suited for StarLogo explorations. Of course, simulating the construction of an entire termite nest would be a monumental project (involving many details unrelated to my interests). So I chose a far more modest goal: program some artificial termites to collect wood chips and put them into piles. (Real termites don't actually carry wood chips from place to place. Rather, they eat pieces of wood, then build structures with "fecal cement" that they produce from the digested wood.)