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# 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 constructed 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 people 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 “Möbius 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