Learning About Life

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Abstract The growing interest in Artificial Life is part of a broader intellectual movement toward decentralized models and metaphors. But even as decentralized ideas spread through the culture, there is a deep-seated resistance to these ideas. People have strong attachments to centralized ways of thinking: they often assume centralized control where none exists. New types of computational tools and construction kits are needed to help people move beyond this "centralized mindset." Perhaps most important are new tools and activities for children, to help them develop new ways of looking at the world.

Keywords
decentralized systems, emergence, education, simulations, centralized mindset, epistemology

1 Introduction

For 300 years, the models and metaphors of Newtonian physics have dominated the world 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 $F = ma$ formula: force gives rise to acceleration, cause gives rise to effect.

These Newtonian images have spread beyond the community of scientists, deeply influencing work in the social sciences, the humanities, and the arts. Newtonian metaphors have formed the foundation for how people think about science—and, more generally, how they make sense of the world around them.

In recent years, a new set of models and metaphors has begun to spread through the scientific community, and gradually into the culture at large. Many of these new ideas come not from physics but from biology. In a growing number of disciplines, researchers are now viewing the systems they study less like clockwork mechanisms and more like complex ecosystems. Increasingly, ideas from ecology, ethology, and evolution are spreading beyond their disciplinary boundaries. Ideas like self-organization and emergence are affecting the direction and nature of research in many other fields, from economics to engineering to anthropology. In general, there is a pronounced shift toward *decentralized* models, in which patterns are determined not by some centralized authority, but by local interactions about decentralized components. The growing interest in the field of Artificial Life is both a reflection of and a contributor to this broader intellectual shift.

Biology-inspired models and metaphors will have their greatest influence when they spread outside of the scientific community and into the general culture. For children growing up in the world today, learning about living systems is taking on a new urgency. The point is not just to understand the biological world (although that, of course, is a worthy endeavor). Rather, decentralized models of living systems provide a basis for understanding many other systems and phenomena in the world. As these ideas seep out of the scientific community, they are likely to cause deep changes in how children (and adults too) make sense of the world. This paper explores ways to help make that happen.

2 New Ways of Thinking

Among living systems, there are many examples of decentralized phenomena. As ants forage for food, for example, their trail patterns are determined not by the dictates of the queen ant, but by local interactions among thousands of worker ants. In the immune system, armies of antibodies seek out bacteria in a systematic, coordinated attack—without any "generals" organizing the battle plan. The antibodies are organized without an organizer, coordinated without a coordinator.

But seeing the world in terms of decentralized interactions is a difficult shift for many people. It requires a fundamental shift in perspective, a new way of looking at the world. At some deep level, people 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). And in constructing artificial systems, people often impose centralized control where none is needed (e.g., using top-down, hierarchical programming structures to control a robot's behavior).

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. As William Paley [14] argued nearly two centuries ago, "If you found a watch on the ground, you would assume that it must have had a maker; so must not the same be true of living systems, which are incredibly more complex?"

This assumption of centralized control, a phenomenon I call the *centralized mindset*, is not just a misconception of the scientifically naive. The history of science is filled with examples of scientists remaining committed to centralized explanations, even in the face of discrediting evidence. When fossil records showed that very different creatures existed at different times in history, scientists did not give up on ideas of supernatural creation. Rather, they hypothesized that there must have been a whole series of extinctions and new creations. In the 20th century, as the genetic basis of evolution became understood, scientists initially adopted a too centralized view of genes, focusing on the actions and fitness values of individual genes, rather than studying interactions among genes.

Even today, centralized thinking persists in evolutionary debates. In trying to explain the periodic massive extinctions of life on earth, many scientists assume some external cause—for example, periodic waves of meteors hitting the earth. But more decentralized explanations are possible. Recent computer simulations show that simple interactions within the standard evolutionary process can give rise to periodic massive extinctions, without any outside intervention [12].

The history of research on slime-mold cells, as told by Keller [9], provides another example of centralized thinking. At certain stages of their life cycle, slime-mold cells gather together into clusters. For many years, scientists believed that the aggregation process was coordinated by specialized slime-mold cells, known as "founder" or "pacemaker" cells. According to this theory, each pacemaker cell sends out a chemical signal, telling other slime-mold cells to gather around it, resulting in a cluster. In 1970, Keller and Segel [10] proposed an alternative model, showing how slime-mold cells can aggregate without any specialized cells. Nevertheless, for the following decade, other researchers continued to assume that special pacemaker cells were required to initiate the aggregation process. As Keller [9] writes, with an air of disbelief, "The pacemaker view was embraced with a degree of enthusiasm that suggests that this question was in some sense foreclosed." By the early 1980s, based on further research by Cohen and Hagan [4], researchers began to accept the idea of aggregation among homogeneous cells, without any pacemaker. But the decade-long resistance serves as some indication of the strength of the centralized mindset.

The centralized mindset can manifest itself in many different ways. When people observe patterns or structures in the world, they tend to assume that patterns are created either *by lead* or *by seed.* That is, they assume that a *leader* orchestrated the pattern (e.g., the bird at the front of the flock, the pacemaker slime-mold cell), or they assume that some *seed* (some preexisting, built-in inhomogeneity in the environment) gave rise to the pattern, much as a grain of sand gives rise to a pearl.

In some ways, it is not surprising that people tend to assume centralized control, even where none exists. Many phenomena in the world *are,* in fact, organized by a central designer. These phenomena act to reinforce the centralized mindset. When people see neat rows of corn in a field, they assume (correctly) that the corn was planted by a farmer. When people watch a ballet, they assume (correctly) that the movements of the dancers were planned by a choreographer. Moreover, most people participate in social systems (such as families and school classrooms) where power and authority are very centralized (sometimes excessively so).

In fact, centralized strategies are often very useful. Sometimes, it is a good idea to put someone or something in charge. The problem is that people, in the past, have relied almost entirely on centralized strategies. Decentralized approaches have been ignored, undervalued, and overlooked. Centralized solutions have been seen as *the* solution.

3 Tools for Learning

How can people move beyond this centralized mind-set? How can they develop new intuitions about decentralized phenomena? The methodology of Artificial Life suggests a solution. One of the basic tenets of Artificial Life is that the best way to learn about living systems is to try to construct living systems (or, at least, models and simulations of living systems). This idea holds true whether the learners are scientists or children. To help people move beyond the centralized mindset, it makes sense to provide them with opportunities to create, experiment, and play with decentralized systems.

This approach has strong backing in educational and psychological research, most notably in the so-called constructionist theory of learning [16,17]. Constructionism involves two types of construction. First, borrowing from the "constructivist" theories of Jean Piaget, it asserts that learning is an active process, in which people actively construct knowledge from the experiences in the world. To this, constructionism adds the idea that people construct new knowledge with particular effectiveness when they are engaged in constructing personally meaningful artifacts—be they sand castles, stories, LEGO robots, or computer programs.

Though constructionism shares certain ideas with "hands-on" approaches to education, it goes beyond hands-on in several important ways. In many hands-on activities, students simply follow a "recipe" of what to do. Students are limited in how far they can improvise and explore. Consider prepackaged simulations. No matter how well a prepackaged simulation is designed, it cannot take into account all of the possible "what if" questions that users will want to ask. A constructionist alternative is to provide students with tools so that they can construct (and modify) their own simulations. This approach not only expands the possible range of explorations, it also makes those explorations more personally meaningful.

The constructionist approach received a lasting endorsement from the great physicist Richard Feynman. On the day that Feynman died, the following message was found on his office blackboard: "What I cannot create, I do not understand" [6]. What was true for Feynman is true for the rest of us. One of the best ways to gain a deeper understanding of something is to create it, to construct it, to build it.

So to help people learn about decentralized systems, we need to provide them with new sets of tools for creating and experimenting with such systems. But what types of tools are needed? Over the years, computer scientists have developed a wide variety of decentralized computational models—such as neural networks [21], the subsumption architecture [3], and cellular automata [23]. In all of these models, orderly patterns can arise from interactions among a decentralized collection of computational objects. In neural networks, patterns of "activation" arise from interactions among low-level "nodes." With the subsumption architecture, actions of a robotic creature arise from interactions among low-level "behaviors."

These models, while very useful for professional researchers, are ill-suited for people who have little experience with (or little interest in) manipulating formal systems. In general, these models are based on objects and interactions that most people are not familar with. For example, the idea of writing "transition rules" for "cells" is not an idea that most people can relate to.

In recent years, a number of computer programs have attempted to bring ideas about decentralized systems to a broader audience. Some programs, such as Vehicles (based on Braitenberg [2]) and LEGO/Logo [18], allow people to explore simple animal behaviors. Other programs, such as Agar [24], SimAnt [13], and StarLogo [19,20], allow people to explore the collective behavior of social insects. Still others, such as SimLife [8], Echo [7], and Simulated Evolution [15], allow people to explore evolutionary behavior.

These programs, too, are limited as learning tools. Too often, these programs shield users from underlying mechanisms, preventing users from investigating, let alone modifying, the underlying models. And in many cases, the programs focus too much on achieving interesting behaviors and too little on helping users make sense of those behaviors. But these programs represent a good first step in making ideas about decentralized systems accessible to a broader (and younger) audience.

4 Learning Experiences

This section examines the types of learning experiences made possible by these new computational tools. The examples focus on two tools that I helped develop: LEGO/Logo and StarLogo.

LEGO/Logo is a type of creature construction kit. With LEGO/Logo, children can build robotic "creatures" out of LEGO pieces, using not only the traditional LEGO building bricks but also newer LEGO pieces like gears, motors, and sensors. Then, they write computer programs (using a modified version of the programming language Logo) to control the behaviors of the creatures.

StarLogo is a massively parallel programming language, designed especially for nonexpert programmers. With StarLogo, people can write rules for thousands of graphic creatures on the computer screen, then observe the group level behaviors that emerge from the interactions. People can also write rules for "patches" of the world in which the creatures live, allowing new types of creature–environment interactions. For example, Figure 1 shows a StarLogo simulation inspired by the discussion of slime-mold aggregation. Each "creature" emits a chemical pheromone, while also following the gradient of the pheromone. The patches cause the pheromone to diffuse and evaporate. With this simple decentralized strategy, the creatures aggregate into clusters after several dozen time steps.

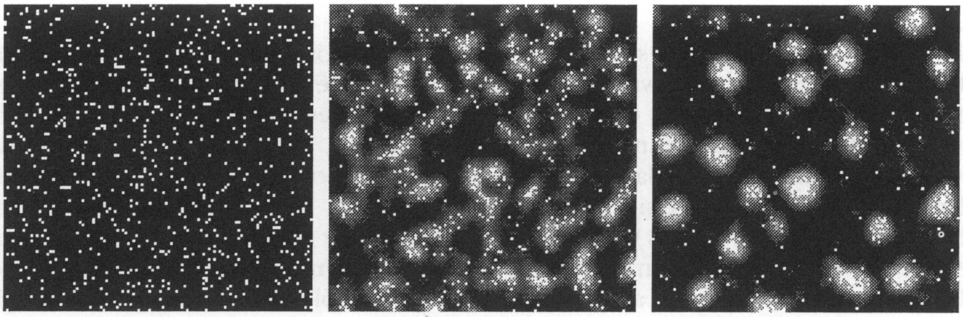

Figure 1. StarLogo simulation inspired by slime-mold aggregation.

4.1 LEGO/Logo Creatures

A major goal of Artificial Life research is to gain a better understanding of emergent phenomena. As Langton [11] put it, "The 'key' concept in Artificial Life is emergent behavior. Natural life emerges out of the organized interactions of a great number of nonliving molecules, with no global controller responsible for the behavior of every part."

In many animal systems, there are two types of emergence. First, the behavior of each individual creature emerges from interactions among the "agents" that make up the creature's mind. At the same time, the behavior of the entire animal colony or society emerges from the interactions among the individual creatures. In short, the colony level emerges from the creature level, which in turn emerges from the agent level.

With LEGO/Logo, children can begin to observe and experiment with simple emergent behaviors. Consider a simple LEGO creature with a light sensor pointing upward. Imagine that the creature is programmed with two rules: (a) move forward when you detect light, (b) move backward when you are in the dark. When this creature is released in the environment, it exhibits a type of emergent behavior: It seeks out the edge of a shadow, then happily oscillates around the shadow edge. The creature can be viewed as an "Edge-Finding Creature." This edge-finding capability is not explicitly represented in the creature's two rules. Rather, it emerges from interactions of those rules with specific structures in the environment.

Here is another example. When we started to develop LEGO/Logo, one of our first projects was to program a LEGO "turtle" to follow a line on the floor. The basic strategy was to make the turtle weave back and forth across the line, making a little forward progress on each swing. First, the turtle veered ahead and to the right, until it lost sight of the line. Then it veered ahead and to the left, until it again lost sight of the line. Then it started back to the right, and so on. This behavior can be represented by two simple rules: (a) If you are veering to the left and you lose sight of the line, begin to veer right; and (b) if you are veering to the right and you lose sight of the line, begin to veer left.

We tried the program, and the turtle followed the line perfectly. But as the turtle approached the end of the line, we realized that we hadn't "programmed in" any rules for what to do at the end of the line. We didn't know what the turtle would do. We were pleased with the behavior that emerged: The turtle turned all the way around and started heading back down the line in the other direction. This "end-of-line" behavior was not explicitly programmed into the turtle. Rather, it emerged from the interactions between the turtle's rules and the unfamiliar environment at the end of the line.

Of course, these examples represent very, very simple cases of emergence. But that is precisely what children (and, for that matter, learners of all ages) need, in order to start making sense of the unfamiliar concept of emergence.

4.2 StarLogo 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 10 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 [25] 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."

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). Instead, I worked together with a high-school student, named Callie, on a simpler project: program the termites to collect wood chips and put them into piles. At the start of the program, wood chips were scattered randomly throughout the termites' world. The challenge was to make the termites organize the wood chips into a few, orderly piles.

We started with a very simple strategy. We made each individual termite obey the following rules:

- If you are not carrying anything and you bump into a wood chip, pick it up.
- If you are carrying a wood chip and you bump into another wood chip, put down the wood chip you're carrying.

At first, we were skeptical that this simple strategy would work. There was no mechanism for preventing termites from taking wood chips away from existing piles. So while termites are putting new wood chips on a pile, other termites might be taking wood chips away from it. It seemed like a good prescription for getting nowhere. But we pushed ahead and implemented the strategy in a StarLogo program, with 1,000 termites and 2,000 wood chips scattered in a 128 × 128 grid.

We tried the program, and (much to our surprise) it worked quite well. At first, the termites gathered the wood chips into hundreds of small piles. But gradually,

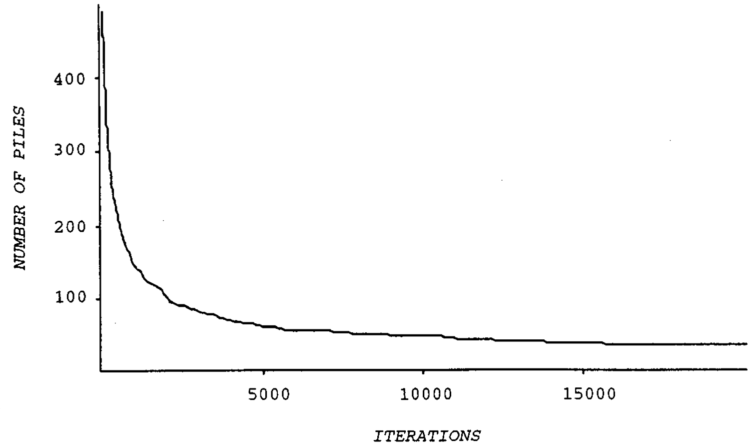

Figure 2. The number of piles decreases monotonically.

the number of piles declined, while the number of wood chips in each surviving pile increased (see Figure 2). After 2,000 iterations, there were about 100 piles, with an average of 15 wood chips in each pile. After 10,000 iterations, there were fewer than 50 piles left, with an average of 30 wood chips in each pile. After 20,000 iterations, only 34 piles remained, with an average of 44 wood chips in each pile. The process was rather slow. And it was frustrating to watch, because termites often carried wood chips away from well-established piles. But, all in all, the program worked quite well.

Why did it work? As we watched the program, it suddenly seemed obvious. Imagine what happens when the termites (by chance) remove all of the wood chips from a particular pile. Because all of the wood chips are gone from that spot, termites will never again drop wood chips there. So the pile has no way of restarting.

As long as a pile exists, its size is a two-way street: It can either grow or shrink. But the *existence* of a pile is a one-way street: Once it is gone, it is gone forever. Thus, a pile is somewhat analogous to a species of creatures in the real world. As long as the species exists, the number of individuals in the species can go up or down. But once all of the individuals are gone, the species is extinct, gone forever. In these cases, zero is a "trapped state": Once the number of creatures in a species (or the number of wood chips in a pile) goes to zero, it can never rebound.

Of course, the analogy between species and piles breaks down in some ways. New species are sometimes created, as offshoots of existing species. But in the termite program, as written, there is no way to create a new pile. The program starts with roughly 2,000 wood chips. These wood chips can be viewed as 2,000 "piles," each with a single wood chip. As the program runs, some piles disappear, and no new piles are created. So the total number of piles keeps shrinking and shrinking.

Callie seemed to thrive in the decentralized environment of StarLogo. At one point, while we were struggling to get our termite program working, I asked Callie if we should give up on our decentralized approach and program the termites to take their wood chips to predesignated spots. Callie quickly dismissed this suggestion:

Mitchel: We could write the program so that the termites know where the piles are. As soon as a termite picks up a wood chip, it could just go to the pile and put it down.

Callie: Oh, that's boring!

Mitchel: Why do you think that's boring?

Callie: 'Cause you're telling them what to do.

Mitchel: Is this more like the way it would be in the real world?

Callie: Yeah. You would almost know what to expect if you tell them to go to a particular spot and put it down. You know that there will be three piles. Whereas here, you don't know how many mounds there are going to be. Or if the number of mounds will increase or decrease. Or things like that.... This way, they [the termites] made the piles by themselves. It wasn't like they [the piles] were artificially put in.

For Callie, preprogrammed behavior, even if effective, was "boring." Callie preferred the decentralized approach because it made the termites seem more independent ("they made the piles by themselves") and less predictable ("you don't know how many mounds there are going to be").

5 Decentralized Thinking

Like Callie, many students are fascinated by decentralized phenomena. But they also have a difficult time understanding and creating such phenomena. They often slip back into centralized ways of thinking. As I have worked with students, I have developed a list of "guiding ideas" that seem to help students make sense of decentralized phenomena. These guiding ideas are not very "strong." They are neither prescriptive nor predictive. They don't tell you precisely how to think about decentralized systems, and they don't tell you how to make accurate predictions about such systems. Rather, they are ideas to keep in mind as you try to make sense of an unfamiliar system, or to design a new one. They highlight some pitfalls to avoid and some possibilities not to overlook. In this section, I discuss five of these guiding ideas.

5.1 Positive Feedback Isn't Always Negative

Positive feedback has an image problem. People tend to see positive feedback as destructive, making things spiral out of control. For most people, positive feedback is symbolized by the screeching sound that results when a microphone is placed near a speaker. By contrast, negative feedback is viewed as very useful, keeping things under control. Negative feedback is symbolized by the thermostat, keeping room temperature at a desired level by turning the heater on and off as needed.

Historically, researchers have paid much more attention to negative feedback than to positive feedback. As Deneubourg and Goss [5] note, "When feedback is discussed in animal groups, it is nearly always negative feedback that is considered, and its role is limited to that of a regulatory mechanism, in which fluctuations are damped and equilibrium is the goal.... Positive feedback is only rarely considered."

When I asked high-school students about positive feedback, most weren't familiar with the term. But they were certainly familiar with the concept. When I explained what I meant by positive feedback, the students quickly generated examples. Not surprisingly, almost all of their examples involved something getting out of control, often with destructive consequences. One student talked about scratching a mosquito bite, which made the bite itch even more, so she scratched it some more, which made it itch even more, and so on. Another student talked about stock market crashes: A few people start selling, which makes more people start selling, which makes even more people start selling, and so on.

Despite these negative images, positive feedback often plays a crucial role in decentralized phenomena. Economist Brian Arthur [1] points to the geographic distribution of cities and industries as an example of a self-organizing process driven by positive feedback. Once a small nucleus of high-technology electronics companies started in Santa Clara County south of San Francisco, an infrastructure developed to serve the needs of those companies. That infrastructure encouraged even more electronics companies to locate in Santa Clara County, which encouraged the development of an even more robust infrastructure. And, thus, Silicon Valley was born.

For some students who used StarLogo, the idea of positive feedback provided a new way of looking at their world. One day, one student came to me excitedly. He had been in downtown Boston at lunch time, and he had a vision. He imagined two people walking into a deli to buy lunch:

> Once they get their food, they don't eat it there. They bring it back with them. Other people on the street smell the sandwiches and see the deli bag, and they say, "Hey, maybe I'll go to the deli for lunch today!" They were just walking down the street, minding their own business, and all of a sudden they want to go to the deli. As more people go to the deli, there's even more smell and more bags. So more people go to the deli. But then the deli runs out of food. There's no more smell on the street from the sandwiches. So no one else goes to the deli.

5.2 Randomness Can Help Create Order

Like positive feedback, randomness has a bad image. Most people see randomness as annoying at best, destructive at worst. They view randomness in opposition to order: Randomness undoes order, it makes things disorderly.

In fact, randomness plays an important role in many self-organizing systems. As discussed earlier, people often assume that "seeds" are needed to initiate patterns and structures. When people see a traffic jam, for example, they assume the traffic jam grew from a seed—perhaps a broken bridge or a radar trap. In general, this is a useful intuition. The problem is that most people have too narrow a conception of "seeds." They think only of preexisting inhomogeneities in the environment—like a broken bridge on the highway, or a piece of food in an ant's world.

This narrow view of seeds causes misintuitions when people try to make sense of self-organizing systems. In self-organizing systems, seeds are neither preexisting nor externally imposed. Rather, self-organizing systems often create *their own* seeds. It is here that randomness plays a crucial role. In many self-organizing systems, random fluctuations act as the "seeds" from which patterns and structures grow.

This combination of random fluctuations plus positive feedback underlies many everyday phenomena. Sometimes, at concerts or sporting events, thousands of spectators join together in rhythmic, synchronized clapping. How do they coordinate their applause? There is no conductor leading them. Here's one way to think about what happens. Initially, when everyone starts clapping, the applause is totally unorganized. Even people clapping at the same tempo are wildly out of phase with one another. But, through some random fluctuation, a small subset of people happen to clap at the same tempo, in phase with one another. That rhythm stands out, just a little, in the clapping noise. People in the audience sense this emerging rhythm and adjust their own clapping to join it. Thus, the emerging rhythm becomes a little stronger, and even more people conform to it. Eventually, nearly everyone in the audience is clapping in a synchronized rhythm. Amazingly, the whole process takes just a few seconds, even with thousands of people participating.

5.3 A Flock Isn't a Big Bird

In trying to make sense of decentralized systems and self-organizing phenomena, the idea of *levels* is critically important. Interactions among objects at one level give rise to new types of objects at another level. Interactions among slime-mold cells give rise to slime-mold clusters. Interactions among ants give rise to foraging trails. Interactions among cars give rise to traffic jams. Interactions among birds give rise to flocks.

In many cases, the objects on one level behave very differently than objects on another level. For high-school students, these differences in behavior can be very surprising, if not confusing. For example, several high-school students used StarLogo to explore the behavior of traffic jams. They wrote simple rules for each car (if there is a car close ahead of you, slow down; if not, speed up), then observed the traffic jams that resulted from the interactions. The students were shocked when the traffic jams began to move backward, even though all of the cars within the jams were moving forward.

Confusion of levels is not a problem restricted to scientifically naive high-school students. I showed the StarLogo traffic program to two visiting researchers, each of whom is involved in the cybernetics research community. They were not at all surprised that the traffic jams were moving backward. They were well aware of that phenomenon. But then one of the researchers said, "You know, I've heard that's why there are so many accidents on the freeways in Los Angeles. The traffic jams are moving backward and the cars are rushing forward, so there are lots of accidents." The other researcher thought for a moment, then replied, "Wait a minute. Cars crash into other cars, not into traffic jams." In short, he felt that the first researcher had confused levels, mixing cars and jams inappropriately. The two researchers then spent half an hour trying to sort out the problem.

5.4 A Traffic Jam Isn't Just a Collection of Cars

For most everyday objects, it is fair to think of the object as a collection of particular parts. (A particular chair might have four particular legs, a particular seat, a particular back.) But not so with objects like traffic jams. Thinking of a traffic jam as a collection of particular parts is a sure path to confusion. The cars composing a traffic jam are always changing, as some cars leave the front of the jam and others join from behind. Even when all of the cars in the jam are replaced with new cars, it is still the same traffic jam. A traffic jam can be thought of as an "emergent object"—it emerges from the interactions among lower-level objects (in this case, cars).

As students work on StarLogo projects, they encounter many emergent objects. In the termite example discussed earlier, the wood chip piles can be viewed as emergent objects. The precise composition of the piles is always changing, as termites take away some wood chips and add other wood chips. After a while, none of the original wood chips remains, but the pile is still there.

Students often have difficulty thinking about emergent objects. Two students, Frank and Ramesh, tried to use StarLogo to create "ant cemeteries." In their own (real) ant farms, they had observed ants gathering their dead colleagues into neat piles. They wondered how the ants did that. This problem is virtually identical to the problem of termites gathering wood chips into piles. But Frank and Ramesh resisted the simple decentralized approach that Callie and I used for the termites. They were adamant that dead ants should never be taken from a cemetery once placed there. They felt that the ants themselves defined the cemetary. How can a cemetery grow, they argued, if the dead ants in it are continually being taken away? In fact, if Frank and Ramesh had viewed the cemetary as an emergent object and allowed the composition of ant cemeteries to vary with time (as Callie and I allowed the composition of the wood chip piles to vary in the termite project), they probably would have been much more successful in their project.

5.5 The Hills are Alive

In *Sciences of the Artificial* [22], Simon describes a scene in which an ant is walking on a beach. Simon notes that the ant's path might be quite complex. But the complexity of the path, says Simon, is not necessarily a reflection of the complexity of the ant. Rather, it might reflect the complexity of the beach. Simon's point: don't underestimate the role of the environment in influencing and constraining behavior. People often seem to think of the environment as something to be *acted upon*, not something to be *interacted with*. People tend to focus on the behaviors of individual objects, ignoring the environment that surrounds (and interacts with) the objects.

A richer view of the environment is particularly important in thinking about decentralized and self-organizing systems. In designing StarLogo, I explicitly tried to highlight the environment. Most creature-oriented programming environments treat the environment as a passive entity, manipulated by the creature that move within it. In StarLogo, by contrast, the "patches" of the world have equal status with the creatures that move in the world. The environment is "alive"—it can execute actions even as creatures move within it. By reifying the environment, I hoped to encourage people to think about the environment in new ways.

Some students, however, resisted the idea of an active environment. When I explained a StarLogo ant-foraging program to one student, he was worried that pheromone trails would continue to attract ants even after the food sources at the ends of the trails had been fully depleted. He developed an elaborate scheme in which the ants, after collecting all of the food, deposited a second pheromone to neutralize the first pheromone. It never occurred to him to let the first pheromone evaporate away. In his mind, the ants had to take some positive action to get rid of the first pheromone. They couldn't rely on the environment to make the first pheromone go away.

6 Conclusions

The centralized mindset has undoubtedly affected many theories and trends in the history of science. Just as children assimilate new information by fitting it into their preexisting models and conceptions of the world, so do scientists. As Keller [9] puts it, "In our zealous desire for familiar models of explanation, we risk not noticing the discrepancies between our own predispositions and the range of possibilities inherent in natural phenomena. In short we risk imposing on nature the very stories we like to hear." In particular, we risk imposing centralized models on a decentralized world.

For many years, there has been a self-reinforcing spiral. People saw the world in centralized ways, so they constructed centralized tools and models, which further encouraged a centralized view of the world. Until recently, there was little pressure against this centralization spiral. For many things that people created and organized, centralized approaches tended to be adequate, even superior to decentralized ones. Even if someone wanted to experiment with decentralized approaches, there were few tools or opportunities to do so.

But the centralization spiral is now starting to unwind. As organizations and scientific models grow more complex, there is a greater need for decentralized ideas. At the same time, new decentralized tools (like StarLogo) are emerging that enable people to actually implement and explore such ideas. Still, many challenges lie ahead. We need to develop better explanations of why people are so committed to centralized explanations. And we need to develop better tools to help people visualize and manipulate decentralized interactions. Ultimately, we need to develop new tools and theories that avoid the simple dichotomy between centralization and decentralization, but rather find ways to integrate the two approaches, drawing on the best of both. Only then will we truly be ready to move beyond the centralized mindset.

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