

An aerial map of a city grid, likely New York City, is visible in the top right corner of the cover. The map is rendered in a light blue color, matching the overall background.

# EMERGENCE

THE CONNECTED LIVES OF ANTS,  
BRAINS, CITIES, AND SOFTWARE



STEVEN JOHNSON

A detailed circuit board pattern is visible in the bottom left corner of the cover. The pattern is rendered in a light blue color, matching the overall background.

## INTRODUCTION

### Here Comes Everybody!

In August of 2000, a Japanese scientist named Toshiyuki Nakagaki announced that he had trained an amoebalike organism called slime mold to find the shortest route through a maze. Nakagaki had placed the mold in a small maze comprising four possible routes and planted pieces of food at two of the exits. Despite its being an incredibly primitive organism (a close relative of ordinary fungi) with no centralized brain whatsoever, the slime mold managed to plot the most efficient route to the food, stretching its body through the maze so that it connected directly to the two food sources. Without any apparent cognitive resources, the slime mold had “solved” the maze puzzle.

For such a simple organism, the slime mold has an impressive intellectual pedigree. Nakagaki’s announcement was only the latest in a long chain of investigations into the subtleties of slime mold behavior. For scientists trying to understand systems that use rela-

tively simple components to build higher-level intelligence, the slime mold may someday be seen as the equivalent of the finches and tortoises that Darwin observed on the Galápagos Islands.

How did such a lowly organism come to play such an important scientific role? That story begins in the late sixties in New York City, with a scientist named Evelyn Fox Keller. A Harvard Ph.D. in physics, Keller had written her dissertation on molecular biology, and she had spent some time exploring the nascent field of "non-equilibrium thermodynamics," which in later years would come to be associated with complexity theory. By 1968, she was working as an associate at Sloan-Kettering in Manhattan, thinking about the application of mathematics to biological problems. Mathematics had played such a tremendous role in expanding our understanding of physics, Keller thought—so perhaps it might also be useful for understanding living systems.

In the spring of 1968, Keller met a visiting scholar named Lee Segel, an applied mathematician who shared her interests. It was Segel who first introduced her to the bizarre conduct of the slime mold, and together they began a series of investigations that would help transform not just our understanding of biological development but also the disparate worlds of brain science, software design, and urban studies.

If you're reading these words during the summer in a suburban or rural part of the world, chances are somewhere near you a slime mold is growing. Walk through a normally cool, damp section of a forest on a dry and sunny day, or sift through the bark mulch that lies on a garden floor, and you may find a grotesque substance coating a few inches of rotting wood. On first inspection, the reddish orange mass suggests that the neighbor's dog has eaten something disagreeable, but if you observe the slime mold over several days—or, even better, capture it with time-lapse photography—you'll discover that it moves, ever so slowly, across the soil. If the weather

conditions grow wetter and cooler, you may return to the same spot and find the creature has disappeared altogether. Has it wandered off to some other part of the forest? Or somehow vanished into thin air, like a puddle of water evaporating?

As it turns out, the slime mold (*Dictyostelium discoideum*) has done something far more mysterious, a trick of biology that had confounded scientists for centuries, before Keller and Segel began their collaboration. The slime mold behavior was so odd, in fact, that understanding it required thinking outside the boundaries of traditional disciplines—which may be why it took a molecular biologist with a physics Ph.D.'s instincts to unravel the slime mold's mystery. For that is no disappearing act on the garden floor. The slime mold spends much of its life as thousands of distinct single-celled units, each moving separately from its other comrades. Under the right conditions, those myriad cells will coalesce again into a single, larger organism, which then begins its leisurely crawl across the garden floor, consuming rotting leaves and wood as it moves about. When the environment is less hospitable, the slime mold acts as a single organism; when the weather turns cooler and the mold enjoys a large food supply, "it" becomes a "they." The slime mold oscillates between being a single creature and a swarm.

While slime mold cells are relatively simple, they have attracted a disproportionate amount of attention from a number of different disciplines—embryology, mathematics, computer science—because they display such an intriguing example of coordinated group behavior. Anyone who has ever contemplated the great mystery of human physiology—how do all my cells manage to work so well together?—will find something resonant in the slime mold's swarm. If we could only figure out how the *Dictyostelium* pull it off, maybe we would gain some insight on our own baffling togetherness.

"I was at Sloan-Kettering in the biomath department—and it was a very small department," Keller says today, laughing. While

the field of mathematical biology was relatively new in the late sixties, it had a fascinating, if enigmatic, precedent in a then-little-known essay written by Alan Turing, the brilliant English code-breaker from World War II who also helped invent the digital computer. One of Turing's last published papers, before his death in 1954, had studied the riddle of "morphogenesis"—the capacity of all life-forms to develop ever more baroque bodies out of impossibly simple beginnings. Turing's paper had focused more on the recurring numerical patterns of flowers, but it demonstrated using mathematical tools how a complex organism could assemble itself without any master planner calling the shots.

"I was thinking about slime mold aggregation as a model for thinking about development, and I came across Turing's paper," Keller says now, from her office at MIT. "And I thought: Bingo!"

For some time, researchers had understood that slime cells emitted a common substance called acrasin (also known as cyclic AMP), which was somehow involved in the aggregation process. But until Keller began her investigations, the conventional belief had been that slime mold swarms formed at the command of "pacemaker" cells that ordered the other cells to begin aggregating. In 1962, Harvard's B. M. Shafer showed how the pacemakers could use cyclic AMP as a signal of sorts to rally the troops; the slime mold generals would release the compounds at the appropriate moments, triggering waves of cyclic AMP that washed through the entire community, as each isolated cell relayed the signal to its neighbors. Slime mold aggregation, in effect, was a giant game of Telephone—but only a few elite cells placed the original call.

It seemed like a perfectly reasonable explanation. We're naturally predisposed to think in terms of pacemakers, whether we're talking about fungi, political systems, or our own bodies. Our actions seem governed for the most part by the pacemaker cells in our brains, and for millennia we've built elaborate pacemakers cells



into our social organizations, whether they come in the form of kings, dictators, or city councilmen. Much of the world around us can be explained in terms of command systems and hierarchies—why should it be any different for the slime molds?

But Shafer's theory had one small problem: no one could find the pacemakers. While all observers agreed that waves of cyclic AMP did indeed flow through the slime mold community before aggregation, all the cells in the community were effectively interchangeable. None of them possessed any distinguishing characteristics that might elevate them to pacemaker status. Shafer's theory had presumed the existence of a cellular monarchy commanding the masses, but as it turned out, all slime mold cells were created equal.

For the twenty years that followed the publication of Shafer's original essay, mycologists assumed that the missing pacemaker cells were a sign of insufficient data, or poorly designed experiments: The generals were there somewhere in the mix, the scholars assumed—they just didn't know what their uniforms looked like yet. But Keller and Segel took another, more radical approach. Turing's work on morphogenesis had sketched out a mathematical model wherein simple agents following simple rules could generate amazingly complex structures; perhaps the aggregations of slime mold cells were a real-world example of that behavior. Turing had focused primarily on the interactions between cells in a single organism, but it was perfectly reasonable to assume that the math would work for aggregations of free-floating cells. And so Keller started to think: What if Shafer had it wrong all along? What if the community of slime mold cells were organizing themselves? What if there were no pacemakers?

Keller and Segel's hunch paid off dramatically. While they lacked the advanced visualization tools of today's computers, the two scratched out a series of equations using pen and paper, equa-

tions that demonstrated how slime cells could trigger aggregation without following a leader, simply by altering the amount of cyclic AMP they released individually, then following trails of the pheromone that they encountered as they wandered through their environment. If the slime cells pumped out enough cyclic AMP, clusters of cells would start to form. Cells would begin following trails created by other cells, creating a positive feedback loop that encouraged more cells to join the cluster. If each solo cell was simply releasing cyclic AMP based on its own local assessment of the general conditions, Keller and Segel argued in a paper published in 1969, then the larger slime mold community might well be able to aggregate based on global changes in the environment—all without a pacemaker cell calling the shots.

"The response was very interesting," Keller says now. "For anyone who understood applied mathematics, or had any experience in fluid dynamics, this was old hat to them. But to biologists, it didn't make any sense. I would give seminars to biologists, and they'd say, 'So? Where's the founder cell? Where's the pacemaker?' It didn't provide any satisfaction to them whatsoever." Indeed, the pacemaker hypothesis would continue as the reigning model for another decade, until a series of experiments convincingly proved that the slime mold cells were organizing from below. "It amazes me how difficult it is for people to think in terms of collective phenomenon," Keller says today.

Thirty years after the two researchers first sketched out their theory on paper, slime mold aggregation is now recognized as a classic case study in bottom-up behavior. Keller's colleague at MIT Mitch Resnick has even developed a computer simulation of slime mold cells aggregating, allowing students to explore the eerie, invisible hand of self-organization by altering the number of cells in the environment, and the levels of cyclic AMP distributed. First-time users of Resnick's simulation invariably say that the on-screen

images—brilliant clusters of red cells and green pheromone trails—remind them of video games, and in fact the comparison reveals a secret lineage. Some of today's most popular computer games resemble slime mold cells because they are loosely based on the equations that Keller and Segel formulated by hand in the late sixties. We like to talk about life on earth evolving out of the primordial soup. We could just as easily say that the most interesting digital life on our computer screens today evolved out of the slime mold.

You can think of Segel and Keller's breakthrough as one of the first few stones to start tumbling at the outset of a landslide. Other stones were moving along with theirs—some of whose trajectories we'll follow in the coming pages—but that initial movement was nothing compared to the avalanche that followed over the next two decades. At the end of its course, that landslide had somehow conjured up a handful of fully credited scientific disciplines, a global network of research labs and think tanks, and an entire patois of buzzwords. Thirty years after Keller challenged the pacemaker hypothesis, students now take courses in "self-organization studies," and bottom-up software helps organize the Web's most lively virtual communities. But Keller's challenge did more than help trigger a series of intellectual trends. It also unearthed a secret history of decentralized thinking, a history that had been submerged for many years beneath the weight of the pacemaker hypothesis and the traditional boundaries of scientific research. People had been thinking about emergent behavior in all its diverse guises for centuries, if not millennia, but all that thinking had consistently been ignored as a unified body of work—because there was nothing unified about its body. There were isolated cells pursuing the mysteries of emergence, but no aggregation.



Indeed, some of the great minds of the last few centuries—Adam Smith, Friedrich Engels, Charles Darwin, Alan Turing—contributed to the unknown science of self-organization, but because the science didn't exist yet as a recognized field, their work ended up being filed on more familiar shelves. From a certain angle, those taxonomies made sense, because the leading figures of this new discipline didn't even themselves realize that they were struggling to understand the laws of emergence. They were wrestling with local issues, in clearly defined fields: how ant colonies learn to forage and built nests; why industrial neighborhoods form along class lines; how our minds learn to recognize faces. You can answer all of these questions without resorting to the sciences of complexity and self-organization, but those answers all share a common pattern, as clear as the whorls of a fingerprint. But to see it as a pattern you needed to encounter it in several contexts. Only when the pattern was detected did people begin to think about studying self-organizing systems on their own merits. Keller and Segel saw it in the slime mold assemblages; Jane Jacobs saw it in the formation of city neighborhoods; Marvin Minsky in the distributed networks of the human brain.

What features do all these systems share? In the simplest terms, they solve problems by drawing on masses of relatively stupid elements, rather than a single, intelligent "executive branch." They are bottom-up systems, not top-down. They get their smarts from below. In a more technical language, they are complex adaptive systems that display emergent behavior. In these systems, agents residing on one scale start producing behavior that lies one scale above them: ants create colonies; urbanites create neighborhoods; simple pattern-recognition software learns how to recommend new books. The movement from low-level rules to higher-level sophistication is what we call emergence.

Imagine a billiard table populated by semi-intelligent, motor-

ized billiard balls that have been programmed to explore the space of the table and alter their movement patterns based on specific interactions with other balls. For the most part, the table is in permanent motion, with balls colliding constantly, switching directions and speed every second. Because they are motorized, they never slow down unless their rules instruct them to, and their programming enables them to take unexpected turns when they encounter other balls. Such a system would define the most elemental form of *complex* behavior: a system with multiple agents dynamically interacting in multiple ways, following local rules and oblivious to any higher-level instructions. But it wouldn't truly be considered *emergent* until those local interactions resulted in some kind of discernible macrobehavior. Say the local rules of behavior followed by the balls ended up dividing the table into two clusters of even-numbered and odd-numbered balls. That would mark the beginnings of emergence, a higher-level pattern arising out of parallel complex interactions between local agents. The balls aren't programmed explicitly to cluster in two groups; they're programmed to follow much more random rules: swerve left when they collide with a solid-colored; accelerate after contact with the three ball; stop dead in their tracks when they hit the eight ball; and so on. Yet out of those low-level routines, a coherent shape emerges.

Does that make our mechanized billiard table *adaptive*? Not really, because a table divided between two clusters of balls is not terribly useful, either to the billiard balls themselves or to anyone else in the pool hall. But, like the proverbial *Hamlet*-writing monkeys, if we had an infinite number of tables in our pool hall, each following a different set of rules, one of those tables might randomly hit upon a rule set that would arrange all the balls in a perfect triangle, leaving the cue ball across the table ready for the break. That would be adaptive behavior in the larger ecosystem of the pool hall, assuming that it was in the interest of our billiards

system to attract players. The system would use local rules between interacting agents to create higher-level behavior well suited to its environment.

Emergent complexity without adaptation is like the intricate crystals formed by a snowflake: it's a beautiful pattern, but it has no function. The forms of emergent behavior that we'll examine in this book show the distinctive quality of growing smarter over time, and of responding to the specific and changing needs of their environment. In that sense, most of the systems we'll look at are more *dynamic* than our adaptive billiards table: they rarely settle in on a single, frozen shape; they form patterns in time as well as space. A better example might be a table that self-organizes into a billiards-based timing device: with the cue ball bouncing off the eight ball sixty times a minute, and the remaining balls shifting from one side of the table to another every hour on the hour. That might sound like an unlikely system to emerge out of local interactions between individual balls, but your body contains numerous organic clocks built out of simple cells that function in remarkably similar ways. An infinite number of cellular or billiard-ball configurations will not produce a working clock, and only a tiny number will. So the question becomes, how do you push your emergent system toward clocklike behavior, if that's your goal? How do you make a self-organizing system more adaptive?

That question has become particularly crucial, because the history of emergence has entered a new phase in the past few years, one that should prove to be more revolutionary than the two phases before it. In the first phase, inquiring minds struggled to understand the forces of self-organization without realizing what they were up against. In the second, certain sectors of the scientific community began to see self-organization as a problem that transcended local disciplines and set out to solve that problem, partially by comparing behavior in one area to behavior in another. By

watching the slime mold cells next to the ant colonies, you could see the shared behavior in ways that would have been unimaginable watching either on its own. Self-organization became an object of study in its own right, leading to the creation of celebrated research centers such as the Santa Fe Institute, which devoted itself to the study of complexity in all its diverse forms.

But in the third phase—the one that began sometime in the past decade, the one that lies at the very heart of this book—we stopped analyzing emergence and started creating it. We began building self-organizing systems into our software applications, our video games, our art, our music. We built emergent systems to recommend new books, recognize our voices, or find mates. For as long as complex organisms have been alive, they have lived under the laws of self-organization, but in recent years our day-to-day life has become overrun with *artificial* emergence: systems built with a conscious understanding of what emergence is, systems designed to exploit those laws the same way our nuclear reactors exploit the laws of atomic physics. Up to now, the philosophers of emergence have struggled to interpret the world. But they are now starting to change it.

What follows is a tour of fields that aren't usually gathered between the same book jacket covers. We'll look at computer games that simulate living ecologies; the guild system of twelfth-century Florence; the initial cell divisions that mark the very beginning of life; and software that lets you see the patterns of your own brain. What unites these different phenomena is a recurring pattern and shape: a network of self-organization, of disparate agents that unwittingly create a higher-level order. At each scale, you can see the imprint of those slime mold cells converging; at each scale, the laws of emergence hold true.

This book roughly follows the chronology of the three historical phases. The first section introduces one of the emergent world's crowning achievements—the colony behavior of social insects such as ants and termites—and then goes back to trace part of the history of the decentralized mind-set, from Engels on the streets of Manchester to the new forms of emergent software being developed today. The second section is an overview of emergence as we currently understand it; each of the four chapters in the section explores one of the field's core principles: neighbor interaction, pattern recognition, feedback, and indirect control. The final section looks to the future of artificial emergence and speculates on what will happen when our media experiences and political movements are largely shaped by bottom-up forces, and not top-down ones.

Certain shapes and patterns hover over different moments in time, haunting and inspiring the individuals living through those periods. The epic clash and subsequent resolution of the dialectic animated the first half of the nineteenth century; the Darwinian and social reform movements scattered web imagery through the second half of the century. The first few decades of the twentieth century found their ultimate expression in the exuberant anarchy of the explosion, while later decades lost themselves in the faceless regimen of the grid. You can see the last ten years or so as a return to those Victorian webs, though I suspect the image that has been burned into our retinas over the past decade is more prosaic: windows piled atop one another on a screen, or perhaps a mouse clicking on an icon.

These shapes are shorthand for a moment in time, a way of evoking an era and its peculiar obsessions. For individuals living within these periods, the shapes are cognitive building blocks, tools for thought: Charles Darwin and George Eliot used the web as a



way of understanding biological evolution and social struggles; a half century later, the futurists embraced the explosions of machine-gun fire, while Picasso used them to re-create the horrors of war in *Guernica*. The shapes are a way of interpreting the world, and while no shape completely represents its epoch, they are an undeniable component of the history of thinking.

When I imagine the shape that will hover above the first half of the twenty-first century, what comes to mind is not the coiled embrace of the genome, or the etched latticework of the silicon chip. It is instead the pulsing red and green pixels of Mitch Resnick's slime mold simulation, moving erratically across the screen at first, then slowly coalescing into larger forms. The shape of those clusters—with their lifelike irregularity, and their absent pacemakers—is the shape that will define the coming decades. I see them on the screen, growing and dividing, and I think: That way lies the future.

## Street Level

Say what you will about global warming or the Mona Lisa, *Apollo 9* or the canals of Venice—human beings may seem at first glance to be the planet's most successful species, but there's a strong case to be made for the ants. Measured by sheer numbers, ants—and other social insects such as termites—dominate the planet in a way that makes human populations look like an evolutionary afterthought. Ants and termites make up 30 percent of the Amazonian rain forest biomass. With nearly ten thousand known species, ants rival modern humans in their global reach: the only large land-masses free of ant natives are Antarctica, Iceland, Greenland, and Polynesia. And while they have yet to invent aerosol spray, ant species have a massive environmental impact, moving immense amounts of soil and distributing nutrients even in the most hostile environments. They lack our advanced forebrains, of course, but human intelligence is only one measure of evolutionary success.

All of which raises the question, if evolution didn't see fit to endow ants with the computational powers of the human brain, how did they become such a dominant presence on the planet? While there's no single key to the success of the social insects, the collective intelligence of the colony system certainly played an essential role. Call it swarm logic: ten thousand ants—each limited to a meager vocabulary of pheromones and minimal cognitive skills—collectively engage in nuanced and improvisational problem-solving. A harvester ant colony in the field will not only ascertain the shortest route to a food source, it will also prioritize food sources, based on their distance and ease of access. In response to changing external conditions, worker ants switch from nest-building to foraging to raising ant pupae. Their knack for engineering and social coordination can be downright spooky—particularly because none of the individual ants is actually “in charge” of the overall operation. It's this connection between micro and macro organization that got Deborah Gordon into ants in the first place. “I was interested in systems where individuals who are unable to assess the global situation still work together in a coordinated way,” she says now. “And they manage to do it using only local information.”

*Local* turns out to be the key term in understanding the power of swarm logic. We see emergent behavior in systems like ant colonies when the individual agents in the system pay attention to their immediate neighbors rather than wait for orders from above. They think locally *and* act locally, but their collective action produces global behavior. Take the relationship between foraging and colony size. Harvester ant colonies constantly adjust the number of ants actively foraging for food, based on a number of variables: overall colony size (and thus mouths needed to be fed); amount of food stored in the nest; amount of food available in the surrounding area; even the presence of other colonies in the near vicinity. No individual ant can assess any of these variables on her own. (I use

her deliberately—all worker ants are females.) The perceptual world of an ant, in other words, is limited to the street level. There are no bird's-eye views of the colony, no ways to perceive the overall system—and indeed, no cognitive apparatus that could make sense of such a view. "Seeing the whole" is both a perceptual and conceptual impossibility for any member of the ant species.

Indeed, in the ant world, it's probably misguided to talk about "views" at all. While some kinds of ants have surprisingly well-developed optical equipment (the South American formicine ant *Gigantiops destructor* has massive eyes), the great bulk of ant information-processing relies on the chemical compounds of pheromones, also known as semiochemicals for the way they create a functional sign system among the ants. Ants secrete a finite number of chemicals from their rectal and sternal glands—and occasionally regurgitate recently digested food—as a means of communicating with other ants. Those chemical signals turn out to be the key to understanding swarm logic. "The sum of the current evidence," E. O. Wilson and Bert Holldobler write in their epic work, *The Ants*, "indicates that pheromones play the central role in the organization of colonies."

Compared to human languages, ant communication can seem crude, typically possessing only ten or twenty signs. Communication between workers in colonies of the fire ant *Solenopsis invicta*—studied intensely by Wilson in the early sixties—relies on a vocabulary of ten signals, nine of which are based on pheromones. (The one exception is tactile communication directly between ants.) Among other things, these semiochemicals code for task-recognition ("I'm on foraging duty"); trail attraction ("There's food over here"); alarm behavior ("Run away!"); and necrophoric behavior ("Let's get rid of these dead comrades").

While the vocabulary is simple, and complex syntactical structures impossible, the language of the ants is nevertheless character-

EMERGENCE

ized by some intriguing twists that add to its expressive capability. Many semiochemicals operate in a relatively simple binary fashion—signaling, for instance, whether another ant is a friend or a foe. But ants can also detect *gradients* in pheromones, revealing which way the scent is growing stronger, not unlike the olfactory skills of bloodhounds. Gradient detection is essential for forming those food delivery lines that play such a prominent role in the popular imagination of ant life: the seemingly endless stream of ants, each comically overburdened with seeds, marching steadily across sidewalk or soil. (As we will see in Chapter 5, Mitch Resnick's program StarLogo can also model the way colonies both discover food sources and transport the goods back to the home base.) Gradients in the pheromone trail are the difference between saying "There's food around here somewhere" and "There's food due north of here."

Like most of their relatives, the harvester ants that Deborah Gordon studies are also particularly adept at measuring the *frequency* of certain semiochemicals, a talent that also broadens the semantic range of the ant language. Ants can sense the difference between encountering ten foraging ants in an hour and encountering a hundred. Gordon believes this particular skill is critical to the colony's formidable ability to adjust task allocation according to colony size or food supply—a local talent, in other words, that engenders global behavior.

"I don't think that the ants are assessing the size of the colony," she tells me, "but I think that the colony size affects what an ant experiences, which is different. I don't think that an ant is keeping track of how big the whole colony is, but I think that an ant in a big colony has a different experience from an ant in a small colony. And that may account for why large old colonies act different than their small ones." Ants, in Gordon's view, conduct a kind of statistical sample of the overall population size, based on their random encounters with other ants. A foraging ant might expect to meet



three other foragers per minute—if she encounters more than three, she might follow a rule that has her return to the nest. Because larger, older colonies produce more foragers, ants may behave differently in larger colonies because they are more likely to encounter other ants.

This local feedback may well prove to be the secret to the ant world's decentralized planning. Individual ants have no way of knowing how many foragers or nest-builders or trash collectors are on duty at any given time, but they can keep track of how many members of each group they've stumbled across in their daily travels. Based on that information—both the pheromone signal itself, and its frequency over time—they can adjust their own behavior accordingly. The colonies take a problem that human societies might solve with a command system (some kind of broadcast from mission control announcing that there are too many foragers) and instead solve it using statistical probabilities. Given enough ants moving randomly through a finite space, the colony will be able to make an accurate estimate of the overall need for foragers or nest-builders. Of course, it's always possible that an individual ant might randomly stumble across a disproportionate number of foragers and thus overestimate the global foraging state and change her behavior accordingly. But because the decision-making process is spread out over thousands of individuals, the margin of error is vanishingly small. For every ant that happens to overestimate the number of foragers on duty, there's one that underestimates. With a large enough colony, the two will eventually cancel each other out, and an accurate reading will emerge.

If you're building a system designed to learn from the ground level, a system where macrointelligence and adaptability derive from local knowledge, there are five fundamental principles you need to follow. Gordon's harvester ants showcase all of them at work:

**More is different.** This old slogan of complexity theory actually has two meanings that are relevant to our ant colonies. First, the statistical nature of ant interaction demands that there be a critical mass of ants for the colony to make intelligent assessments of its global state. Ten ants roaming across the desert floor will not be able to accurately judge the overall need for foragers or nest-builders, but two thousand will do the job admirably. "More is different" also applies to the distinction between micromotives and macrobehavior: individual ants don't "know" that they're prioritizing pathways between different food sources when they lay down a pheromone gradient near a pile of nutritious seeds. In fact, if we only studied individual ants in isolation, we'd have no way of knowing that those chemical secretions were part of an overall effort to create a mass distribution line, carrying comparatively huge quantities of food back to the nest. It's only by observing the entire system at work that the global behavior becomes apparent.

**Ignorance is useful.** The simplicity of the ant language—and the relative stupidity of the individual ants—is, as the computer programmers say, a feature not a bug. Emergent systems can grow unwieldy when their component parts become excessively complicated. Better to build a densely interconnected system with simple elements, and let the more sophisticated behavior trickle up. (That's one reason why computer chips traffic in the streamlined language of zeros and ones.) Having individual agents capable of directly assessing the overall state of the system can be a real liability in swarm logic, for the same reason that you don't want one of the neurons in your brain to suddenly become sentient.

**Encourage random encounters.** Decentralized systems such as ant colonies rely heavily on the random interactions of ants exploring a given space without any predefined orders. Their encounters with other ants are individually arbitrary, but because there are so many individuals in the system, those encounters even-

tually allow the individuals to gauge and alter the macrostate of the system itself. Without those haphazard encounters, the colony wouldn't be capable of stumbling across new food sources or of adapting to new environmental conditions.

**Look for patterns in the signs.** While the ants don't need an extensive vocabulary and are incapable of syntactical formulations, they do rely heavily on patterns in the semiochemicals they detect. A gradient in a pheromone trail leads them toward a food source, while encountering a high ratio of nest-builders to foragers encourages them to switch tasks. This knack for pattern detection allows meta-information to circulate through the colony mind: signs about signs. Smelling the pheromones of a single forager ant means little, but smelling the pheromones of fifty foragers in the space of an hour imparts information about the global state of the colony.

**Pay attention to your neighbors.** This may well be the most important lesson that the ants have to give us, and the one with the most far-reaching consequences. You can restate it as "Local information can lead to global wisdom." The primary mechanism of swarm logic is the interaction between neighboring ants in the field: ants stumbling across each other, or each other's pheromone trails, while patrolling the area around the nest. Adding ants to the overall system will generate more interactions between neighbors and will consequently enable the colony itself to solve problems and regulate itself more effectively. Without neighboring ants stumbling across one another, colonies would be just a senseless assemblage of individual organisms—a swarm without logic.

Gordon's harvester ant colonies contain another mystery. If we understand how local interactions can lead to global problem-solving, we still don't have an answer to the question of how colonies develop over time. This is one of those scientific questions

that nobody thought to ask, because the phenomenon had gone unobserved. And that phenomenon had gone unobserved because people had been thinking about ants—and watching ants—using the wrong *scale*. Until recently, entomologists studied colony behavior in snapshots, surveying a given nest for days or months at a time, then moving on to other nests or back to the lab. But successful colonies can live as long as fifteen years—the life span of the egg-laying queen ant, whose demise signals the final death of the colony itself. Entomologists had been looking at individual colonies in the scale of weeks or months. But to understand how colonies develop, you needed to work on the scale of decades.

In the mideighties, when she first began doing fieldwork in Arizona, Gordon made a bold research gamble that turned out, in hindsight, to be brilliant: she decided to track individual colonies year to year, following them through their birth at the end of a successful mating flight all the way to their fifteen-year-old senescence. After a half decade or so in this time-consuming project, the results began to come in, and they were fascinating. Like a stop-motion film of a vine winding its way around a branch, Gordon's research transformed the way that we think about ants by transforming the temporal scale with which we perceived them. The colonies cycled through a clearly defined infancy, adolescence, and mature phase over their fifteen-year existence. "I had never thought about it, or read anything about it, because without long-term data, nobody really knows the ages of their colonies," she says now. "So it wasn't until I had been watching the same colonies year after year, and began to be able to count how old the colonies were, that I could start to see that young colonies were more active." As she continued her observations, a number of differences emerged between colonies of varying ages, differences that were eerily reminiscent of other developmental cycles in the animal kingdom.

For one, younger colonies are more fickle. "I've done experiments that mimic the kinds of changes in environment that a colony usually experiences—say, a change in the availability of food," Gordon tells me. "If I do the same experiment week after week with older colonies, I get the same results: they respond the same way over and over. If we do the same experiment week after week with a younger colony, they'll respond one way this week, and another way next week, so the younger colonies are more sensitive to whatever's different about this week than last week."

"Typical teenagers," I say, laughing.

"Maybe." She smiles. "And the other thing that might be more typical of teenagers would be the difference between older and younger colonies in the ways that they respond to their neighbors. Neighboring harvester ant colonies meet when foragers from the two colonies overlap and search the same places for food. If older colonies meet a neighbor one day, the next day they're more likely to turn and go in the other direction to avoid each other. The younger colonies are much more persistent and aggressive, even though they're smaller. So they meet one day and they'll go right back the next day—even if they have to fight."

The developmental cycles of colonies may be intriguing enough at face value, but consider this additional fact: while the overall colony evolves and adapts over fifteen years, the ants that make up the colony live no longer than twelve months. Indeed, the hapless male ants—who only show up once a year for the mating flight—only live for a single day. (Their life span is so abbreviated that natural selection didn't bother to endow them with jaws to eat, since they don't live long enough to get hungry.) Only the queen ant lasts for more than a year, and yet she does nothing but lay eggs and is entirely uninvolved with the behavior of worker ants out in the field. The colony grows more stable and less impetuous as it develops, and yet the population of the colony starts over from scratch



each year. How does the whole develop a life cycle when the parts are so short-lived?

It would not be wrong to say that understanding emergence begins with unraveling this puzzle. The persistence of the whole over time—the global behavior that outlasts any of its component parts—is one of the defining characteristics of complex systems. Generations of ants come and go, and yet the colony itself matures, grows more stable, more organized. The mind naturally boggles at this mix of permanence and instability. We can understand it when we stumble across, say, a Tudor house in the Cotswolds whose every plank and beam and brick has been replaced at least once in its lifetime, because those bricks are being replaced by “master planners”: craftsmen or residents who know what the house itself is supposed to look like, and who deliberately follow the original blueprints. Gordon’s ant colonies are more like a house that automatically replaces its skin once a year, without anybody helping out. Or better yet, given that ant colonies grow more durable over time, it’s like a house that spontaneously develops a sturdier insulation system after five years and sprouts a new garage after ten.

The ant colony may amaze us with its capacity to grow and evolve while discarding entire generations of worker ants, but as it turns out, we’re not all that different from social insects like ants, termites, or bees. As the science writer Matt Ridley observes, “The relationship between body cells is indeed very much like that between bees in a hive. The ancestors of your cells were once individual entities, and their evolutionary ‘decision’ to cooperate, some six hundred million years ago, is almost exactly equivalent to the same decision, taken perhaps fifty million years ago by the social insects, to cooperate on the level of the body; close genetic relatives discovered they could reproduce more effectively if they did so vic-

ariously, delegating the task to germ cells in the cells' case, or to a queen, in the case of bees."

The human body is made up of several hundred different types of cells—muscle, blood, nervous, and so on. At any given time, approximately 75 trillion of these cells are working away in your body. In a very real sense, you are the sum of their actions; there is no *you* without them. And yet those cells are dying all the time! Thousands probably died in the time it took you to read the last sentence, and by next week, you will be composed of billions of new cells that weren't there to enjoy the reading of that sentence, much less enjoy your first step or your high school prom. Cells are dying all the time in your body—and most of them are being replaced at a tremendous clip. (Even brain cells turn out to regenerate themselves far into adulthood.) And yet somehow, despite that enormous cellular turnover, you still feel like yourself week to week and year to year. How is this possible?

Some readers might be inclined to object at this point that humans are in fact closer to that endlessly rebuilt Tudor house than an ant colony, because in the case of human development we do have a master planner and a blueprint that we can follow: those coils of DNA wrapped neatly in every cell in our body. Our cells know how to build our bodies because natural selection has endowed them with a meticulously detailed plan, and has seen to it that 75 trillion copies are distributed throughout our bodies at any given time. The tyranny of DNA would seem to run counter to the principles of emergence: if all the cells are reading from the same playbook, it's not a bottom-up system at all; it's the ultimate in centralization. It would be like an ant colony where each ant started the day with a carefully planned agenda: forage from six to ten; midden duty until noon; lunch; and then cleanup in the afternoon. That's a command economy, not a bottom-up system.

So does this mean our genes are secret Stalins, doling out the

fixed plan for growth to the Stakhanovites of our cells? Are we more like a socialist housing complex than an ant colony? No one questions that DNA exerts an extraordinary influence over the development of our cells, and that each cell in our body contains the same genetic blueprint. If each cell were simply reading from the chromosomal playbook and behaving accordingly, you could indeed make the argument that our bodies don't function like ant colonies. But cells do more than just follow the dictates of DNA. They also learn from their neighbors. And without that local interaction, the master plan of our genetic code would be utterly useless.

Cells draw selectively upon the blueprint of DNA: each cell nucleus contains the entire genome for the organism, but only a tiny segment of that data is read by each individual cell: muscle cells read from the lines of code that concern muscle cells, while blood cells consult the passages that relate to blood cells. This seems simple enough, until you ask the question, how did a muscle cell get to be a muscle cell in the first place? And that question underlies one of the most fundamental mysteries of emergence, which is how complicated organisms, with a wide variety of building blocks, can develop out of such simple beginnings. We all start life as a single-celled organism, and yet by the end of our development cycle, we're somehow composed of two hundred variations, all intricately connected to one another, and all performing stunningly complex tasks. How does an egg somehow know how to build a chicken?

The answer is not all that different from the solution that ant colonies rely on. Cells self-organize into more complicated structures by learning from their neighbors. Each cell in your body contains an intricate set of tools for detecting the state of surrounding cells, and for communicating to those cells using various chemical messengers. Where ants used pheromones to inform each other of

their activities, cells communicate via salts, sugars, amino acids—even larger molecules such as proteins and nucleic acids. The messages are partially transmitted through cell “junctions,” small passageways that admit molecules from one cell’s cytoplasm to another. This communication plays an essential role in all cellular activity, but it is particularly critical for embryonic development during which a single-celled organism self-organizes into a mouse or a roundworm or a human being.

We all begin life as a single-celled embryo, but seconds after conception, the embryo divides itself into two compartments: a “head” and a “tail.” At that point, the organism has joined the ranks of multicellular life, being composed now of two distinct cells. And those two cells—the head and the tail—have separate instructions for growth encoded in their DNA: one cell turns to the “head cell” chapter, the other to the “tail cell” chapter. At this early stage of development, the instructions follow a predictable pattern: divide into another “head” and “tail.” Thus, in the second round of embryonic development, there are four cells: the head of the head, the tail of the head, the head of the tail, and the tail of the tail. Those four units may not sound like much, but this cycle of cell division continues at a blistering clip. A frog embryo self-divides into nearly ten thousand cells in a matter of hours. The runaway power of geometric progression is not just a mathematical oddity—it is also essential to the very origins of life.

Once the embryo reaches a certain size, cell “collectives” start to form, and here matters get more complicated. One group of cells may be the beginning of an arm, while another group may be the first stirrings of the brain’s gray matter. Each cell has somehow to figure out where it is in the larger scheme of things—and yet, like the ants, cells have no way of seeing the whole, and they have no fixed address stamped upon them when they come into the world, no factory serial number. But while cells lack a bird’s-eye view of

the organism that contains them, they can make street-level assessments via the molecular signals transmitted through the cell junctions. This is the secret of self-assembly: cell collectives emerge because each cell looks to its neighbors for cues about how to behave. Those cues directly control what biologists call "gene expression"; they're the cheat sheet that enables each cell to figure out which segment of DNA to consult for its instructions. It's a kind of microscopic herd mentality: a cell looks around to its neighbors and finds that they're all working away steadily at creating an eardrum or a heart valve, which in turn causes the cell to start laboring away at the same task.

The key here is that life does not simply reduce down to transcribing static passages from our genetic scripture. Cells figure out which passages to pay attention to by observing signals from the cells around them: only with that local interaction can complex "neighborhoods" of cell types come into being. The Nobel laureate Gerald Edelman calls this process topobiology, from the Greek word for "place," *topos*. Cells rely heavily on the code of DNA for development, but they also need a sense of place to do their work. Indeed, the code is utterly worthless without the cell's ability to determine its place in the overall organism, a feat that is accomplished by the elegant strategy of paying attention to one's neighbors. As Ridley writes, "The great beauty of embryo development, the bit that human beings find so hard to grasp, is that it is a totally decentralized process. Since every cell in the body carries a complete copy of the genome, no cell need wait for instructions from authority; every cell can act on its own information and the signals it receives from its neighbors." And so we have come full circle back to Gordon's ants, and their uncanny ability to generate coordinated global behavior out of local interactions.

\* \* \*

*Neighbors* and *neighborhoods*. The words seem more attached to the communities of human settlements than the microscopic domains of muscle cells or harvester ants. But how do we extend our vision up one more level on the chain of life to the cultural "superorganism" of the city? Certainly it is possible to *model* the behavior of cities by using the tools of swarm logic. Computer-based simulations can teach us a tremendous amount about complex systems: if a picture is worth a thousand words, an interactive model must be valued in the millions. But a quick look at the software best-seller lists will tell you that city simulations are more than just an educational device. Will Wright's SimCity franchise has now sold millions of copies; it's likely that the number of virtual towns created using Wright's tools exceeds the number of real towns formed in modern human history. Some games attract our attention by appealing to our appetite for storytelling, following a linear progression of move and countermove, with clearly defined beginnings and endings; other games catch the eye by blowing things up. SimCity was one of the first games to exploit the uncanny, bottom-up powers of emergence. Wright's genius was not simply in recognizing the fun of simulating an entire metropolis on your screen. He also hit upon a brilliant programming trick that enabled the city to evolve in a more lifelike way—a trick that closely resembles the behavior of ant colonies and embryos.

Much has been made of the fact that you can't ever "win" at SimCity, but it's probably more important to note that you don't really "play" SimCity either, at least the way we talk about playing conventional games. Users *grow* their virtual cities, but the cities evolve in unpredictable ways, and control over the city's eventual shape is always indirect. You can create commercial zones or build a highway, but there's never a guarantee that the neighborhood will take off or the crime rate go down. (It's far from random, of course—longtime players learn how to push their virtual citizens in certain



directions.) For most people, the sight of their first digital town sprouting upscale neighborhoods and chronically depressed slums is downright eerie, as though the hard math of the digital computer had somehow generated a life-form, something more organic and fluid, somewhere between the rigid dictates of programming and pure randomness.

How did Wright create this extraordinary illusion? By designing the game as an emergent system, a meshwork of cells that are connected to other cells, and that alter their behavior in response to the behavior of other cells in the network. A given city block in SimCity possesses a number of values—the price of the land, say, or its pollution level. As in a real-world city, these values change in response to the values of neighboring blocks; if the block to the west drops in value, and the eastern neighbor develops a higher crime rate, then the current block may well grow a little less valuable. (A sophisticated SimCity player might counter the decline by placing a police station within ten blocks of the depressed area.) The algorithms themselves are relatively simple—look at your neighbors' state, and change your state accordingly—but the magic of the simulation occurs because the computer makes thousands of these calculations per second. Because each cell is influencing the behavior of other cells, changes appear to ripple through the entire system with a fluidity and definition that can only be described as lifelike.

The resemblance to our ants and embryos is striking. Each block in SimCity obeys a set of rigid instructions governing its behavior, just as our cells consult the cheat sheet of our genes. But those instructions are dependent on the signals received from other blocks in the neighborhood, just as cells peer out through gap junctions to gauge the state of their neighbors. With only a handful of city blocks, the game is deathly boring and unconvincingly robotic. But with thousands of blocks, each responding to dozens of vari-

ables, the simulated cityscape comes to life, sprouting upscale boroughs and slums, besieged by virtual recessions and lifted by sudden booms. As with ant colonies, more is different. "Great cities are not like towns only larger," Jane Jacobs writes. "They are not like suburbs only denser. They differ from towns and suburbs in basic ways." She was writing, of course, about real-world cities, but she could just as easily have been talking about SimCity's networked algorithms, or the teeming colonies of Arizona harvester ants.

Economists and urban sociologists have also been experimenting with models that can simulate the ways that cities self-organize themselves over time. While actual cities are heavily shaped by top-down forces, such as zoning laws and planning commissions, scholars have long recognized that bottom-up forces play a critical role in city formation, creating distinct neighborhoods and other unplanned demographic clusters. In recent years, some of those theorists—not to mention a handful of mainstream economists—have developed more precise models that re-create the neighborhood-formation process with startling precision.

The economist (and now *New York Times* editorialist) Paul Krugman's 1995 lectures, "The Self-Organizing Economy"—published as a book the following year—include a remarkably simple mathematical model that can account for the "polycentric, plum-pudding pattern of the modern metropolis." Building on the game-theory models that Thomas Schelling developed to explain how segregated cities can form, Krugman's system assumes a simplified city made up only of businesses, each of which makes a decision about where to locate itself based on the location of other businesses. Some centripetal forces draw businesses closer to one another (because firms may want to share a customer base or other local services), and some centrifugal forces drive businesses farther apart (because firms compete for labor, land, and in some cases cus-

tomers). Within that environment, Krugman's model relies on two primary axioms:

1. There must be a tension between centripetal and centrifugal forces, with neither too strong.
2. The range of the centripetal forces must be shorter than that of the centrifugal forces: business must like to have other businesses nearby, but dislike having them a little way away. (A specialty store likes it when other stores move into its shopping mall, because they pull in more potential customers; it does not like it when stores move into a rival mall ten miles away.)

"And that's all that we need," Krugman continues. "In any model meeting these criteria, any initial distribution of businesses across the landscape, no matter how even (or random), will spontaneously organize itself into a pattern with multiple, clearly separated business centers."

Krugman even provides a chart demonstrating the city's self-organization in time—an image that captures the elegance of the model. Scatter a thousand businesses across this landscape at random, then turn on the clock and watch them shuffle around the space. Eventually, no matter what the initial configuration, the firms will gather into a series of distinct clusters evenly spaced from each other. There's no rule for clustering that the businesses are directly obeying: their motives are strictly local. But those micromotives nevertheless combine to form macrobehavior, a higher order that exists on the level of the city itself. Local rules lead to global structure—but a structure that you wouldn't necessarily predict from the rules.

Krugman talks about his "plum pudding" polycentrism as a feature of the modern "edge city," but his model might also explain an older convention: the formation of neighborhoods within a larger

metropolitan unit. Neighborhoods are themselves polycentric structures, born of thousands of local interactions, shapes forming within the city's larger shape. Like Gordon's ant colonies, or the cells of a developing embryo, neighborhoods are patterns in time. No one wills them into existence single-handedly; they emerge by a kind of tacit consensus: the artists go here, the investment bankers here, Mexican-Americans here, gays and lesbians here. The great preponderance of city dwellers live by those laws, without any legal authority mandating that compliance. It is the sidewalk—the public space where interactions between neighbors are the most expressive and the most frequent—that helps us create those laws. In the popular democracy of neighborhood formation, we vote with our feet.

A friend of mine who moved to California a few years ago once remarked to me, with a straight face, "The class segregation in Los Angeles is not nearly as bad as you might think. You'd be surprised how many low-income areas I pass on the freeway when I'm driving into work."

It was one of those comments that reveals an entire weltanschauung. "It's not 'an encounter with the working class,'" I thundered back, "if you're gazing down at them from the overpass." But he had a point. In a dispersed, car-centric city like Los Angeles, highways are the connecting nodes, one of the few zones where the city's different groups encounter each other—albeit at sixty-five miles an hour.

Ever since *Death and Life* was first published in the early sixties, Jacobs-inspired critics have lambasted the dispersed communities of L.A. and Phoenix, and their even more anonymous descendants—the "edge cities" that have sprouted up around convenient freeway intersections or high-volume parking lots, the way towns once nestled up to harbors or major rivers. Progressive

## See What Happens

For years mathematicians have puzzled over a classic brainteaser known as the “traveling salesman problem.” Imagine you’re a salesman who has to visit fifteen cities during a business trip—cities that are distributed semirandomly across the map. What is the shortest route that takes you to each city exactly once? It sounds like a simple enough question, but the answer is maddeningly difficult to establish. Even with the number of cities set at a relatively modest fifteen, billions of potential routes exist for our traveling salesman. For complicated reasons, the traveling salesman problem is almost impossible to solve definitively, and so historically mathematicians—and traveling salesmen, presumably—have settled for the next best thing: routes that are tolerably short, but not necessarily the shortest possible.

This might sound like an arcane issue, given the real-world decline of the traveling salesman, but the core elements of the

problem lie at the epicenter of the communications revolution. Think of those traveling salesmen as bits of data, and the cities as Web servers and routers scattered all across the globe. Being able to calculate the shortest routes through that network would be a god-send for a massive distributed system like the Internet, where there may be thousands of "cities" on any given route, instead of just fifteen. The traveling salesman may finally have been killed off for good by online retailers like Amazon.com, but the traveling salesman *problem* has become even more critical to the digital world.

In late 1999, Marco Dorigo of the Free University of Brussels announced that he and his colleagues had hit upon a way of reaching "near-optimal" solutions to the traveling salesman problem that was notably more time-efficient than any traditional approach. Dorigo's secret: let the ants do the work.

Not literal ants, of course. As we saw at the beginning of this book, ant colonies have an uncanny ability to calculate the shortest path to different food sources, using their simple language of pheromone trails. Dorigo's insight was to solve the traveling salesman problem the way an ant colony would: send out an army of virtual salesman to explore all possible routes on the map. When a salesman successfully completes a journey to all fifteen cities, he then traces his path back to the starting city, depositing a small amount of virtual "pheromone" along the way. Because the total amount of pheromone is finite, it is spread more thinly along longer routes, and more heavily along shorter ones. With thousands of ants exploring the map, some sections of shorter routes quickly accumulate thick layers of pheromone, while less efficient routes have almost no pheromone at all. After the first round of exploration, a new batch of virtual salesmen are released and encouraged to follow the routes that have been most heavily dosed with pheromones. After several repeated sessions, the salesmen swarm starts homing in on the shortest routes, reaching a near-optimal



solution to the traveling salesman problem without using anything resembling traditional calculus or a central problem-solver. Since Dorigo's announcement of his results, France Telecom, British Telecommunications, and MCI have applied antlike routing strategies to their telephone and data networks. Early studies show that Dorigo's approach is significantly more efficient than the Open Shortest Path First routine used by the Internet to distribute data between nodes on the network. A few years from now, our online interactions may be sustained by the bottom-up power of swarm intelligence. And once again, the ants will have figured it out long before we did.

What kind of data will those future networks transmit? Soon after this book's publication, the Net will be teeming with the digital inhabitants of Will Wright's latest creation, *The Sims Online*. A fusion of *The Sims* and *SimCity*, the game allows players to collectively build cities as part of a massive network collaboration. Unlike either previous game, all the citizens of the world are controlled by actual human beings, logged into the system from all around the world. As in *The Sims*, you can zoom into your own character's living room, or visit a friend's house down the street for a neighborhood barbecue. But you can also zoom out to see the entire landscape that the players have created. An early draft of the game that Wright showed me included a brilliant neighborhood-creation system that seemed straight out of the pages of Jane Jacobs. City neighborhoods are defined from the bottom up, as players establish their own homesteads in various regions of the virtual space. Any player can create his or her own private neighborhood, the way they can create a name for their virtual character on the screen. But you can also persuade your neighbors to adopt your neighborhood name as well. When a certain number of citizens have declared their allegiance to a specific neighborhood, the system officially recognizes that district and gives it a special sign,

along with various tax breaks. The bigger the neighborhood, the bigger the sign, and the more lucrative the benefits. It's a classic marriage of bottom-up growth and top-down management: let the neighborhoods come from below, but build incentives into the system to encourage their growth.

Our newfound access to virtual cities on the computer screen hasn't abated our appetite for real-world city living. Five years ago, most digital-savvy social critics predicted that the rise of the Web and various telecommuting appliances would deliver the death blow to city living, finishing a forty-year process that had begun with the suburban flight of the postwar years. We'd all be living on our Wyoming ranches in ten years, dialing into the office instead of straphanging on an overcrowded subway. Of all the lofty predictions of the midnineties, none have proven to be more misguided than those eulogies for urban life. The digital revolution has turned out to be a tremendous energizer for dense urban centers like San Francisco, New York, and Seattle—for reasons that date back to the guild system and trade clusters of twelfth-century Florence. Industries driven by ideas naturally gravitate toward physical centers of idea generation, even in an age of instant data transmissions. Bright minds with shared interests still flock together, even when they have wireless modems and broadband in their living rooms. Now smaller settlements are trying to learn from the street-centered dynamism of the traditional organic city: the New Urbanist movement has begun to transform America's suburban development practices, by following the rules outlined by Jane Jacobs almost a half century ago: shorter blocks, livelier sidewalks, mixed-used zoning, and pedestrian-based transportation. Despite the Bengali typhoon of the digital revolution—or perhaps, in part, because of it—the old-style self-organizing city is today as vital and relevant as it has ever been.

The vitality has its downsides, of course: rents, congestion, traf-

fic jams. Even in the most sidewalk-centric cities, the flow of automobiles through the complex latticework of streets poses an organizational problem that rivals the traffic of information across the World Wide Web. For decades, urban engineers have built ever-more-complicated systems to direct the paths of automobiles through congested city streets, by observing the patterns of traffic and tweaking the stoplights and street directions where problems arose. But city traffic is a problem of organized complexity, and it is best tackled with bottom-up solutions, not top-down ones. Almost fifty years after he first came up with the idea for Pandemonium, Oliver Selfridge has embarked on a quest for exactly that solution, building a learning network of traffic lights that will find an optimal system in changing conditions. Selfridge wants to attack the problem of traffic the way Danny Hillis attacked the problem of number sorting: by giving the network the general goal of minimizing delays, but letting the overall system figure out the details, using the tools of feedback, neighbor interaction, and pattern recognition that are the hallmark of all self-organizing systems. Traffic jams themselves are a particularly crude form of emergent behavior, and for years we've been battling them with engineering solutions. Selfridge wants to take the master planners out of the equation. Make the traffic lights smart—by connecting them and feeding them information about backups or accidents—and you have a solution that can actually manage the immense and constantly changing problem of urban movement. You can conquer gridlock by making the grid itself smart.

What connects these developments? Imagine a kind of conceptual tracking shot of life two or three years from now, a movement from scale to scale—like the wonderful Charles and Ray Eames film, *Powers of Ten*, which starts with a view of the Milky Way and

steadily zooms all the way to a person lying in a park in Chicago, and then all way to the subatomic particles contained within that person's hand.

Only in our long zoom do we find, at each scale, the same behavior repeating itself again and again. Begin on the scale of the city itself, its neighborhoods pulsing and thriving, as they have for centuries, sending signals out to the world, and drawing human beings into those neighborhoods, like massive global magnets. The flow of people through the city is now regulated by an intelligent traffic network, evolving and learning in response to patterns of automobile movement. You or I live in one of those immense systems, contributing to its continued development the way a single slime mold cell contributes to the larger aggregation—and as part of our life in that city we entertain ourselves by simulating the self-organizing energy of city life by playing a game on our computer screen, building virtual neighborhoods collectively with thousands of other networked players all across the world. On the scale of the city, and the scale of the screen, our lives embrace the powers of emergence.

Now zoom in another level, to the individual bits of information that convey our virtual city-building to our networked compatriots. These too find their way across the infosphere by drawing on the distributed logic of swarm behavior, building their complex itineraries from below. The network is smart, but its intelligence is the intelligence of an ant colony, not a centralized state. And how did these new smart networks come into being? Drop down one more level on the chain, to the neural networks of the human mind, and their extraordinary aptitude for pattern recognition. The mind of a researcher in Brussels sees a connection between the collective behavior of ant colonies and the routing problems endemic to large-scale information networks—sees the connection because his brain contains a marvelously agile device for detecting shared pat-

terns in disparate fields. That device runs on its own kind of swarm logic, with no central office in command. One kind of decentralized intelligence (the human brain) grasps a new way to apply the lessons of another decentralized intelligence (the ants), which then serves as a platform (the network) for the transmission of another kind (the virtual cities), which we enjoy while sitting safely in our apartments in the neighborhoods of the planet's largest man-made self-organizing system (the real city). It is emergence all the way down the chain.

Can that chain be extended in new directions—both on the atomic scale of digital information and the macroscale of collective movements? Will computers—or networks of computers—become self-aware in the coming years, by drawing upon the adaptive open-endedness of emergent software? Will new political movements or systems explicitly model themselves after the distributed intelligence of the ant colony or the city neighborhood? Is there a fourth stage in the developing web of emergence that takes us beyond the mind readers into something even more lifelike? Is there a genuine global brain in our future, and will we recognize ourselves in it when it arrives?

Certainly the world has never been better prepared for these developments to become reality; if we don't enter the fourth phase of emergence in the coming decades, it won't be for lack of trying. But it is both the promise and the peril of swarm logic that the higher-level behavior is almost impossible to predict in advance. You never really know what lies on the other end of a phase transition until you press play and find out. That is the lesson of Gerald Edelman's recipe for simulating a flesh-and-blood organism: you set up a system of various pattern-recognition devices and feedback loops, connecting the virtual organism to a simulated environment. And then you see what happens.

Even the most optimistic champions of self-organization feel a

little wary about the lack of control in such a process. But understanding emergence has always been about giving up control, letting the system govern itself as much as possible, letting it learn from the footprints. We have come far enough in that understanding to build small-scale systems for our entertainment and edification, and to appreciate more thoroughly the emergent behavior that already exists at every scale of our lived experience. Are there new scales to conquer, new revolutions that will make the top-down revolutions of the industrial age look minor by comparison? On the hundred-year scale, or the scale of millennia, there may be no question more interesting, and no question harder to answer.