Why Nature
Went to the Trouble of Creating…You

BY **NATHAN COLLINS**

In a complex world where plants and animals and everything else are duking it out to survive, an organism stands to gain from becoming more complex.
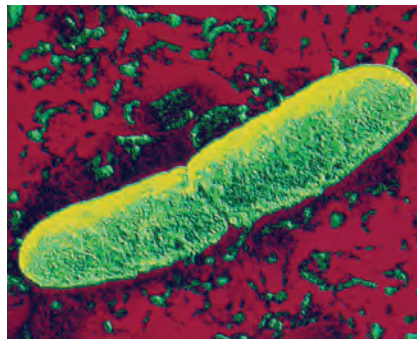
Life on earth began some 3.5 billion years ago, not all that long after the planet itself first formed, and for 1.5 billion years it chugged along, single-celled creatures self-replicating, dividing, diversifying. Remarkably, it took that long – 7,500 times longer than all of human history – for the first multicellular life to emerge, and still longer for it to evolve into life as we know it.

Despite that, the question many researchers ask isn't what took so long, but rather why complex life would have evolved in the first place. Consider this: single-celled organisms make up more than half of the biomass on earth, and even one of the tiniest organisms – *Y. pestis*, better known as bubonic plague – can effortlessly, thoughtlessly kill you.

Nature, it seems, doesn't need you. Indeed, there isn't any obvious reason it would go to the trouble of creating something as complex as a human being, complete with its differentiated organs and top-down control systems. And yet, despite four billion years of Nature's great "meh," here you are, alive, multicellular, complex – even intelligent enough to ponder your own existence.

What was Nature thinking? According to one argument, bacteria first bound together in colonies that enhanced cooperation and hence survival. Eventually, those bacteria bound together physically as well, creating the first multicellular life. And so on.

"You could say that's an answer, but then you could go a bit further and ask what is it exactly that makes you a better compet-

Y. pestis, the bacterium that causes bubonic plague (a.k.a. The Black Death of the Middle Ages)

itor," says David Krakauer, who with SFI External Professor Jessica Flack co-directs the Wisconsin Institute for Discovery's Center for Complexity and Collective Computation, or C4, and SFI's John Templeton Foundation-funded "Evolution of Complexity and Intelligence on Earth" research project.

"Well, you're outsmarting everyone else," Krakauer says.

Simple versus complex

Despite its seeming indifference, Nature does seem to have thought highly enough

of complex structures to produce a few of them, and to have ratcheted up the complexity further by embedding complex structures within complex structures – animals with hearts and lungs and circulatory systems, or groups of people capable of building their own social institutions.

But why? What purpose does it serve? "Why life is hierarchically organized is not at all obvious," Flack says, and how an organism's or a society's complexity relates to the complexity of its environment remains unclear.

Our anthropomorphized Nature might have started with one very simple idea, what Krakauer calls the reflection principle, which presupposes that living things can't be more complex than their environments, an idea rooted in experiments. "If you take organisms and you place them in simpler environments, they just throw everything [superfluous] away. They lose genes," Krakauer says.

At the same time, the world does seem to favor an intelligent creature. Even the tiniest living things need to be able to comprehend, predict, and react to their environments; that's what allows them to outsmart each other, he says. In a complex world where plants and animals and everything else are duking it out to survive, an organism stands to gain from becoming more complex.

That tension between simplicity and complexity is the starting point for C4 postdoctoral fellow Christopher Ellison.
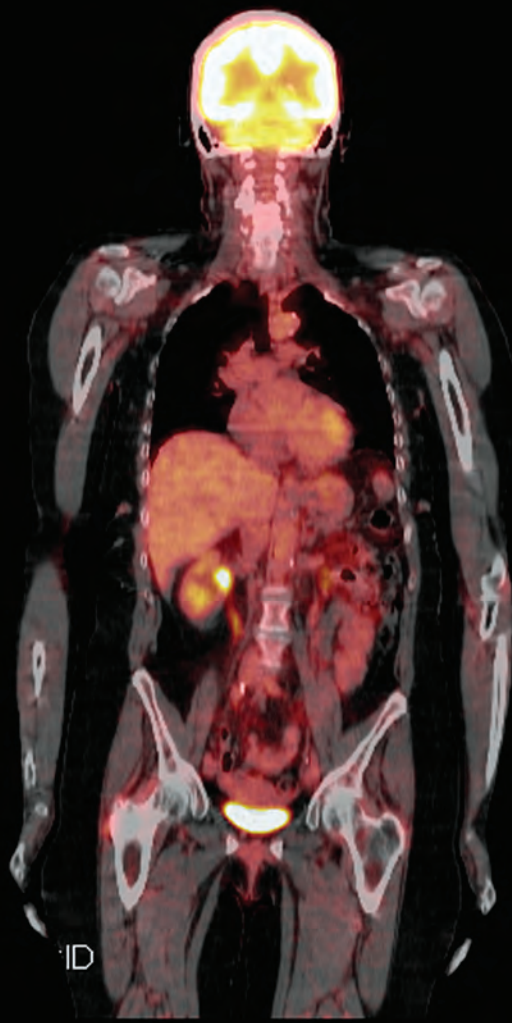
What does Nature care about hearts, brains, and other organs, or, for that matter, political parties – in other words, structures within structures?

"We'd like to understand the implications this has for the environment," he says. "For example, do simple or complex organisms experience and live in simple or complex environments?"

Working with Flack and Krakauer, Ellison developed "Markov organisms," computer-simulated creatures that merge

insights from biology with information processing techniques from computer science, to help figure out how life balances these trade-offs. Rather than modeling real

organisms themselves, he focuses on how information flows in the ecological system.

It's early days, Ellison says, but his simulations suggest that life will often evolve to match its environment's complexity – findings that are in line with the reflection principle, but with some interesting caveats. For one thing, evolving Markov organisms tend to overshoot their worlds' complexity and might take a long time to prune unnecessary complexities. They're also susceptible to "basis mismatch," a problem you know well if you've ever tried to explain to a tourist how to get around in your hometown. To you there are just a few steps, but to the novice it's a complex process with many twists and

turns, and every intersection represents a possible misdirection; in sprawling cities like Los Angeles, a direction as simple as "take Sunset to Vermont and turn left" becomes infinitely complex. Markov organisms are the same: if their way of solving a problem doesn't line up with how their environments constructed it, Ellison's simulations show, Markov organisms' complexity keeps evolving upward forever.

But Ellison's information-centric approach has some benefits. One, he says, "is that it attempts to answer the question of how complexity evolves in an organism-independent fashion," meaning that the ideas apply equally well to anything from bacteria to politics. Similarly, Ellison's method allows the team to describe both an organism and its environment's complexity in the same terms, because both derive from the same underlying models of information processing. Surprisingly, that's something few, if any, other researchers have done.

Constructing predictability

So it appears Nature might favor multicellular life if it affords a certain computational power not readily available to single-celled organisms. But what does Nature care about hearts, brains, and other organs, or, for that matter, political parties – in other words, structures within structures?

The answer, Flack says, is that living things like their worlds to be predictable, and what makes cells and people more likely to survive, Nature favors.

Much of the structure we observe in the world, Flack says, probably evolved because structure begets stability, hence predictability. Groups of genes, cells, or animals change their collective behaviors slowly compared with individual genes, cells, or animals, giving the faster-moving individual components a chance to anticipate changes more easily.

Biologists call the idea that plants and animals – and genes and organs and so on – structure their environments to be more stable and predictable "niche construction," and it usually applies to physical structure like ants building nests. But it also can be applied to temporal structure.

Politics offers, perhaps, a simple example. Early U.S. politicians were explicit about designing Congress and the rest of government so that it would change gradually and

According to the reflection principle, organisms are reflections of their environments. Here the environment is represented as a prose excerpt from Darwin's *Origin of Species*, wherein he contemplates an entangled bank filled with "endless forms most beautiful and most wonderful," each evolved through natural selection. Organism A matches the environment's complexity while Organism B is less complex than the environment and Organism C is more complex than the environment. The research team is asking when evolution satisfies or violates the reflection principle.

be more stable. Even when we complain about our slow-moving government, we are undoubtedly comforted by that very characteristic, because slow is predictable. And when our environment is predictable, we know how to make sound decisions.

So people construct relatively slow-moving, predictable institutions. At the same time, those institutions help shape the behavior of the individuals who created them, points out C4 postdoctoral fellow Philip Poon, who is examining feedback from institutions to explain (in the government case) why, for example, Democrats and Republicans seem to trade off controlling the White House and Congress every few terms. A critical issue is, of course, how that feedback works from a mechanical perspective – that is, how the ways individuals perceive and understand institutions influence their decision-making.

Drawing on the theory of phase transitions, the same one that explains why changing a seemingly minor variable can suddenly shift an entire system from one state to another, Flack, Krakauer, and C4 researcher and former SFI Postdoctoral Fellow Bryan Daniels argue that hierarchical structures bestow another advantage: efficient information flow from the collective to its individual parts. Systems perched on the edge of a phase transition are exquisitely sensitive, so that a small or localized change "leads to a large change in the global dynamics," Daniels says. Though that might seem unstable or chaotic, systems near the critical point where a phase transition begins are actually quite predictable.

Groups of macaque monkeys – one of Flack and the team's earliest sources of data and inspiration – are one system that appears to be resting near a phase transition. When monkeys aren't feeling especially aggressive, Daniels says, things are stable, and "if I suddenly act out, nothing's going to happen… but if [the group is] sitting at the critical point then [my] contribution is always more important," and one extra monkey picking a fight is enough to kick off a large-scale brawl.

Below the critical point, individual monkeys act fairly independently, but right at the transition, their behavior is tightly coordinated and individual monkeys act together as one. That, Krakauer emphasizes, eases the flow of information from the system as a whole to its constituent parts, making it all the more predictable. Nature is rife with examples: one bird's sudden course correction changing the

> **"When monkeys aren't feeling especially aggressive, things are stable, but if the group is sitting at the critical point, one extra monkey picking a fight is enough to kick off a large-scale brawl."**

direction of an entire flock, alternating Democrat and Republican control of Congress, and so on.

Social circuitry

In the abstract, Nature has good reason to favor complexity and hierarchy – each in its own way makes the tasks of comprehension, prediction, and strategizing easier. But its a third concept, circuits, that grounds Flack and Krakauer's team and lays the practical foundation for much of their work.

Usually the word "circuit" conjures images of the transistors, microprocessors,
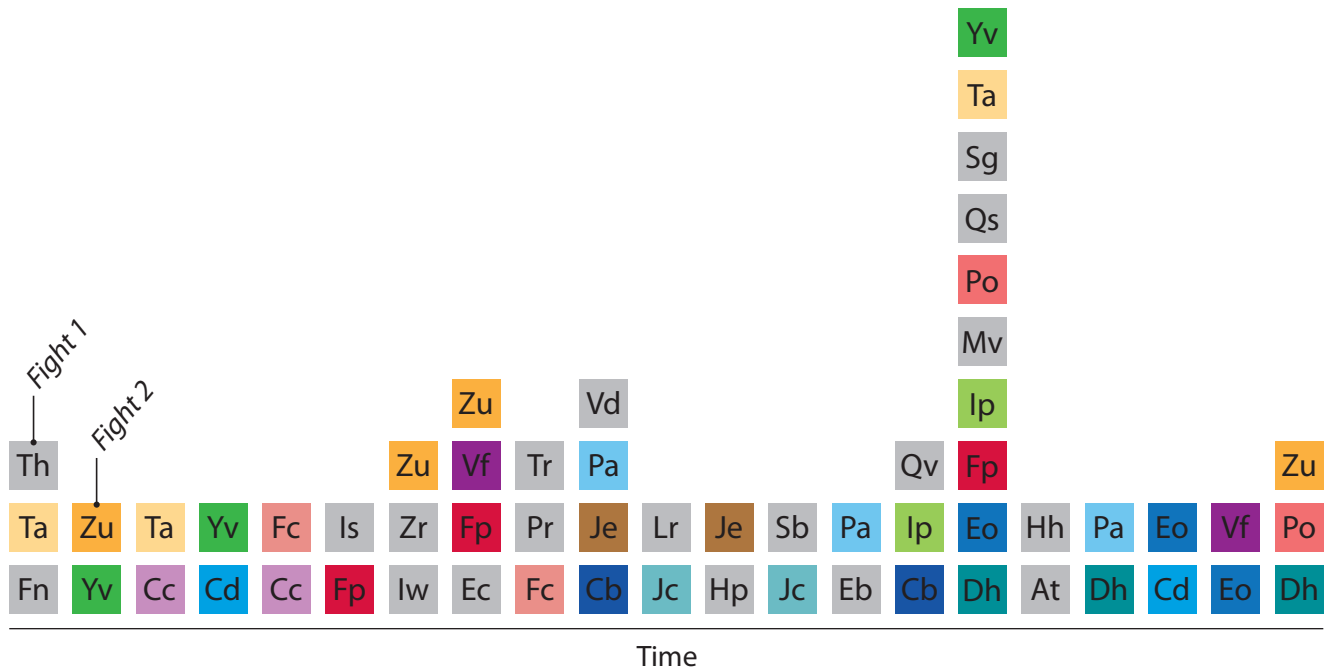
Time series representation of the distribution of fight sizes in a macaque society. Individuals who fought more than once are represented by a color. Grey squares represent individuals who fought only once. An outburst by an individual won't normally tip the scales. But when the system is perched at a phase transition, a brawl among many individuals can erupt.

and lengths of copper wire that make up a computer. The analogy is apt. Like an electronic circuit, individual components – genes, organs, people – informationally bind living things to form a kind of biological or social computer. In fact, the circuit approach to describing a system stems from a hunch that the hierarchical scales present throughout nature "arise through a process of collective computation," creating slow-changing, predictable social and biological structures, Flack says.

Circuits are more than just an analogy, though – they're the tools that bridge the gap between individual and collective behavior. And in a scientific field where it's easy to avoid real data, circuits are one way Flack and Krakauer's research group makes sure their theories are a good match to the real world. "Our group is committed to an empirical approach," Flack says. "We believe that only when these measures are developed with an understanding of the data generated by real systems will they be useful."

The process of building circuits begins by analyzing how a system's individual parts work together. Using the macaque fight data, Flack, Krakauer, and former SFI Omidyar Fellow Simon DeDeo (now at Indiana University Bloomington) developed a statistical method they dubbed inductive game theory to analyze how the monkeys reacted to others' fights. The resulting social circuit, Flack says, serves as a detailed model "for how the microscopic behavior maps to the functionally important macroscopic features of social structure," such as the distribution of fight sizes. In other words, to construct a social or biological circuit is to understand how a group builds and maintains stable, predictable information hierarchies.

The final step is to produce a simplified social circuit, what the researchers call a "cognitive effective theory," that accurately predicts how groups behave. The aim is to extract the key sorts of interactions

People gather in Washington, D.C. before Martin Luther King Jr.'s "I Have a Dream" speech on Aug. 28, 1963, to demand equalities. Individuals tend to move faster and be less predictable than the slow-moving institutions they create.

responsible for power structures, fight-size distributions, or other macroscopic features, using "what we know about individual or component cognition to coarse grain or compress" social circuits, Flack says. Such compression is essential, she says, because living things can't base their decisions on what every other living thing is doing; instead, they're forced to pay attention to just a few patterns or details of what's going on around them.

The key question here, as collaborator and Princeton University graduate student Eleanor Brush puts it, is how little information individuals need to successfully outsmart others.

Accidental or inevitable

Answering questions like that one – or testing some of the team's more abstract predictions – remains a central challenge. Poon, for example, describes his studies of election cycles and policy change as "toy models" – they capture qualitative features of the data such as party switching, but don't stand up to more precise, quantitative tests.

Meanwhile, Krakauer and others say it's not always clear how to test particular hypotheses, such as the prediction that basis mismatch leads to ever-increasing complexity

> **"Living things can't base their decisions on what every other living thing is doing; instead, they're forced to pay attention to just a few patterns."**

in living things. "We're still looking for some compelling example," Ellison says. "Part of the issue is that one can often play the devil's advocate and call into question the example," one reason why his work to construct formal, precise measures of complexity is so important, he says.

New techniques for rapidly analyzing genetic data, Krakauer says, might improve the situation. Combining those techniques with laboratory-based "experimental evolution," in which researchers study the effects of precise environmental changes on small organisms such as bacteria, could help test some of the endeavor's core ideas, such as the reflection principle or the role of phase transitions.

Another potential avenue is to use "digital sources like computer games, where we can control, to a large extent, the form of the data or the conditions under which they were collected," Krakauer says.

Testing their theories is just one part of the team's ambitious aims. They hope, Flack says, to achieve nothing less than an understanding of why life is organized the way it is, from the smallest bacteria to the largest human institutions. That requires combining real-world observation and abstract mathematical theory in novel and creative ways.

And as if that wasn't enough, Krakauer has one more question in mind: is life an accident, or is it inevitable? And if life is inevitable, well, are we alone?

"If it's not a product of a series of random accidents, but there's an underlying law-like regularity, that would give us confidence in believing in the possibility of life present everywhere in the universe," he says. "So when one asks why does it matter whether it's chance or necessity, it matters if we care whether we're alone are not." ■

Nathan Collins is a freelance science writer, new father, and film aficionado based in San Francisco.