

Biologists Find New Rules for Life at the Edge of Chaos

In the space between order and chaos, a zone usually described with the mathematics of impending avalanches and crystallizing liquids, scientists are finding new rules for life.

They're researching the dynamics of criticality, where one system transforms rapidly into another. Scientists have studied such behavior in physical systems for decades; some have [theorized that it might be found in living systems](#) too, perhaps underlying some of biology's fundamental and largely unexplained phenomena: how a few interacting genes shape an organism's development, and how networked neurons give rise to complex cognitive functions.

Such speculation has been intriguing, but also difficult to study. Only now, with the advent of exquisitely sensitive biological probes and high-powered data analysis, have experiments started catching up to theory.

"In the past, there has been a lot of discussion about the potential benefits of biological systems poised at criticality," said theoretical biophysicist Dmitry Krotov of Princeton University, co-author of a [Feb. 10 Proceedings of the National Academy of Sciences paper on criticality in genetic networks](#). "Now high-quality experimental data are appearing, and we are able to quantitatively test these ideas."

In the new study, Krotov and co-author William Bialek, also a biophysicist at Princeton, measured protein-coding activity in a genetic network crucial to the development of fruit fly embryos. Expressed in mathematical terms, the activity contained the signatures — relationships between gene activity, patterns of correlation at far-flung locations in embryos — characteristic of criticality.

The study is just one data point, a bit of extra weight on the evidentiary scale. But other researchers have made similar findings, observing apparently critical patterns [in the genetic networks of single-celled](#) and [also multicellular organisms](#). Criticality seems to be an integral part of life.

Presence alone doesn't signify importance, but the essential properties of critical networks should make them useful to biological systems, said physicist Maximino Aldana of the National Autonomous University of Mexico. His work suggests criticality could be an optimal evolutionary solution for systems that [need to balance resilience with adaptability](#).

Another key feature of critical networks is the speed at which information passes through them. Though easier to describe in the rarefied language of statistical biophysics than in conversational terms, a tangible example comes from Bialek's work

on flocks of starlings, which [fly in critically networked formations](#). Within them, thousands of birds move with uncanny coordination, with individual movements rippling almost instantaneously across the entire group.

Another instructive analogy, said biophysicist John Beggs of Indiana University, is of sand grains dropped one-by-one from a single point. For a long time, nothing much happens: a conical pile slowly accumulates. Eventually, however, it becomes so steep that the addition of just one more grain can trigger a miniature avalanche, though not in a predictable way. Avalanches can be small or large, and sometimes they don't happen at all.

Just before the pile enters its avalanche-prone state, said Beggs, it's poised at criticality. From a biological perspective, the trick is to harness the capacity for small perturbations — such as a protein's presence or a neuron's firing — to produce large effects without entirely entering that avalanche-prone state, in which perturbations would soon become overwhelming. Researchers studying such behaviors sometimes refer to this as the "[edge of chaos](#)."

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"You've got randomness, and you've got order. And right between them, you've got the phase transition," Beggs said. "The idea is, you want to get as close as possible to chaos, but you don't want to go into the chaos. You want to be on the edge, on the safe side."

Beggs' own research involves these [avalanche behaviors in networks of neurons](#). These have been documented at small scales encompassing a few hundred or thousand cells, and also in [large-scale, across-the-brain activity](#) in organisms as disparate [as roundworms and humans](#).

It's been proposed that these criticalities may underlie cognition — the extraordinary dynamics of memory formation and [sensory integration](#) and on-the-fly processing — and even be involved in cognitive disorders, though these remain open and largely untested questions.

"It's not clear how critical this phenomenon is to biology," cautioned Krotov. He characterized the present state of research as one in which scientists, flush with results from early rounds of experiments, can now refine and update their models of criticality, and use those to inform new investigations.

One important insight, said Krotov, is that criticality in biology won't precisely resemble what's seen in the classical, physical systems where criticality was first studied. In the latter — the aforementioned pile of sand, or magnets losing their magnetization at high temperatures — criticality is a global property, the same at every point in a system.

Biology could involve many critical networks, nestled together in hierarchies that generate ever more complex phenomena.

Another open question is whether criticality is found at even higher scales. Apart from group dynamics — in addition to starlings, crowds of people sometimes seem to be [poised at the edge of chaos](#) — criticality may even operate at ecological levels. This has primarily been studied in a [catastrophic context](#), as when a diseased coral reef turns into an underwater desert, but it's possible that communities of plants and animals also function as information-processing networks, exhibiting what one speculative early paper described as "[coevolution to the edge of chaos](#)."

"Maximum information at a state of criticality in biodiversity has not been explored so much," said ecologist Marten Scheffer of Wageningen University, who specializes in [ecological tipping-point dynamics](#). "It's a potentially interesting area."

It's also a very difficult area to investigate, and may prove impossible to test at Earth-system levels, said Scheffer. In the meantime, progress continues on the more tractable fronts of genes, cells and brains. Material scientists are also applying principles of biological criticality [to the design of computers](#).

Beggs likened the present moment to when Darwin visited the Galapagos, counting bird varieties and measuring beak shapes en route to his theory of evolution.

"All that cataloguing led to a beautiful theory," said Beggs. "There's a lot of cataloguing going on now. It's a golden age for collecting data. It's there for the taking, and people are thinking about how to organize it, and what rules govern how it all fits together."