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New Science of Complex Systems Takes Aim at Age-Old Problems

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From neural networks to weather patterns, complex systems are everywhere. Researchers across the university are helping develop this new field that offers promising insight into our messy world.

Take a neuron. Alone, it's a cell that conducts a chemical signal. But billions together, each woven with thousands of links that adapt and change over time, emerge as a brain capable of following a hunch and the smell of coffee.

While the human mind may be the ultimate complex system, other examples appear everywhere. Take army ants. Despite their name, they have no general, and their queen sends out no instructions. No ant is aiming to get across that gully, and there is no blueprint. Yet millions of ants, following the same instinctive rules of individual behavior, can build bridges with their bodies and forage for food along vast, efficient highways.

"That's emergence," says computer scientist Maggie Eppstein, director of the UVM Complex Systems Center launched in 2006 by the College of Engineering and Mathematical Sciences. "You can't just look at the rules each little thing is following and then describe what is going to happen in the whole system. You've got to run the model or observe the whole to understand what happens at the next scale."

Small bumps

Complex systems come in all sizes -- scientists see them under the microscope but also whirling across the Great Plains -- strangely robust and maddeningly fickle. Ferociously chaotic air currents suddenly resolve into a tornado that moves across the landscape maintaining its form -- then it vanishes. "In complex systems, through local interactions and self-organization, stable or semi-stable patterns emerge at a next level or a higher scale," Eppstein says, "but they are difficult to predict because they can be so sensitive to small changes in the system or initial conditions."

Models of social networks -- think Facebook -- created by UVM mathematician Peter Dodds and his colleagues suggest that people are more like army ants than armies. Cascades of social change often happen, they argue, not because of especially powerful commanders but because of a critical mass of easily influenced individuals influencing other easy-to-influence people.

"Small, and possibly random, bumps or nudges at the right moment determine the direction a large group will head," Dodds says, "but it doesn't matter so much who does the bumping." The size of a forest fire is not determined by the size of the match. "When the right conditions exist, any spark will do," Dodds wrote in the *Journal of Consumer Research*, "when it does not, none will suffice."

A magnificent mess

Applying insights like these, Eppstein, Dodds and their colleagues across the university -- including famed theorist Stuart Kauffman who joined the UVM faculty this year-- are helping to lead the quickly developing field of complex systems science.

Propelled forward by the brute force of ever-faster computers -- and by an increasingly elegant set of mathematical and statistical approaches that more accurately reflect the interpenetrating, bumpy, evolving, buzzing, contingent, convoluted, magnificently messy world that really exists -- these researchers are developing new approaches to some of the planet's most vexing problems:

- Insights from chaos theory allow mathematician Chris Danforth to make on-the-fly corrections to errors in global weather models used by the National Weather Service, with an eye toward improved hurricane forecasts.
- Robotics expert Josh Bongard explores one kind of complex system: groups of autonomous robots that interact with themselves and learn. He has built a resilient robot that can adapt to unforeseen problems, like a lost leg. By evolving a revised "self image" this robot discovers new methods to move forward.
- A team of UVM scientists led by biologist Judith Van Houten use "artificial neural networks" that learn as they go -- mimicking how the brain works -- to churn vast pools of data about Lake Champlain. They're searching

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for hidden triggers and ecological thresholds that lead to problems like toxic algae blooms.
- Eppstein teamed with UVM plant biologist Jane Molofsky to develop a complex model -- using a dynamic grid called a "cellular automaton" -- that simulates how plants interact in new territory. As numerous simulated ecological interactions play out over the grid, patterns appear that may help unravel the ecological mystery of why some species become invasive while others remain quiet.
- UVM Mathematician Richard Foote published a paper in *Science* that explores how mathematics itself is a complex system: starting with simple axioms, increasingly complex "layers" build up that produce profoundly unexpected mathematical outcomes like the Enormous Theorem and the Monster Simple Group.

Summing the parts

Of course, many of the underlying ideas behind complex systems are far older than the name. It was Aristotle who stated that the "whole is more than the sum of the parts." But complex systems science takes this realization further. As physicist P.W. Anderson wrote, in a complex system "the whole becomes not only more than, but very different from the sum of its parts."

"And the deeper part of the complex systems science story is that the universe is evolving in some particular way, and, of all the possibilities, we have this tiny path that we're actually following," says UVM's Peter Dodds. Complex systems theory makes it increasingly clear that in science, "history matters," he says.