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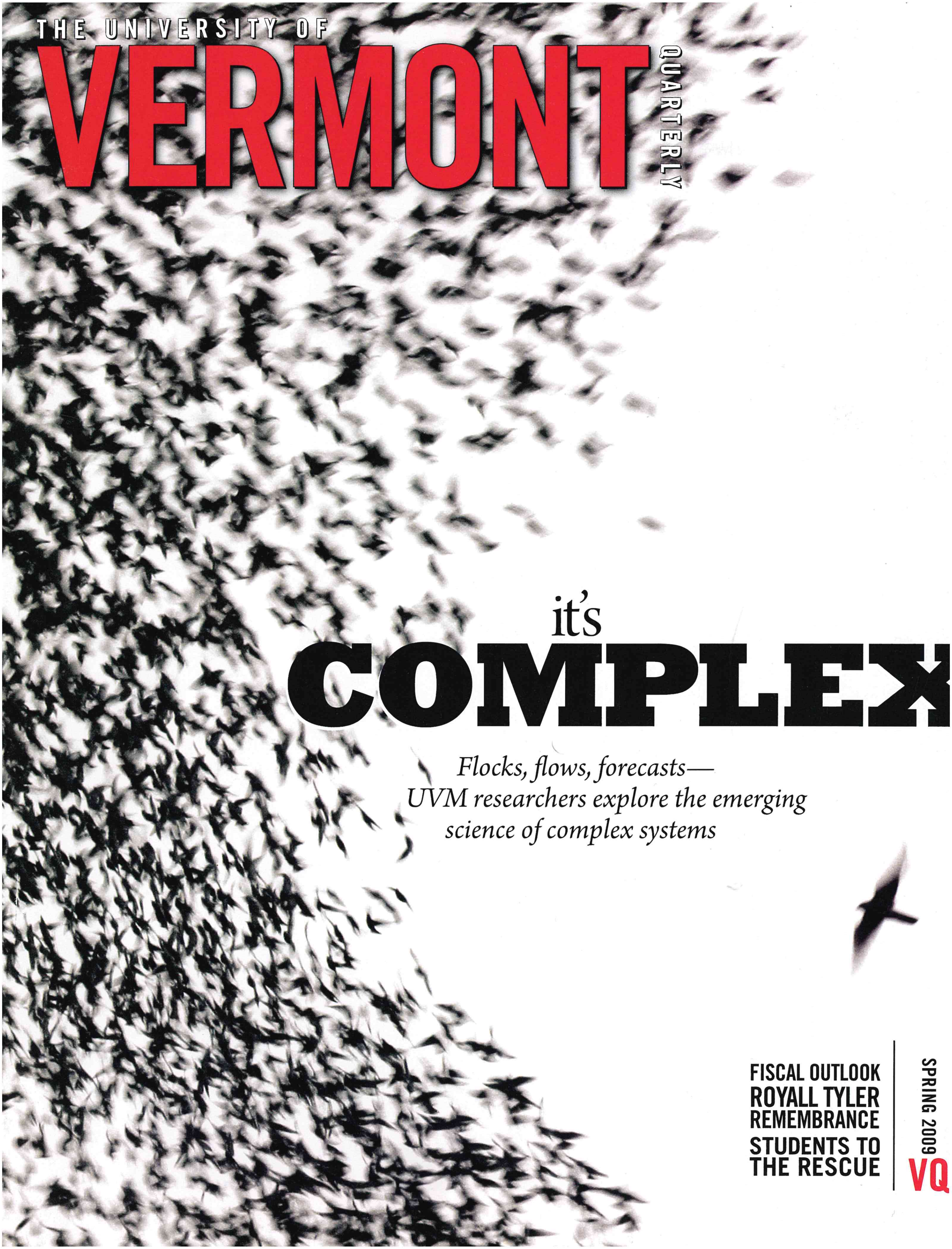

it's

COMPLEX

Flocks, flows, forecasts—
UVM researchers explore the emerging science of complex systems

FISCAL OUTLOOK

ROYALL TYLER REMEMBRANCE

STUDENTS TO THE RESCUE

SPRING 2009 VQ

Ecosystems to electric grids, hurricanes to human behavior, UVM researchers explore the intricacies of complex systems

it's Complex

by
JOSHUA E. BROWN

Peter Dodds is lost.

Well, not exactly. He knows he's going to meet me at 2:30 in the Davis Center. But just where? He doesn't remember. And yet, without hesitation, he walks into the atrium, past crowds of people, up the sweeping staircase, and directly into Henderson's coffee shop.

There I sit, gulping a latte. How did he figure out where to go?

"It's an interesting kind of search problem," Dodds says, sliding a white running hat back and forth over his shaved head. A rangy Australian who competes in triathlons with an intensity on par with his intellectual endeavors, he pauses to think. "It just seemed like the right place to go. I figured you wouldn't be hanging out with the students, and that coffee might have something to do with this. I was right."

That kind of intuitive problem-solving, he thinks, is not simple to explain and even harder to replicate with a computer. It's way beyond the best artificial intelligence programs, and it would be charitable to say that neuroscience has a firm grasp of how the brain manages such a task. But it's not magical either.

"It's complex," he says.

And complexity lies at the heart of Dodds's research and teaching as an assistant professor of mathematics and statistics. He's part of a group of researchers who make up UVM's Complex Systems Center, launched in 2006 by the College of Engineering and Mathematical Sciences.

"In its most simple form, a complex system is many distributed parts interacting in some distributed way," Dodds says, "giving rise to some interesting, often unexpected, macrophenomena." 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 brain 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 or traffic light. 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. "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."

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," she says, "but they are difficult to predict because they can be so sensitive to small changes in the system or initial conditions."

That fact may be a disappointment to marketers and other fans of Malcolm Gladwell's best-selling book *The Tipping Point*. Gladwell's argument that "social epidemics" are driven by a handful of exceptional, socially powerful—and talkative—people seems compelling. Convince the right person—what the $1-billion-per-year viral marketing industry calls an "influential"—to speak highly of your company's new alligator handbag and you're set, right?

"Not likely," says Dodds. Mathematical models he and Duncan Watts at Columbia University developed of social networks—think Facebook—suggest that people are more like army ants than armies. Cascades of social change often happen, they argue, not because of especially powerful commanders or carefully positioned tastemakers, 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 skier that starts an avalanche did not do so because of extraordinarily powerful skis. 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."

Applying insights like these, Dodds, Eppstein, and their colleagues across the University 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. (See sidebar on page 21.)

SEEING THE LIGHTS

Recall what happened on the afternoon of August 14, 2003. In a cascade, the lights went out in Cleveland, New York City, Baltimore, Albany, and Detroit. Eventually more than 50 million people were without power across the Northeast and Canada as 265 power plants shut down.

This famous blackout was a complex systems failure. No one pulled the plug; numerous local problems and mistakes created a series of dynamic feedback loops. The result: an unpredictable regional disaster.

"Nobody's in charge of the electric grid," says Paul Hines, assistant professor of engineering and a power expert who is part of the UVM complex systems group, "there are hundreds of companies and entities who all have a role. What's amazing is that in the midst of this system, with millions of human and non-human actors—a lot that we can't predict—we still get order. Most of the time, when you flip the switch, you get light."

> In a complex system, one plus one might add up to a lot more than you'd guess.

Or, as Dodds says, complex systems are "typically highly balanced, flexible, and robust, but are also susceptible to systemic collapse."

Decades of work to improve overall control of this patchwork of operators, power plants, substations, and transmission wires—a product of history more than rational design—haven't gotten very far. "The reliability of the grid has basically been constant for the last twenty-five years," Hines says. He recently presented data that shows the frequency of blackouts has remained the same since 1984, and also that very large blackouts are more frequent than would be expected from traditional exponential statistics and risk assessments.

"Traditional methods have tried to estimate the reliability of the system by taking each component individually," Hines says. Any one substation is pretty straightforward and may not appear to be hard to manage. "But this misses what happens when combinations of components fail," he says.

In a complex system, one plus one might add up to a lot more than you'd guess. These kinds of nonlinear interactions don't show up in a static model that simply describes the electric grid, which is why Hines is developing dynamic graph-based models instead that draw on new methods from network theory.

"Our goal is not to create a complex model, our goal is to create a useful model," he says, "a simple model that helps us understand a complex system." He's feeding data from actual power systems into his model, seeking sets of components that cluster together when he runs the model, because these may be particularly important to maintaining the robustness of electricity delivery systems.

THE NEXT STEP

"Complex systems science is just the evolution of science," Dodds says, stepping out of the coffee shop. Since the revolution that Newton and Descartes helped launch, the main thrust of so-called normal science has been to look for smaller pieces and more fundamental laws. Molecules yield atoms yield quarks.

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eye ON THE HURRICANE
and other complex systems under study at UVM

- Insights from chaos theory allow mathematician Chris Danforth to make on-the-fly corrections to errors in the 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. Now, drawing on insights from child psychology, Bongard is working on robots that can discern the intention behind an action.
- 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 for hidden triggers and ecological thresholds that lead to problems like toxic algae blooms (See article "Running Deep" in the winter 2008 edition of *Vermont Quarterly*, alumni.uvm.edu/VQ).
- Computer scientist Maggie Eppstein teamed with 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.
- In 2007, 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. This trend points to a future in mathematics where many proofs can no longer be verified by hand and reside only in computers.

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"There are many problems that we figure out by breaking things into little pieces," he says, as we look down on a knot of students in the atrium hunched around a laptop computer, one with a Frisbee resting on his head. "Scientists figured out DNA with its double helix. And then they figured out the human genome by measuring like crazy. There was a sense conveyed that once we understood all the bits of the genome, we'd understand everything human," he says, "but that's totally insane."

"It's like saying once we understand atoms we understand matter," he says as we meander back down the Davis Center stairs. "But we don't."

As Dodds talks, I am reminded of what UVM physicist Dennis Clougherty told me: "It's nonsensical to talk about electrical conduction when you have a single atom. It's an emerging property that arises from large numbers of atoms, large numbers of degrees of freedom. Many of the concepts in complex systems science have a foundation in physics."

Of course, many of the underlying ideas behind complex systems are far older than the name. Scottish economists in the eighteenth century argued that chaotic markets composed of thousands of independent agents—Adam Smith's self-interested butchers, bakers, and brewers —produce an ordered economy whose invisible hand could benefit the whole society. John Muir was not the only observer of nature who saw that when we try to pick out anything by itself, we find it hitched to everything else in the universe.

And 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 seminal 1972 paper in *Science*, in a complex system "the whole becomes not only more than, but very different from the sum of its parts."

"The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe," Anderson wrote.

Peter Dodds stands at the bottom of the Davis Center stairs and watches students playing pool. "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," Dodds says. "History matters, details matter."

One after the other, the students rub their cue sticks with chalk, hitch up their jeans, and lean over the table. "If you want to understand how humans behave collectively you have to understand what their psychology is: and you will never get that from studying quarks or DNA or cells," he says, as a stream of students pass around him like he's a rock in a river. "Never." **VQ**