

## A Distributed Santa Fe System

By Kevin Kelly

Be careful. Watch out for that spider!" exclaims the boyish figure fidgeting in front of the computer screen. He turns to his audience. "Spiders are thoroughly bad news in this world." Like Peter Pan leading an expedition to Never-never Land, the grown-up John Holland can hardly contain his enthusiasm as he guides his listeners through a hi-res simulation of an ant colony. "Remember," he cautions, "we're the yellow ant."

The audience nods in appreciation. A simulated ant colony is the latest adaptive system introduced by Holland this week. Twenty scientists of many stripes—biologists, political scientists, mathematicians, and computer specialists—study the demo intently. Then they begin free-associating what they've seen with similar phenomenon in their own specialities. As they talk they struggle to translate the phenomenon of simulation into as many scientific dialects as possible, and then to unify the lingo. After an hour they'll move on to another deeply complex subject—another complex adaptive system—and repeat the brainstorming, the translations, and the attempt at synthesis. Today, ant colonies; tomorrow, population genetics; the day after, alliances in World War II. During two weeks of freewheeling discussions, someone of the 20 present is sure to flesh out an idea or two later with a mathematical formulation or experiment. Eventually they'll report their findings back to this unique interdisciplinarian group of graduate students and professors dedicated to exploring the vast no-man's land between official branches of science.

### Santa Fe—Michigan Collaboration

This could only be a convening of the Santa Fe Institute, if it weren't in Ann Arbor, Michigan. But it is definitely Michigan, during an unseasonably bitter cold two weeks in November 1991, and it is definitely a Santa Fe gathering. John Holland, with the encouragement of the Santa Fe Institute, has incubated a prototype Santa Fe collaboration at the University of Michigan.

Participants in the collaboration investigate a heady mix of interwoven topics. Currently, Arthur Burks explores the tradeoff between short-term and long-term goals in different types of machine learning. Carl Simon investigates the role of interacting populations in epidemics. Michael Cohen probes the structure of human organizations to see how groups routinely learn, especially in surprising environments. Melanie Mitchell evaluates the characteristic components of complex adaptive structures using a simple but versatile learning system she developed called CopyCat. Rick Riolo examines

classifier systems—a type of adaptive algorithm—for evidence of internal models which allow the system to anticipate change. Once a week, this group meets to critique their ideas. And for the second year in a row, the University of Michigan and Santa Fe Institute have sponsored a two-week colloquium where collaboration members and other Santa Fe Institute regulars can swap reports of their current work.

### Complex Adaptive System Traits

Some common threads crisscross this year's seminars. A few themes keep emerging with enough bite that John Holland takes out a red grease pencil and in the glare of the overhead projector makes a quick catalog of candidates for distinctive characteristics of complex adaptive systems. I've expounded upon his bullets with a synthesis derived from conversations with researchers individually, from debates overheard among them, and from attendance at parts of the two-week colloquia. The short list of traits of complex adaptive systems follows.

#### Perpetual Novelty

You know you've got a complex adaptive system on your hands when it continues to surprise you no matter how long its been running. The author of the yellow ant simulation (sold as a commercial game) reports that he is amazed by the large number of completely unexpected novel tricks other users have found in his world. They write and tell him how clever he is. In reality he is clever by programming a type of connectivity which generates viable surprises. Perpetual novelty is highly desired in a game, but perpetual novelty is sheer disaster in aviation systems or telephone networks. To control perpetual novelty—where and when novelty is wanted—is a fundamental challenge for this new science.

#### Resilience

The capacity for self-repair is a hallmark of biology, and a goal for synthetic adaptive systems such as networks or computer models. Even if a system cannot mend itself, if it can degrade gracefully—limp along instead of dying—it's got the spunk of a complex adaptive system. Modelers praise a network that can work around troubles and failure, the way a computer hard disk will automatically reformat around its bad sectors. They call it "robust." The more adaptive a system is the more robust and resilient, and presumably vice versa.

#### Emergence of the Aggregate

The whole is greater than the sum of the parts. It's an old idea that is presently gaining experimental proof

and precision. When is the whole greater? Under what conditions? Does the sequence in which parts are added make any difference? What causes a complex system to unravel? Bob Axelrod notes that a whole does not break up randomly, but fails by splintering along hierarchical boundaries. Look at the former Soviet Union, he says. It first broke up into republics, then into autonomous regions, and will lastly unhinge into ethnic enclaves. One critical challenge on this frontier, John Holland says, is understanding the way in which the whole begins to influence and modify the parts that sum it. Over time, a cell joining one body will diverge in operation from a cell joining no body. A whole can unravel into a different set of sub-parts than the set that first created it. To use the Soviet example, the former U.S.S.R. may unravel into a different set of ethnic enclaves from those which originally comprised the Union.

#### Formation of Individuality

Another mark of living things is that each has its own individuality. The components of highly adaptive systems are arranged in nested hierarchies, which breed slightly unique behaviors as the parts are altered or rearranged. In contrast, an unliving electrical appliance or protein molecule can have complication without individuality. Substantial alteration of their complicated parts produces drastically different output of the whole. The deep hierarchy stacked up in a natural organism—molecules, cells, tissues, and organs—compensates for significant variation of parts. Sub-sub-structures can differ slightly while still generating similar top behavior. A complex system such as a peacock may vary in the exact

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arrangement or numbers of muscle, feather, and brain cells. Every peacock acts both like a standard peacock system and a unique peacock personality. At the same time, the combination of hierarchical dynamics and individual variation permits the system to generate an identity of self—a sense of “me” and “not me”—in the way skin grafts are rejected by nearly identical siblings. Holland says, “Identity of individuality is an emergent property of these systems.” He points out that the emergence of individual identity forms a structure upon which new evolutionary pressures can focus. For example, the emer-

gent identity of a colony draws natural selection onto an additional layer, that of the individual colony, and alters the character of the cells constituting the new colony.

#### Internal Models

There is a suspicion among researchers that the hierarchical architecture of a complex adaptive system permits it to represent a level of abstraction internally. A high-order representation persists longer than the flux of changing influences in lower-level structures. Thus, a dynamic representation serves as a platform for limited anticipation of the future. To anticipate may, in fact, be one of the chief benefits of complex systems. Even the mildest look-ahead ability speeds learning and adaptation. As an example, Stephanie Forrest cites the immune system, which models (almost mirrors) the disease environment in anticipation of an infection. The immune apparatus, she says, “is a very massively parallel, distributed system.” It can remember for over 50 years, which is truly astounding since the body is turning over all its molecules weekly. It also means this memory model isn’t residing anywhere in particular. Over evolutionary time, the immune system has abstracted the notion of infectious disease and represented it in a very distributed way so that the system itself anticipates diseases it has never seen.

#### Non-Zero Sum

Game theory was the very first attempt to grasp complex adaptive systems. von Neumann invented game theory at almost the same moment he helped cook up computers. One insight from game theory has penetrated science and contemporary thought: the distinction between zero- and non-zero-sum games. In a zero-sum game, every win is offset by a loss; if there is a winner, there must be a loser. In a non-zero-sum game, both sides can lose, or both sides can win. Complex adaptive systems tend to be non-zero-sum games. The emergence of beneficial properties arising from adversarial parts—take wealth in capitalism as an example—is the first clue that the conservation of gain is broken. Conventional theories of economics and ecology stress the way the game seeks equilibrium, winner balancing loser, as if on a pivoting scale. The new view stresses the non-equilibrium aspects of complex systems. The non-zero-sum, non-equilibrium aspect of life as a system is why more varieties of organisms on a planet increase the opportunity for yet more new species, rather than decrease opportunity for diversity, as in a zero-sum game. In this open-ended kind of a system, non-equilibria moves can have a big impact. Bob Axelrod gave the example of Gorbachov’s fundamental insight, “that the Soviets could

*Kevin Kelly is a former editor/publisher of the Whole Earth Review, and Signal, a Whole Earth catalog of communication tools. He is now on sabbatical, writing a book for Addison-Wesley on how machines are becoming biological.*

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get more security with fewer tanks rather than with more tanks. They threw away 10,000 tanks unilaterally, and made it harder for U.S. and Europe to have a big military budget.”

#### An Exploration Tradeoff

The price of learning is a sacrifice in efficiency. A complex adaptive system will have one side that seeks new ways to survive (exploration, learning) and one side that seeks to maximize what it knows (exploitation, efficiency). Every act of new learning diverts resources from exploitation of the known. Holland defines the chief task of complex systems as coming up with a mechanism that can optimally balance these diverging poles. Says he, “If I spend all my time looking for the very best rule, I might never get around to using the rules I already have to their best. On the other hand, I’ll never discover a better rule while only exploiting the rules I already have.” Each type of discovery is rooted in a different mathematical structure, which is also to say that different structures of discovery are best suited for different types of problems. Melanie Mitchell has embarked on a project to characterize the types of problems that genetic algorithms are best for. For instance, one of the drawbacks of genetic algorithms, and even organic genetic crossover in living populations, is that the process tends to converge the population upon a uniform type, so that organisms and solutions begin to look similar to each other. In other words, genetic algorithms emphasize exploitation of the knowledge represented by all the genes inside a population, rather than exploring outside the known gene pool. Mitchell can show on her model how a learning system can get stuck in “brainstorming mode” just as easily as it can get stuck in overspecialization. How might genetic algorithms, or neural nets, and other kinds of structured searches, be combined in appropriate balance to best solve a particular type of problem? A formal answer to this general problem would go a long way not only in artificial intelligence and artificial life fields, but also in practical application to human institutions such as corporations, which must set hard priorities in funding research either for the short term (exploitation) or the long term (exploration).

#### Collaboration Foci

By no means are these eight the only features of complex adaptive systems. Nor are these systems the only target of the Michigan group and the Santa Fe Institute. The collaboration focuses on the subject of complex systems that adapt and learn because it is sufficiently broad to interest the needed multidisciplinary

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crowd, sufficiently specific to hatch tough questions, and because it threads through many of the major problems SFI is addressing, such as: how does the global economy work, what is the nature of evolution, for what good can we use vast computational power? As SFI president Ed Knapp noted in his address to the colloquium, “if we could but know one system well, we’d have a start on the others.”

In many ways the organization of the Michigan/SFI collaboration reflects the unorthodox organization that has proven to make the Santa Fe Institute so successful. In both locations there are no departments, no positions, no permanent research staff, no day-to-day responsibilities for researchers beyond trying out embryonic interests and following them up. Participants have a home institution, where they are prominent. In Knapp’s words, Santa Fe Institute and collaborations are sort of a “homeless idea.” A small group of participants hole up together to practice a “collaboration demanded by proximity.” In the end the universities affiliated with the participants benefit by these ad hoc convenings.

John Holland agrees. “Because of a desperate chasing of dollars for cash flow, universities are no longer the natural repository for long-range stuff. It’s even worse at the top universities because of fights over overhead costs. Almost all the really long-horizon research that I know going on in universities is bootleg, one way or another.” Holland isn’t exaggerating. One prestigious East Coast school stated in their documents that a three-to-five-year horizon is the farthest that they’ll look ahead. “This is going to cost this country tremendously. One of the reasons you find such good people clustering around the Santa Fe Institute is it’s one of the few places where you can do this kind of long-term, long-horizon research. They really encourage it.”

Beginning with the pilot program, the Santa Fe Institute is trying to export this long view back into its “natural repository” of the universities. One who welcomes this approach is Joseph White, Dean of the Business School of University of Michigan, a sponsor of the colloquium. “We are a complex non-adaptive institution,” he sighs. “We need groups like this.”