Using "E-Laboratories" to Study Complex Adaptive Systems

Need

Complex systems are central to many national and global concerns — think of pipelines, electrical distribution systems, ecosystems, and industrial supply chains, to name a few. Each of these systems consists of a highly complex network of interdependent but continually changing entities.

Dynamic networks such as these are termed "complex adaptive systems." In such systems, a slight change sometimes results in severe or widespread effects. To plan for growth or changing demands, decision makers in business and government need better ways to predict the behavior of these systems, particularly the conditions that could lead to instability or failure (Figure 1).

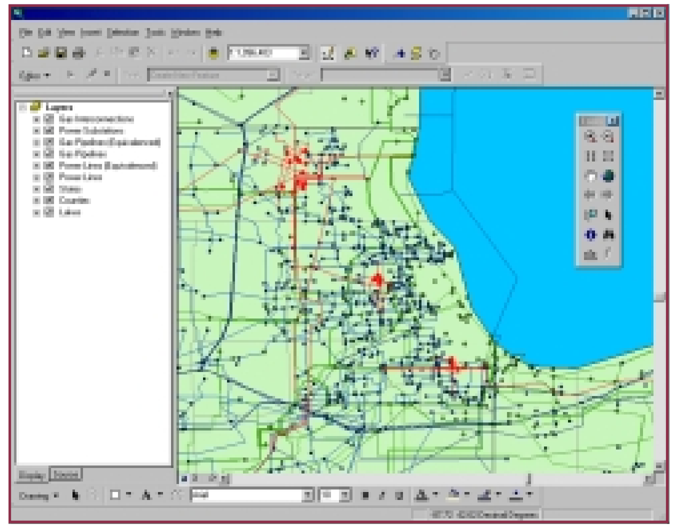

Figure 1. This simulation of dynamic interactions between the electricity grid (green) and the natural gas system (blue) can highlight points where the system reaches some critical condition (red) of interest to decision makers.

Challenge

Conventional experimental and simulation methods often cannot capture the detailed and dynamic interactions that, cumulatively, make a complex adaptive system vulnerable to catastrophic effects. In particular, these methods often cannot reproduce the full range of behaviors inherent in such systems, especially the large-scale patterns that may emerge over time as the parts of the system interact.

Argonne Approach

Argonne is combining new modeling theories and software tools to develop electronic laboratories, or "e-laboratories," for studying complex adaptive systems. The core technique is agent-based modeling, in which complex systems are modeled as collections of individual entities or "agents" (see Figure 2). This concept is implemented using flexible, scalable software environments, developed or improved at Argonne, in which systems can be simultaneously modeled at many different levels of detail.

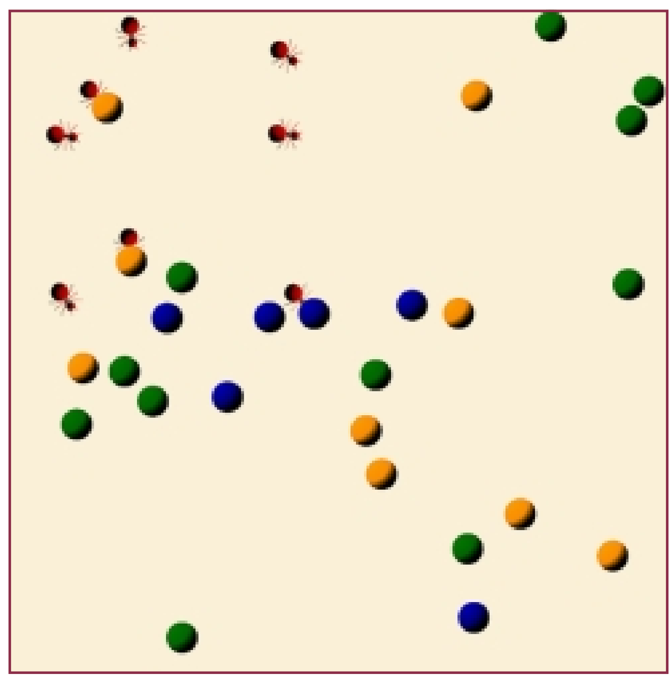

Figure 2. Ecosystems are modeled by developing simple, rule-based descriptions of individual behavior. For example, in the simulation illustrated here, a colony of ants uses individual rules to work together to organize a group of colored balls.

Benefits

This e-laboratory approach allows researchers to study complex adaptive systems under systematic, controlled conditions that elicit a wide range of behaviors. The result is simulations that are far more realistic. Furthermore, these simulations allow decision makers to:

- Test alternative system configurations in a simulated world before implementing them in the real world,
- Understand and predict conditions that could lead to system instability, and
- Anticipate system dynamics for various ways in which the system might evolve.

Figure 3. The endangered red-cockaded woodpecker has very specific habitat and mating requirements that can be represented effectively in an agent-based model. The model can then be used to explore how different habitat management strategies might affect the population and long-term survival of the species. (Photo courtesy of Walter G. Burch, Jr.)

Applications

Working with a variety of sponsors and collaborators, Argonne is applying the e-laboratory concept to national infrastructure analysis (particularly for energy industries), telecommunications, environment and ecology, and transportation and logistics. The program has attracted sustained sponsorship and achieved technical leadership and wide acceptance in the scientific and computing communities.

Infrastructure analysis

- Models represent both physical components and corporate operations.
- Results mimic real-world behavior patterns (e.g., of California electricity markets).

Environment and ecology

- Models capture nesting and reproductive behaviors of the endangered red-cockaded woodpecker (Figure 3).
- Results guide land-use and habitat-management decisions by the U.S. Department of Defense.

Transportation and logistics

- Models explore increased demands caused by economic growth and just-in-time manufacturing.
- Results highlight consequences of various modes of operation.

Collaborators

The University of Chicago, Social Science Research Computing
U.S. Department of Energy, National Infrastructure Simulation and Analysis Center
U.S. Department of Defense
Santa Fe Institute, Business Network
University of Illinois at Urbana-Champaign, Department of Electrical and Computer Engineering
Illinois Commerce Commission

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