Complex Adaptive Systems Modeling at Argonne National Laboratory

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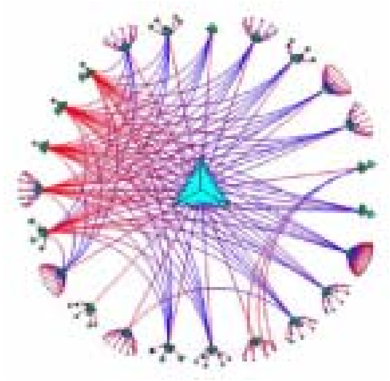
What Is CAS? (1 of 2)

- **Complex Adaptive Systems (CAS) are systems of agents which interact and reproduce while adapting to a changing environment**
- **CAS exhibit coherence under change in spite of constant disruptions and a lack of central planning**
- **CAS are made up of a large number of agents that are diverse in both form and capability**
- **Agent structure and interaction changes based on system experience:**
  - Individual agents learn from experience
  - Learning is the basis for agent adaptation
- **Aggregate agent behavior depends on the interactions of the component agents**
- **Aggregates of agents can in turn act as agents at a higher level to form meta-agents**

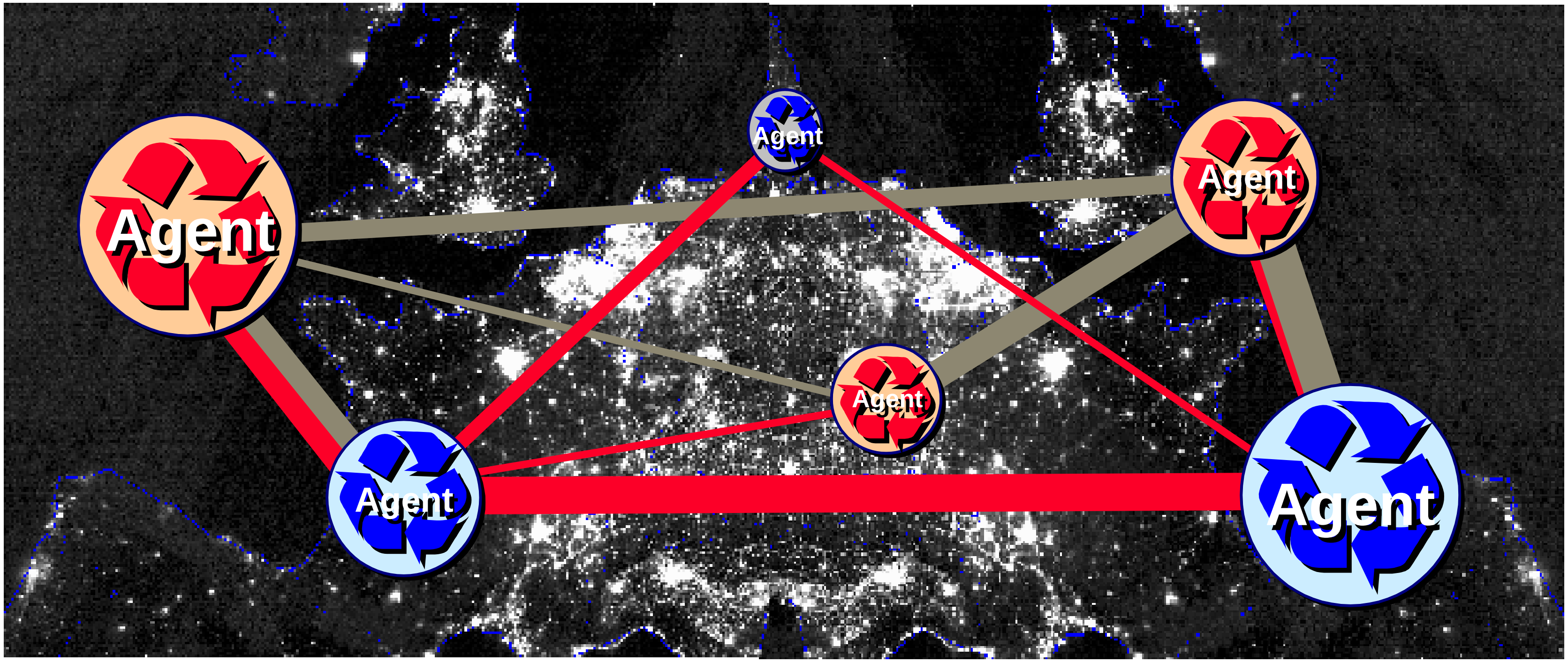
What Is CAS? (2 of 2)

- **An agent simulation consists of agents and a framework for agent interactions**
- **An agent is a software representation of a decision-making unit and can be:**
  - A physical component
  - A decision maker
  - An organization
- **Agent decisions are usually modeled with a set of simple decision rules**
- **Agents interact over time and often exhibit emergent behaviors that are “unpredictable”**



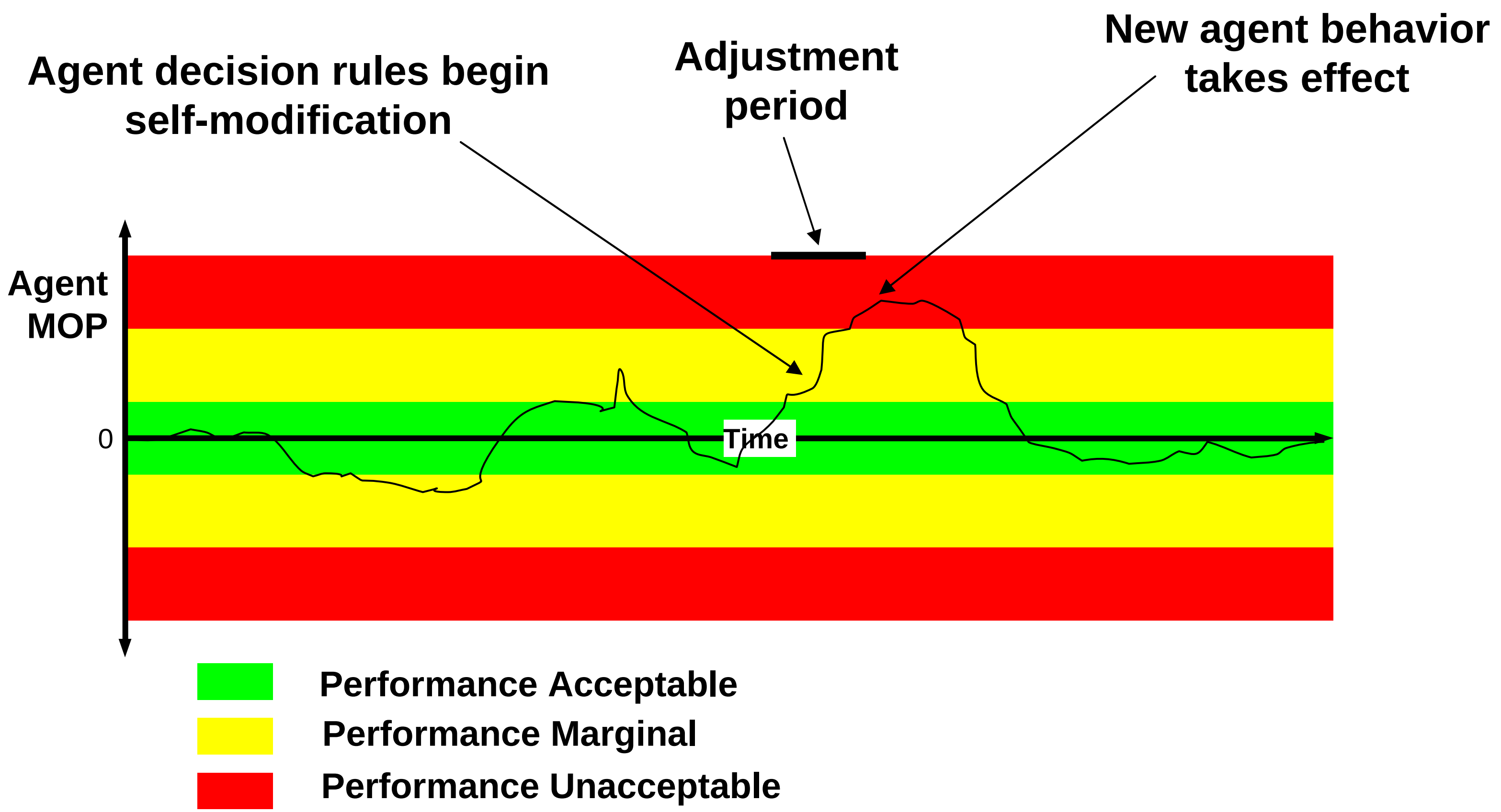
Agents Are Highly Interdependent and Interact Through Networks

- **Effects of events in one network ripple through other networks**
- **Agents have diverse behaviors and characteristics resulting in the dominance of a few tendencies**



Agent Behavior Adapts to Dynamic Environment and System Behavior Evolves

- Agents modify their decision rules in response to changing conditions



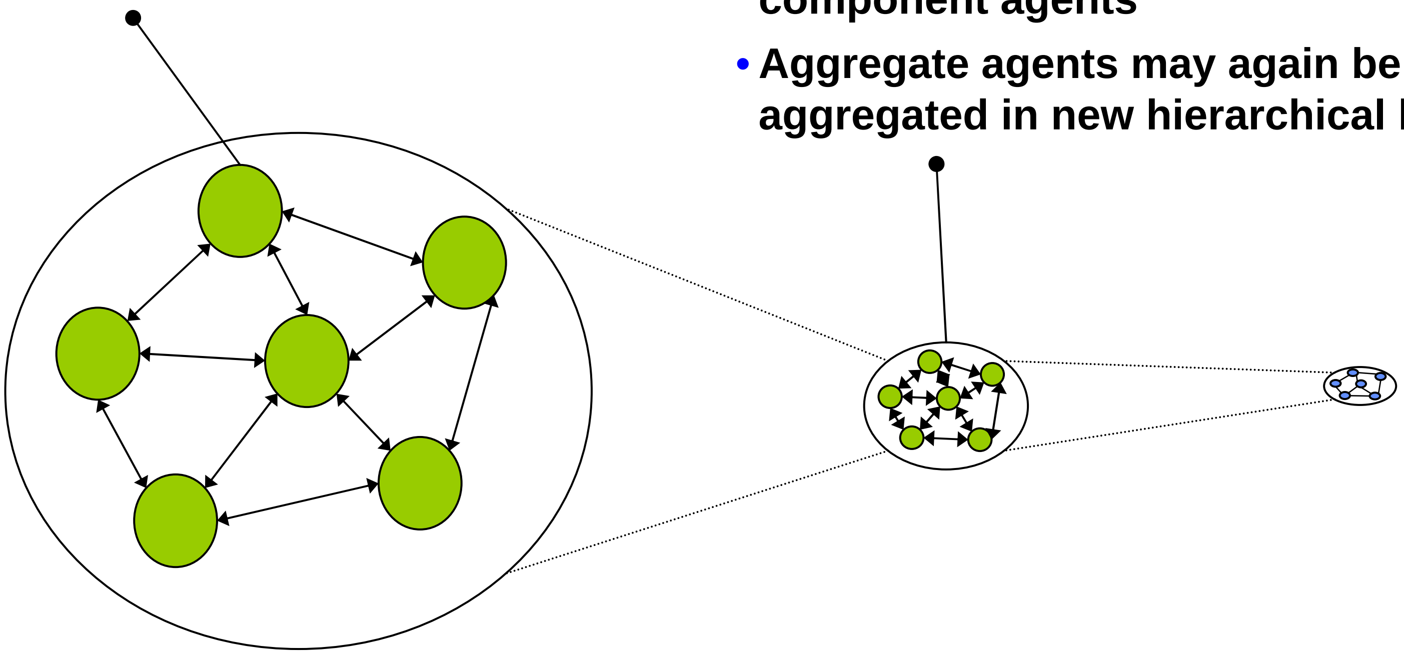
Agents in Complex Adaptive Systems May Cooperate and Form Communities

Adaptive agent

- **Behavior depends on rules**

Aggregate agent (meta-agent)

- **Behavior depends on interactions of component agents**
- **Aggregate agents may again be aggregated in new hierarchical levels**



CAS Emergent Behavior

- **Cooperation in complex adaptive systems can create emergent behavior**
- **Emergent behavior occurs when the behavior of a system is more complicated than the simple sum of the behavior of it components**
- **Traditional modeling techniques such as linear programming do not include emergent behavior**
- **The ability to model emergent behavior is what makes CAS unique and powerful**

How Can CAS Be Used?

- **CAS can be used to model many complicated quantitative structures**
- **CAS is particularly well suited to modeling large scale systems including:**
  - Economic systems
  - Social systems
  - Physical infrastructures and infrastructure interdependencies
- **Examples include:**
  - Electric power marketing and transmission systems
  - Natural gas marketing and distribution systems
  - The interdependencies between electric power and natural gas systems

A CAS Example: Electric Power and Natural Gas Interdependency Modeling

- **Complex Adaptive Systems (CAS) can be applied to investigate current real-world policy analysis and decision-making problems**
- **Viewing such problems from an agent-based perspective allows innovative computational policy analysis**
- **Argonne National Laboratory (ANL) has taken such a perspective to produce an integrated model of the electric power and natural gas markets**
- **This model focuses on the organizational interdependencies between these markets**
- **These organizational interdependencies are being strained by fundamental market transformations**

Market Transformations

- The electric power and natural gas markets are undergoing fundamental transformations
- These transformations include major changes in electric generator fuel sources
- Electric generators that use natural gas as a fuel source are rapidly gaining market share
- Electric generators using natural gas introduce direct interdependency between the electric power and natural gas markets
- The interdependencies between the electric power and natural gas markets introduced by these generators can be investigated using the emergent behavior of CAS model agents

SMART II+

- **The CAS model agents within the Spot Market Agent Research Tool Version 2.0 Plus Natural Gas (SMART II+) allow investigation of the interdependencies between the electric power and natural gas markets:**
  - SMART II+ is an extension to SMART II, the SwarmFest 2000 Best Presentation winner
  - The cutting edge SMART models where featured in the Computerworld TechnologyFuture Watch column ("The Perfect Swarm," August 14, 2000) (www.computerworld.com/cwi/story/0,1199,NAV47_STO48402,00.html)

- **SMART II+ includes an integrated set of agents and interconnections representing each of the following:**
  - The electric power marketing and transmission infrastructure
  - The natural gas marketing and distribution infrastructure
  - The interconnections between the two infrastructures in the form of natural gas fired electric generators

SMART II+ Infrastructure Features

- **Both SMART II+ infrastructures include many features:**
  - Two different kinds of agents, producers and consumers, represent the market participants
  - Interconnections represent transmission or distribution systems with capacities on each line or pipe and complex routing
  - Important economic issues are considered such as investment capital, demand growth for successful consumers, new generation capacity for profitable producers, and bankruptcy for noncompetitive organizations
  - Components can be disabled in real time to simulate failures

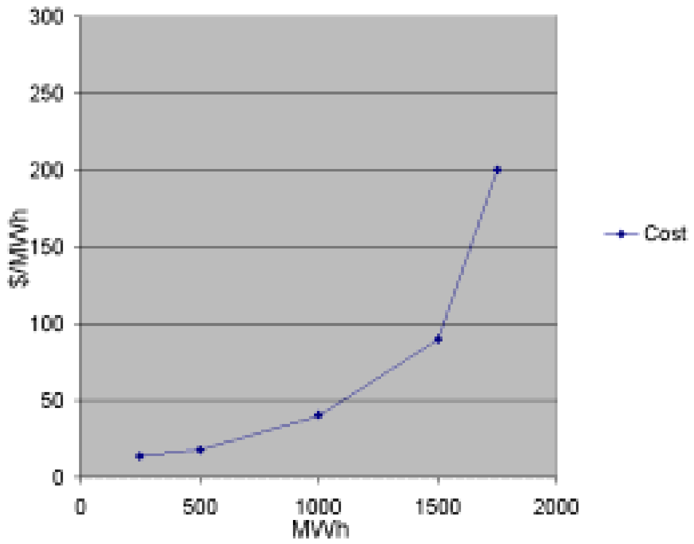
- **The electric power infrastructure includes the added feature of natural gas fired electric generators:**
  - These generators buy fuel from the natural gas market
  - The resulting electricity is then sold in the electric power market

SMART II+ Producers (1 of 3)

- **Producers determine their production level based on the potential profit to be made**
- **Each producer has investment capital that is increased by profits and reduced by losses:**
  - If a producer reaches a predetermined level of investment capital it can purchase additional production capacity in the form of new electric generators or new natural gas sources
  - New producers are similar to their owner and can connect to the distribution network in either the same location or a new one
  - Producers that run out of investment capital go bankrupt and no longer participate in the market
- **Producers choose whether or not to sell energy based on either their cost curves or natural gas prices**

SMART II+ Producers (2 of 3)

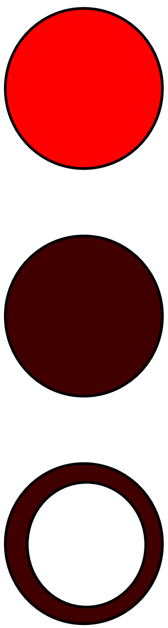
- **Standard producers derive their costs and capacities from cost curves with maximum generation limits**



- **Natural gas fired electric generators derive their costs and capacities from the natural gas market:**
  - These generators are consumers in the natural gas marketplace
  - Their costs are based on the price they pay for natural gas
  - Their capacities are based on both the amount of natural gas they can purchase and their design limits

SMART II+ Producers (3 of 3)

- **Producer appearance is determined by current profit levels:**



Profitable producers are highlighted

Unprofitable producers are dim

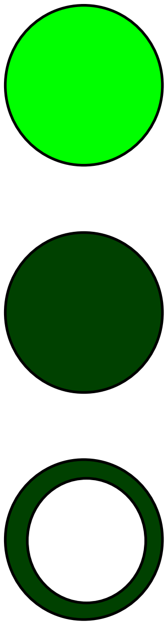
Bankrupt producers are hollow

SMART II+ Consumers (1 of 2)

- **Consumers buy energy for their own use:**
  - Businesses buy fixed amounts of energy to remain in business
  - Populations buy fixed amounts of energy to live their lives
  - Natural gas fired electric generators buy natural gas to produce salable electric power
- **Each consumer has investment capital that is increased by profits and reduced by losses:**
  - If a consumer reaches a predetermined level of investment capital it can grow in the form of new consumers
  - Consumers that run out of investment capital go bankrupt and no longer participate in the market
- **Investment capital represents several things:**
  - For industrial users it is their total financial capital
  - For individuals it is the employment and personal opportunities that keep them in an area or encourage them to leave

SMART II+ Consumers (2 of 2)

- **Consumer appearance is determined by current profit levels:**



Profitable consumers are highlighted

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SMART II+ Interconnections

- **Interconnections represent transmission lines or distribution pipes each with an individual capacity limit**

- **Individual capacity limits vary by interconnection type:**
  - Central transmission lines or main distribution pipes have high capacity limits and are drawn with thick marks
  - Outlying transmission lines or secondary distribution pipes have moderate capacity limits and are drawn with medium marks
  - Feeder lines or pipes have low capacity limits and are drawn with thin marks

- **Interconnection color represents contents and usage**

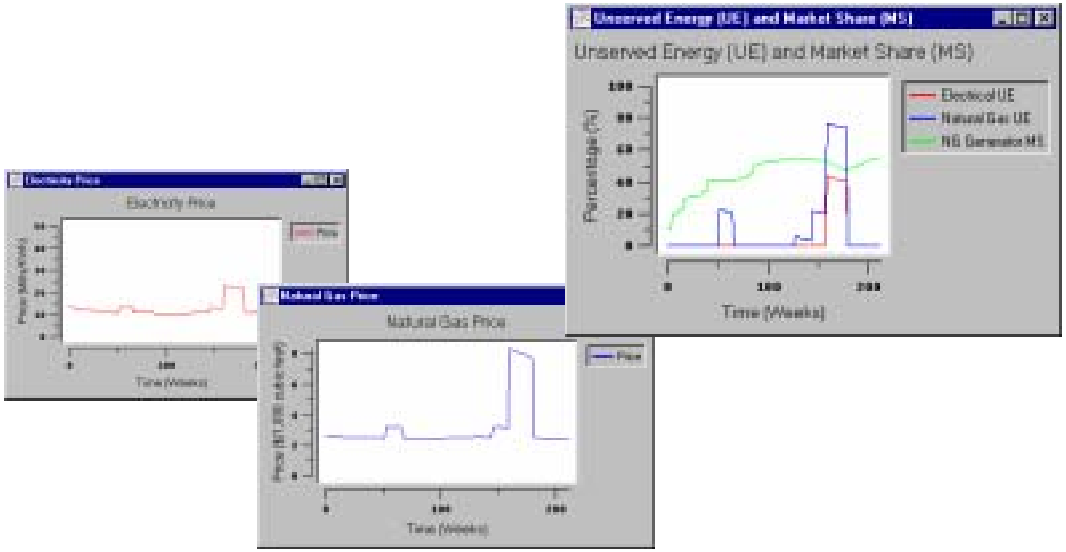
Electrical lines are red

Natural gas pipes are blue

Key Market Indicators

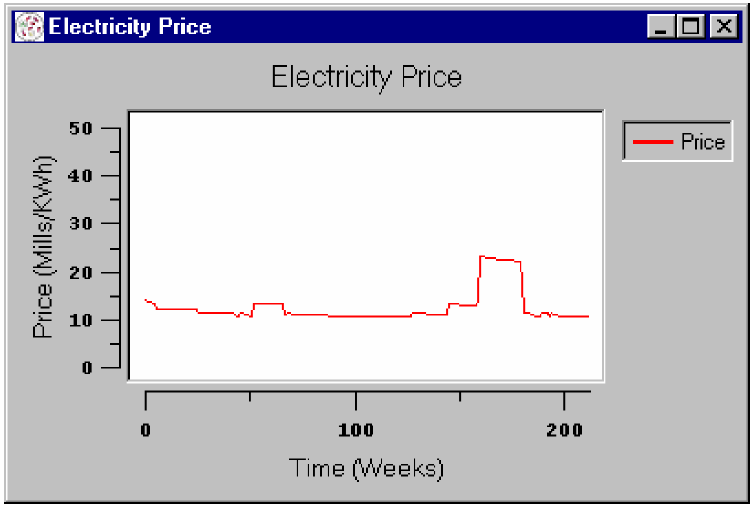
- **The key SMART II+ market indicators are:**
  - Market prices
  - Unserved energy
  - Natural gas fired electrical generator market share

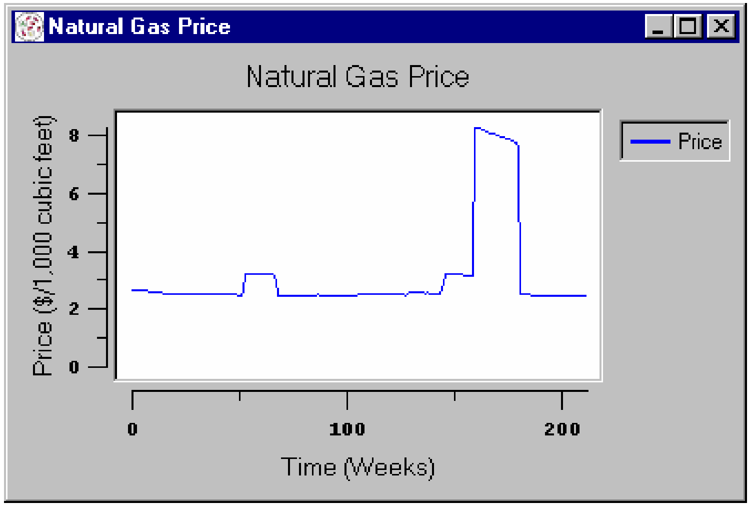
- **All key SMART II+ indicators are represented by graphs updated in real time**



Key Market Indicators: Price

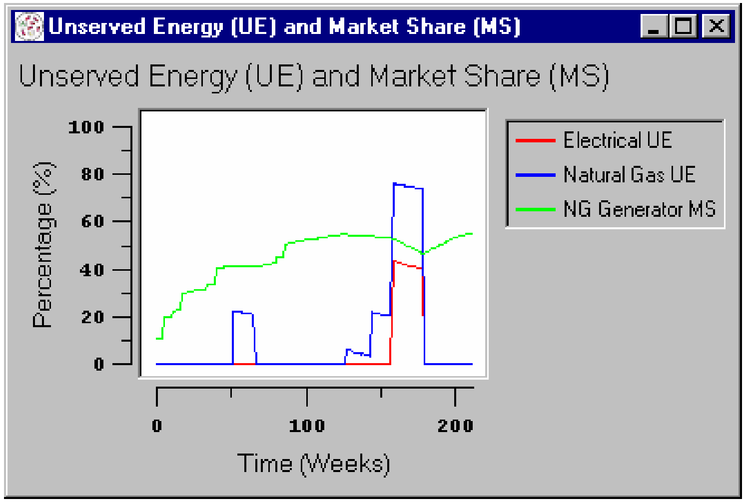
- **Market price is the per unit purchase price of the given energy resource:**
  - Electric power prices are given in tenths of a cent per kilowatt hour (Mills/KWh)
  - Natural gas prices are given in dollars per thousand cubic feet ($/1,000 cubic feet)





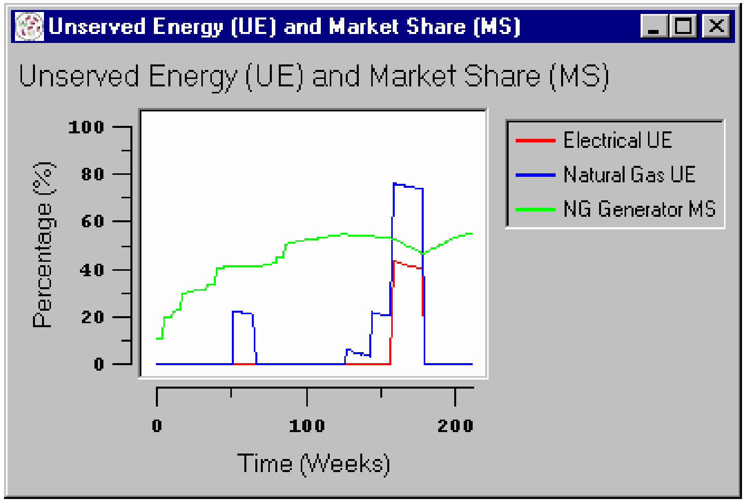
Key Market Indicators: Unserved Energy

- **Unserved energy (UE) is the energy demand that was not met by the market:**
  - UE represents a form of market failure
  - UE is given as a percentage of total energy demand



Key Market Indicators: Natural Gas Market Share

- **Natural gas fired electric generator market share (NG Generator MS) is a measure of the electric generation capacity that is supplied by natural gas units**
  - NG Generator MS is key to infrastructure interdependency
  - NG Generator MS is given as a percentage of total capacity



SMART II+ Emergent Behavior (1 of 2)

- **The emergent behavior of SMART II+ agents allows investigation of the interdependencies between the electric power and natural gas markets**

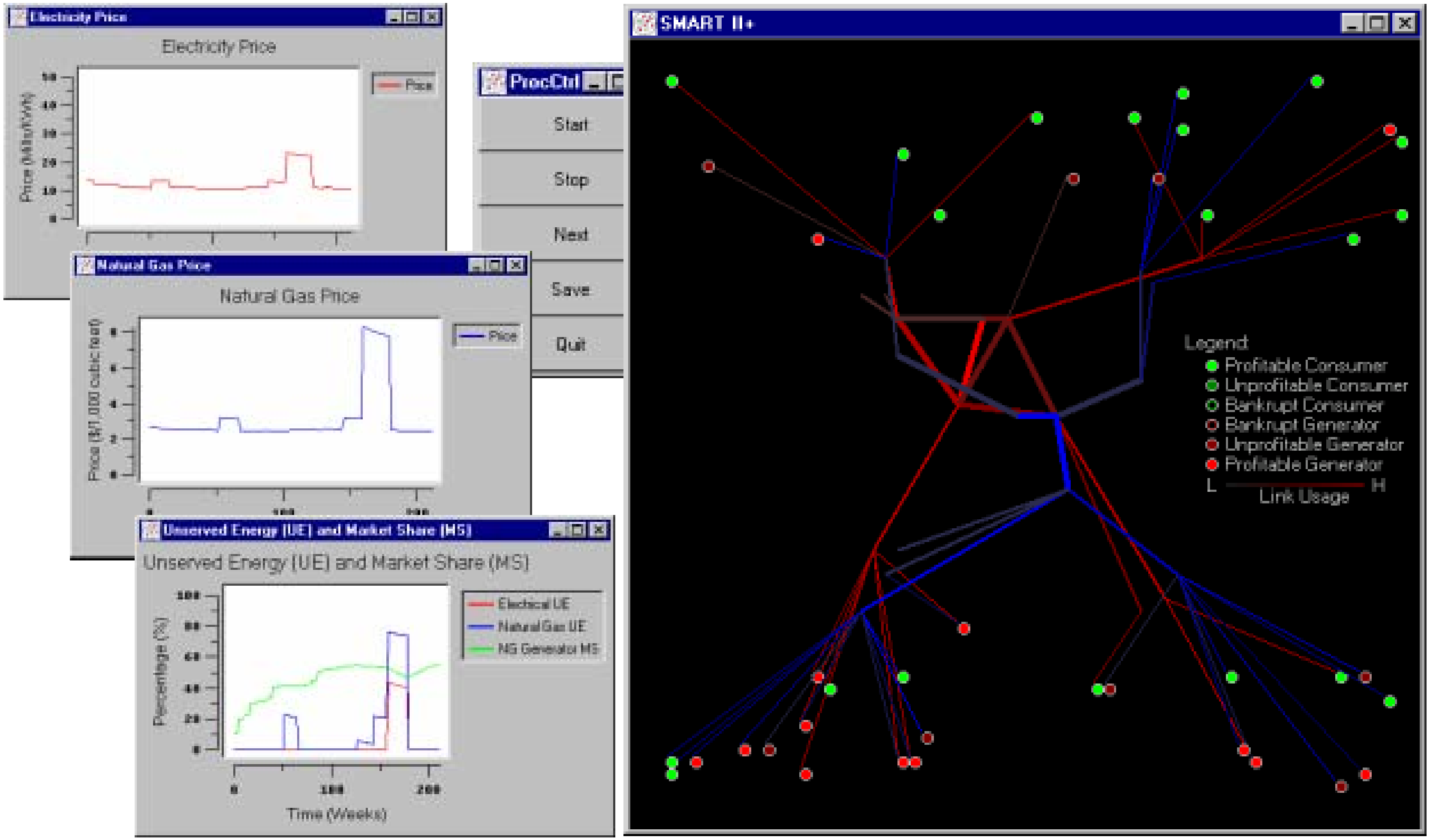
- **SMART II+ emergent behavior indicates:**
  - Natural gas fired electrical generators are highly competitive which causes their market share to rapidly rise
  - Rising natural gas fired electrical generator market share radically increases market interdependence
  - Increasing market interdependence pits the electric power and natural gas markets against one another during simultaneous failures since both markets are fighting for the same underlying resource, natural gas

SMART II+ Emergent Behavior (2 of 2)

- **Natural gas market share is rapidly rising in the current market place**
- **This fact leads to the following conclusion:**

Emergency natural gas purchases by electrical generators need to be carefully monitored to prevent electrical failures from spreading to the natural gas infrastructure

SMART II+ Demonstration



A CAS Example: Conclusions

- **Developing the initial capability to create CAS models requires substantial organizational investment as demonstrated by the SMART II+ effort**
- **Once this initial investment has been made tools can be created that allow innovative investigations of current real-world policy analysis and decision-making problems**
- **ANL has made this investment by creating and applying SMART II+**
- **ANL is leveraging this investment by creating a completely new CAS electric power system model:**
  - The new model's internal working name is the Flexible Agent Simulation Toolkit for Electricity (FAST:E)
  - The new model will feature more more detail and a wider range of modeling options
  - The new model will focus on issues of market structure and competition

How Can CAS Be Built?

- **CAS models can be built using a variety of techniques:**
  - Standard tools such as C++ and Java can be directly used:
    - Large amounts of work are needed for complicated situations
    - Effort is replicated when frameworks are recreated
  - CAS tools can be used:
    - Swarm is the current standard:
      - Swarm is a free open source tool (www.swarm.org)
      - Swarm was developed at the Santa Fe Institute as part of
      - their Artificial Life program (www.santafe.edu)
      - Swarm is written in Objective-C and Tcl/Tk and now includes a Java interface
      - ANL is member of the Swarm Development Group
    - RePast is a Java alternative:
      - RePast is a free open source tool (repast.sourceforge.net)
      - RePast was developed at the University of Chicago (www.uchicago.edu)
    - Ascape is another Java alternative:
      - Ascape is a free open source tool (www.brook.edu/es/dynamics/models/ascape/)
      - Ascape was developed at the Brookings Institution (www.brook.edu)
- **Scalable computing can be used to combine these techniques**

Scalable Computing

- **Scalable computing efficiently matches computing resources to computing tasks so tougher tasks get more resources:**
  - Scalable computing is a design strategy not a specific architecture or product
  - Scalable computing requires platform independent code and open architectures
- **Scalable computing directly complements CAS:**
  - Scalable computing leverages existing tools
  - Scalable computing directly supports distributed modeling
  - Scalable computing directly supports multiple resolution modeling
- **Scalable computing is being developed at ANL as part of the CAS program**

Scalable Computing Resources (1 of 2)

- **Scalable computing at ANL focuses on a range of software and hardware resources**

- **A variety of software will be used:**
  - Swarm will be used to build many of the complex CAS objects
  - Java will be used to build many of the simpler CAS objects
  - RMI and CORBA will connect the CAS objects together
  - Dynamic HTML will connect the CAS model to its users via any web browser anywhere

- **All major operating systems will be supported:**
  - Microsoft Windows NT, 95, 98 and 2000
  - Linux in desktop, networked and Beowulf cluster configurations
  - Sun Solaris in desktop, networked and cluster configurations

Scalable Computing Resources (2 of 2)

- **A variety of hardware will be used**
  - Desktop PCs and PC networks will be used
  - Sun Workstations and Sun networks will be used
  - The ANL UltraSparc Agent Beowulf Cluster (USABC) will be used:
    - The USABC is the world's largest hybrid Sun UltraSparc/IBM PC Beowulf Cluster
    - At least ten Sun UltraSparc workstations are included
    - Many IBM compatible PCs will be included
    - At least one Cicso 5000 Network Switch is included
    - Linux will be the operating system

Scalable Computing Gives Users a Choice

- **Scalable computing gives users a choice:**
  - Small tasks can be completed on desktop PCs:
    - Learning can be completed on desktop PCs
    - Model construction can be completed on desktop PCs
    - Initial model validation can be completed on desktop PCs
    - Initial model runs can be completed on desktop PCs
  - Larger tasks can be completed on larger systems:
    - Moderately large tasks can be completed on networked PCs
    - Large tasks can be completed on networked Sun workstations
    - Extremely large tasks can be completed on a Beowulf Cluster such as the USABC
- **This flexibility allows CAS model users to efficiently match computing resources to computing tasks so tougher tasks get more resources**