Models of Complex Adaptive Systems

Lecture to POLI 126/330: Complexity, Science and Society

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What are we modeling

- **Complex Adaptive Systems**
  - *No agreed definitions*
- **A system:** (A perception of) a collection of entities which interact with one another in some ways, and with the environment outside the collection.
  - Note that a system may be entirely constructed (an artifact).
- **Complex:** The system exhibits global properties which arise only from local interactions between the entities; the global properties are not imposed on the system.
- **Adaptive:** The entities change and/or their relationships change as a result of the interactions and/or as a result of the environment.

Main types of models

- Dynamical system models
  - We focus on the variables which change (usually the global properties)
- Graph-theoretic or network models
  - We focus on connections between the entities and their global impact.
- Agent-based models
  - We focus on the entities in the system and their local interactions.

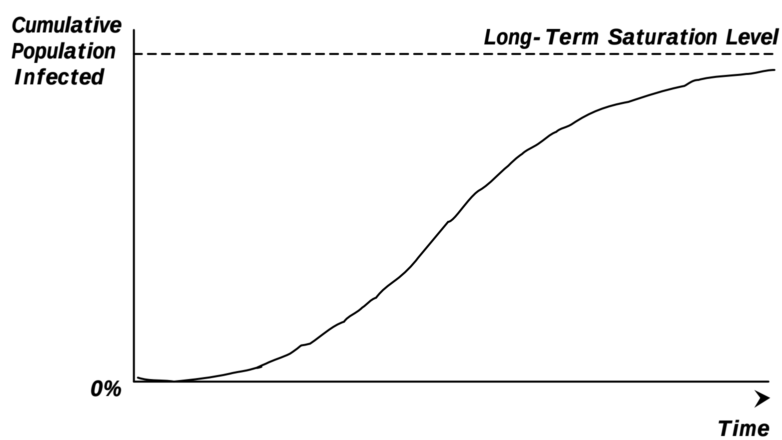
Nonlinear systems

- These models use the differential calculus
  - Isaac Newton, Gottfried Leibniz (late 17th century)
  - A mathematical model of change over time
- Example:
  - If traveling, you travel some distance
  - Your speed is:
    - How fast you change distance over time
  - Your acceleration is:
    - How fast you change speed over time.

Differential equation models

- We can use the methods of the differential calculus to model change in a complex adaptive system
  - The mathematical theory is called nonlinear systems theory or dynamical systems theory, and typically involves partial differential equations.
- For example, consider the diffusion of an epidemic through a population
  - Numbers of people who have been infected should not decrease over time (ie, stay the same or increase).
  - We might assume that the increase in the next period of time depends on
    - The number who already have been infected, and
    - The number who have not yet been infected.

Diffusion of an epidemic



We can extend this

- Multiple variables
- For example, models of predator and prey populations
  - eg hares (prey) and foxes (predators)
    - The foxes eat the hares
    - If the foxes are too successful at killing hares, then the numbers of hares fall.
    - If there are not enough hares, the foxes then starve.
    - This reduces the numbers of foxes, allowing the population of hares to increase.
    - An increase in numbers of hares provides more food for the foxes.
- So we have a cyclic pattern.
- If we assume that there is no limit to the prey population (hares), then we get the following picture:

Predator and prey populations vs. time

Plotting predator vs. prey populations

Finite carrying capacity

- But, this assumed the prey population could increase without limit in the absence of predators.
- In reality, there will be some finite upper limit for the prey population
  - eg. due to the carrying capacity of the environment.
- Introducing a finite carrying capacity creates a different picture.
- We now have a stable equilibrium point.

Predator vs. prey populations with carrying capacity

Chaos

- In the context of dynamical systems, chaotic models are defined as follows:
  - A model is chaotic if it is sensitively dependent on the initial conditions.
- In other words, if the global properties of the model change markedly even when there are small changes in the assumptions of the model.
- So, we may get a *butterfly effect*:
  - A butterfly flapping its wings in the jungle of Brazil causes changes to the weather globally, leading to a tornado in Texas.

Dynamical systems models

- Usually hard to specify
  - We need to have an understanding of the qualitative relationships between the variables involved. This is usually difficult if there are many variables or they have complex relationships.
- The mathematics seeks to quantify systems for which only qualitative information may be available.
- Often difficult or impossible to solve the resulting equations
  - For example, we usually cannot find equilibrium points easily, even when these are known to exist.

Graph-theoretic/Network models

- Here we ignore the agents themselves and focus on the connections between them.
- Diagram.

Six Degrees of Separation

- 1960s: Stanley Milgram (Harvard)
- Letter from random 160 people in Omaha, Nebraska → person in Sharon, Massachusetts
- Each person asked to post it on to someone closer to the addressee.
  - Most letters arrived in 5 or 6 steps
  - Many letters reached the addressee via the same 3 persons.
- Conclusions:
  - A few people have many connections.
  - The majority are linked to others via these few.

Graph notions

- Average path length
  - How many connections on average along the shortest path between any 2 agents?
- Clustering co-efficient
  - Are there some agents with lots of connections?
  - A number between 0 and 1: the higher this is, the more clustering there is.
- Random graph: connections distributed randomly
- Small worlds graph:
  - Short path length
  - High clustering coefficient

Examples of small world networks

- Movie actors
- Scientific collaboration networks
- Perhaps most human societies.

Implications

- For spread of disease through a population
- In a random network, there is usually a threshold percentage infection level (eg 5%)
  - The entire population only gets infected if the percentage of agents infected goes over the threshold level.
- In a small world network, there is no such threshold percentage
  - No matter how few agents are infected, eventually the entire population will be infected.
  - The reason is the agents with lots of connections.

Agent-based models

- Here we study the entities in the system and their interactions
- We call these entities “agents”
- Two broad approaches:
  - We just model the decisions made by agents: Outside-in
  - We model the mental states of the agents: Inside-out.

Outside-in

- We model the decisions made by the agents from the *outside*
  - ie without explicitly modeling the beliefs or attitudes of the agents.
  - Developed from the 1960s onwards.
- For example: Consider a traffic system
  - Each person can choose to commute by by bicycle, car, by train, or by tube.
  - What factors are important to this choice?
    - Commuting distance, time taken, cost, traffic levels.
    - Income of person, health, attitudes to different modes, etc.
- We can build a statistical model of the decisions a hypothetical commuter will make, and then aggregate these to see how many commuters choose each option.
  - We might collect data from actual or potential commuters to calibrate the model.

Outside-in (2)

- Often used in Marketing Research (Conjoint Analysis) and Public Policy Formulation (Discrete Choice Modeling).
- Typical application
  - We ask people to compare different products (eg breakfast cereals)
  - We try to identify background variables which may influence their choice
  - For Breakfast cereals, the main influencing factor is the household decision-making style regarding cereals
    - Democratic households: the children decide
    - Dictator households: the parents decide
    - Hybrid households: mostly the parents decide, but they sometimes let the children decide (eg, on holidays)
  - These factors influence the marketing & communications strategy of the cereal manufacturer.

Inside-out

- Here we attempt to model the decision processes of the agents *from within* using a model of the mental states of the agents
- Draws on recent work in the philosophy of rational action and very important now in computer science
  - Many large-scale computer systems (eg, the Internet) may be viewed as systems of interacting rational entities.
- A software agent is a computational entity with (some degree of):
  - Social awareness
  - Proactive behavior towards defined goals
  - Reactive behavior in response to its environment
  - Decision-making autonomy.

(Wooldridge & Jennings 1995)

Types of agent models

- Agent decision-making models:
  - Rational agents
    - eg, BDI models (Beliefs, Desires, Intentions)
  - Cellular automata
- Agent interaction models:
  - Ant models
    - Communications via pheromones
  - Economic interactions
    - Buying/selling
  - Dialogue interactions
    - eg, Internet Protocols, such as HTTP.

Cellular automata

The simplest agent models

- We have a grid.
- We assume time is discrete (comes in steps).
- Each cell is occupied by an agent which may have any one of several states.
- The state of an agent at any time depends on the states of its neighbours at the previous time.
  - Typically, we have some rules which determine the state of each agent.
  - These are local rules.
- Sophisticated global patterns may emerge from simple local rules.

Cellular Automata Examples: Rule 30

- Each agent can be in 2 states: Yellow or Black.
- As the CA computes, each agent checks the colour of itself and the agent directly to the left and right of it, and then paints the agent below it according to Rule 30:

Y Y Y	Y Y B	Y B Y	Y B B
B	B	B	Y
B Y Y	B Y B	B B Y	B B B
Y	Y	Y	B

- For example, if we have a Rule 30 CA, and the current cell is black and its left neighbour is yellow and its right neighbour is yellow, the cell below it is painted black.

Cellular Automata Examples: Rule 90

- Each agent can be in 2 states: Yellow or Black.
- As the CA computes, each agent checks the colour of itself and the agents directly to the left and right of it, and then paints the agent below it according to Rule 90:

B B B	B B Y	B Y B	B Y Y
B	Y	B	Y
Y B B	Y B Y	Y Y B	Y Y Y
Y	B	Y	B

- For example, if we have a Rule 90 CA, and the current cell is black and its left neighbour is yellow and its right neighbour is yellow, the cell below it is painted black.

CA model of Society: Segregation

- Two types of turtles in a mythical pond: red and green turtles.
- The two types get along, but each wants to live near some of its own colour.
  - Each red turtle likes to have some other red ones nearby.
  - Each green turtle likes to have some other green ones nearby.
- So, at each time point, some turtles move to be near others of the same colour.
  - This changes the new neighbourhood, leading some in that area to move also.
- This example shows the global emergence of segregation, even when only a minority of turtles (say, 30%) wish to live with turtles of the same colour.

Some Issues

- Calibration and testing
- Simulations
- Anticipatory and reflective systems
- Prediction.

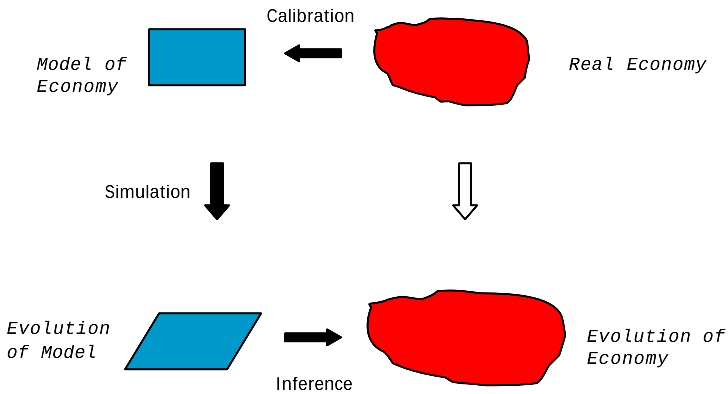
Calibration and testing

- Calibration: Task of assigning quantitative estimates to parameters of a model.
- Testing: Task of comparing outputs of model to real-world, in order to refine the model.
- Problems:
  - Parameters may not be observable
    - An agent's beliefs, desires, intentions
    - An agent's future intentions.
  - Parameters may be entirely artifactual
    - eg, all economic variables.
  - There may be too many parameters to calibrate or outputs to test

Simulations

- What is a simulation?
  - Still no coherent, formal theory of simulations and models.
- Different possible roles:
  - A model as a description of a CAS to aid understanding
    - Economic theorizing
  - A model as a simulation of a CAS to aid policy intervention
    - eg Economic policy
  - A model to manage and control an CAS
    - eg Telecommunications networks
  - A model as a design metaphor for an CAS
    - Multi-agent systems in Computer Science.
- Robert Rosen ("Life Itself"):
  - We can only make valid inferences if our diagram commutes
  - ie, if we can in either direction from top-right to bottom-right.

A theory of simulation



Anticipatory and reflective systems

- Anticipatory systems (Rosen): systems of agents where (some) agents themselves have a model of the system.
- Reflective systems: Anticipatory systems where there is communication about the system models of agents.
  - Rational Expectations in economics.
- Example: Central Bank monetary policy
  - Bank of England decides interest rate levels (Monetary Policy Committee)
  - Investors try to predict the Bank's decisions
  - The Bank takes these predictions and likely investor reactions into account when making its decisions
  - Investors take the Banks decision-processes into account when making predictions and deciding their reactions
  - The Bank tries to manage investor reactions by releasing its deliberations
  - Etc.

Prediction

- Agents may make predictions which impact the future states of a system
  - Self-fulfilling prophecies
  - Self-denying prophecies.
- Predictions and even modeling may be performative activities:
  - Utterances which become true by virtue of being uttered.
  - eg, "I now pronounce you man and wife."
- Example: Economic modeling as performative activity:
  - Economic theorists assume people are utility maximizers
  - Modern financial markets are designed with this assumption
  - Because of the structure of the market mechanism, participants then act in accordance with the assumption
  - The model of reality has created the reality it purports to describe.

Conclusions

- Much interesting research to be done:
  - Theory of simulations and modeling
  - Theory of cellular automata
  - Theory and design of multi-agent systems
  - Modeling of anticipatory and reflective systems
  - Theory of predictions and interventions.
- Many interesting applications:
  - Complex decision-making domains
    - eg, Global warming; medical policy; hi-tech business strategy
  - Design and management of CAS
    - eg, Societies for e-science; autonomic distributed computational systems
- Need to understand interplay of theory & application (praxis).