Overview of this Week:

- Today: CAS properties, concepts; Why ABM?

- Tuesday: Who interacts with Whom?
  Real networks are not (random; lattice; fully connected). Interaction topology often key to resulting dynamics.

- Wednesday: Co-adaptation, Perpetual Novelty and Emergence.
  The ElFarol Bar Problem (Minority Game).

- Thursday: Simulating Societies (or parts thereof). The SugarScape model; Spread of Opinions; Urban growth.

- Friday: Verification, Validation, and other issues.

Center for the **S**tudy of **C**omplex **S**ystems

- "mission statement"
  Encourage and facilitate education and research in the general area of complex, nonlinear, dynamic and adaptive systems.
- Interdisciplinary center (not a department)
- Associated faculty and students from Biology, Economics, Political Science, Math, Engineering, Computer Science, Anthropology, Physics, Business School, Public Health, Psychology, and more.
- Students can earn a UM Rackham Graduate Certificate in Complex Systems Studies (5 courses – mini-Masters)
- IGERT – funding for PolSci, Econ, Soc grad students. (Talk to Scott Page.)
- Shared interest in CAS:
  - search for (belief in!) common underlying dynamics and structure across many systems
  - transfer techniques and tools (empirical, analytical, computer modeling)

Nonlinear Systems: Agent-Based and Computer Intensive Models of Complex Adaptive Systems. CAS includes:

- Biological systems (ecologies, brains, cells)
- Economies, markets
- Human organizations (firms)
- Political, cultural systems (cities, states,...)

An Introduction to:

- Cmplx Sys Approach: Bottom-up models
  - Agent-Based computer models
  - Simple math models
- Specific models in various areas (IR, OT, markets,voting,...)
- General concepts from C(A)S studies

Morning sessions:

- Rather a lot to read (esp. this week!) Read what you can...much can be read relatively quickly.
- ***Discussion!*** Its more fun for all of us!!

Course will cover key issues / concepts from Complex Systems including:

- Emergence; micro rules to macro patterns
- Distributed systems: no central controllers

- Interdependence; Feedback
- Path dependence
- Dynamics (vs Equilibria)

- Evolution, Learning, Adaptation (Genetic Algorithms)
- Satisficing (vs optimizing)
- Co-adaptation; Niches; Diversity
- Perpetual novelty;

- Interaction Topology (Networks, Space)

- Self-Organized Criticality (SOC)
- Edge of Chaos; Cellular Automata

Why a Complex Systems Approach?
Focus on aspects difficult for other approaches:

CAS Micro-level characteristics

- Medium number of components (agents)

- Model Agents with
  - limited capabilities (bounded rationality)
  - nonlinear behavior (if/then rules, etc)
  - heterogeneous knowledge, capabilities, relations (who they interact with)
  - heterogeneous individual "goals"
  - heterogeneous history, memory
  - adaptive capabilities (strategies, relations)

- Interactions are critical to behavior

- Interactions are (usually) local (social and/or spatial topologies)

- Mix of cooperative and competitive interactions.

Macro-level characterisitcs of CAS

- Aggregate features important: GNP, market prices, organizational structure, population size, ...
- Large scale structure/dynamics (patterns) emerge: power laws; cycles, basins of attraction; bifurcation patterns
- Hard/impossible to predict dynamics and structure in detail.
- Path dependent phenomena:
  - sensitivity to initial conditions
  - accumulation of historical accidents
  - multiple "equilibria"
- Nonlinear dynamics common, e.g., tipping phenomena, punctuated equilibrium, etc.
- Perpetual novelty: behavior in "transients" is important (systems never reach equilibrium)!
- New "emergent structures" are important: cells, organisms; tribes, nation states, firms.

How to Model CAS??

Models:

- Description of **part of** the world.
- Capture structure/dynamics **of interest to modeler**.

Key questions:

- What to include?
- What to leave out?

Answering those: **art and craft of modeling**!

KISS (Keep It Simple, Stupid)

- Easier for you to understand
- Easier to analyze, display results
- Easier to describe and explain to others!

Computer models: great tempation to include too much!

Another key question: What is the purpose of the model?

- Predictive:
  Strongest claims; clear policy implications; most difficult to obtain (CAS–impossible?)
  Note role of abstraction in “predictions:“
  - There will be cycles (vs equil vs chaos)
  - There will be 12-year cycles
  - There will be this particular time series...

- Explanatory:
  Explain observed patterns, but not make detailed predictions. Example: evolutionary models in biology.

- Exploratory:
  Develop intuitions or even theories. Study alternative hypotheses. Determine implictions of assumptions. Examples: Schelling’s segregation model; Axelrod’s Cultural Diversity model.

Modeling languages

- Text description (informal)

- Mathematical (formal)
  Equations (static, dynamic); logic stmts.
  Precise, robust (over assumptions).
  Must be "simple" to get closed form solutions.
  Numerical methods for analysis/estimation.
  (system dynamics equation-based models).
  Difficulties from:
  - heterogenous, non-continuous space
  - heterogenous agents
  - nonlinear mechanisms (if-then rules)
  - adaptive agents: creating new agents.

- Agent-Based Models (simulations).
  (note I don't call EBM "simulations.")
  Formal; precise. (Text description might not be...)
  "Solve" by running the program!

Agent Based Models / Simulations
Specify simple, locally driven mechanisms and interactions. (Bottom-up approach).

Typically three components:

1. Agents
   - Sensors (see neighbors and their types)
   - Effectors (move to new cell)
   - Individual state (type, memory, ...)
   - Behavior rules (if ... then ...)
   - Adaptive mechanisms (learn; genetic)

2. A world
   Some topology; State/dynamics of its own.
   Ex: 2D world, with resource dynamics.

3. Intrumentation for observations
   Not always obvious what to measure, or how to measure it.
   (e.g., what clustering measure? what is a species? what is an new organization?)

EBM: equation based modeling

- Fundemental entities are usually aggregrate variables (GNP, #infected)
- Dynamics: Relate variables by equations (ODE, PDE)
- Top-down, system dynamics approach (macro econ, epidemiology, ...)
- Often based on mean-field assumptions (i.e., ignore or approximate any underlying variance)

ABM: agent (individual) based modeling

- Entities are "agents" each with own state
- Dynamics: behaviors of agents, defining interactions with each other, with objects in the "world," adaptive changes, etc.
- Generally do not include aggregate variables in model dynamics.
- Observe "emergence" of aggregate level dynamics and structure (GNP cycles, trade patterns, nation alliance formation/dissolution).

Why/when use ABM approach:

- Relax constaints & assumptions necessary for equation based approach:
  - Non-linear dynamics: if-then rules.
  - Heterogeneous agents: attributes could be obtained from survey data, etc.
  - Includes/distinguish physical vs social interaction spaces.
- Rich endogenous adaptive mechanisms.
  - Avoid the nano-fox problem:
    Infinite population -> All types always present!
  - Can study *time to discovery* of new types & strategies.
  - Make use of open-ended (generative) adaptive mechanisms.

- Mechanisms / Processed speficied at the agent (micro) level.
  - More intuitive ("natural") level for people: Non-modelers can understand it & become engaged. Easier to get domain expertise and/or "sell" to policy makers.
  - Useful policy *levers* often at this level. (Eg, focus on "hub" individuals in social networks, or on changing agent preference distributions or rules of action)
  - Validate system at *two* levels: check agent behavior as well as the usual aggregate observable behavior.

- Conceptual shift:
  - Emphasize dynamics (vs equilibrium)
  - Focus on path dependence, distribution of histories (typical vs. atypical)
  - "Intuitive" representation of (controlable) agents and their behaviors.
  - Generative approach to social science: plausible model if "realistic" agents generate observed phenomena.
  - Construct artificial worlds about which everything is known; experimentation is (relatively) easy. Use to test hypotheses and assumptions, and to *test survey/statistical* tools themselves.

Problems/Cautions with ABM approach

- Verification: is the program debugged.

- Validation (compared to the world):
  - Valid basic mechanisms? May be hard to validate assumptions (e.g., parasitic load, individual search mechanisms, etc.)
  - Valid predictions: what level of abstraction should be predicted?
  - Are results artifacts of some (unknown) implementation details?

- Understanding and describing the models
  - Too many agent types, mechanisms, variables -> unfathomable model.
  - Text description vs model implementation can mislead.
  - Mountains of data: Can be as complex as observations from the world being modeled!

- Computational constraints.

  How to avoid biases introduced by:
  - small populations (drift),
  - short run length (missed events),
  - limited number of replications (misleading sample of histories)
  - limited sample of parameter space (special cases).

  This is becoming less of a problem with faster computers.

- Not as "general" as equations.
  - No analytic solutions.
  - Results may be tied to specific details and conditions of computer model runs.

  But—generality issue for analytic models: Do the results hold when (often very restrictive) assuptions are violated?!

Readings for today:

- Casti: Modeling in general, types of models, uses of models.

- Rauch: Popular account of Schelling; recent work at Brookings.

- Bonabeau: Why ABM? Several example applications to "real world" (traffic, customers, markets, organizations, crowds, ...)

- Axtell: Compare to "traditional" analytic approaches.

- Bankes: Exploratory vs. consolidative models. Pitfalls of trying to make quantitative, predictive models of very complex systems.

- Parunak etal: ABM vs EBMs, for modeling supply chain dynamics.