Complex Systems Approaches Across the Disciplines

Left to Right: John Holland, Scott Page, Michael Cohen, Bob Axelrod, Rick Riolo, Mark Newman, Carl Simon, Mercedes Pascual

Simplicity in Complexity

Complex Systems Approaches Across the Disciplines

Carl P. Simon
The University of Michigan
Professor of Mathematics, Economics, and Public Policy
Director, UM Center for the Study of Complex Systems

OVERVIEW

- *Systems thinking*
- *Simple systems*
- *Complex systems*
- *The UM Complex Systems Center*
  People and Research

Key insight about problem-solving:

Everything is a ***system***,

composed of interdependent and interacting components.

Ignoring these interconnections

often leads to

unanticipated consequences.

Examples of Systems

Natural Systems

Immune system

Circulatory system

Respiratory system

Body itself

Ecosystems

Man-made systems

Legal Systems

Economies

Business organizations

Automobiles, airplanes

Computers

Failures for lack of Systems Thinking

Natural Systems

- DDT
- Bring some wild rabbits to Australia so you can still hunt

In 1859, Thomas Austin introduced 24 wild rabbits onto his hunting preserve in Victoria, Australia so he could continue his beloved hobby.

Within ten years of the introduction, the original 24 rabbits had multiplied so much that **two million** could be shot or trapped annually without having any noticeable effect on the population.

Good thing Austin didn't introduce the killer rabbits that Monty Python's Knights encountered on their search for the Holy Grail.

Failures for lack of ***Systems Thinking***

Health Systems

- **Hospital director**
  - Use only the strongest antibiotics
  - Use antibacterial soaps
- **Personal physician**
  - Indiscriminate prescription of medications

Failures for lack of
Systems Thinking

Man-made Systems

– Build a new highway lane to address congestion

– Beat urban decay by tearing down neighborhoods and moving the occupants into isolated high-rises

– Raise prices to increase profits

Failures for lack of ***Systems Thinking***

Political Systems

Bring democracy to a country by sending in your army to depose that country's despotic ruler.

Systems Approaches

- Separates college approach from high school

- “Whole picture”
- “Holistic approach”

- For Homework: your own examples

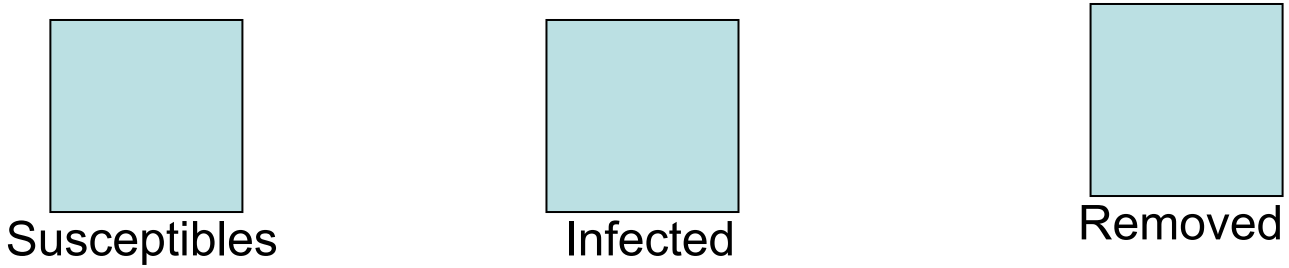
Systems thinking: first steps

- **Identify key variables and main actors**
  - Especially those in the problem under consideration
- **Draw (causal) diagrams** to illustrate connections and feedbacks
- If possible, **quantify** some of those connections
- Result: a ***model***
  - heuristic, computer, mathematical

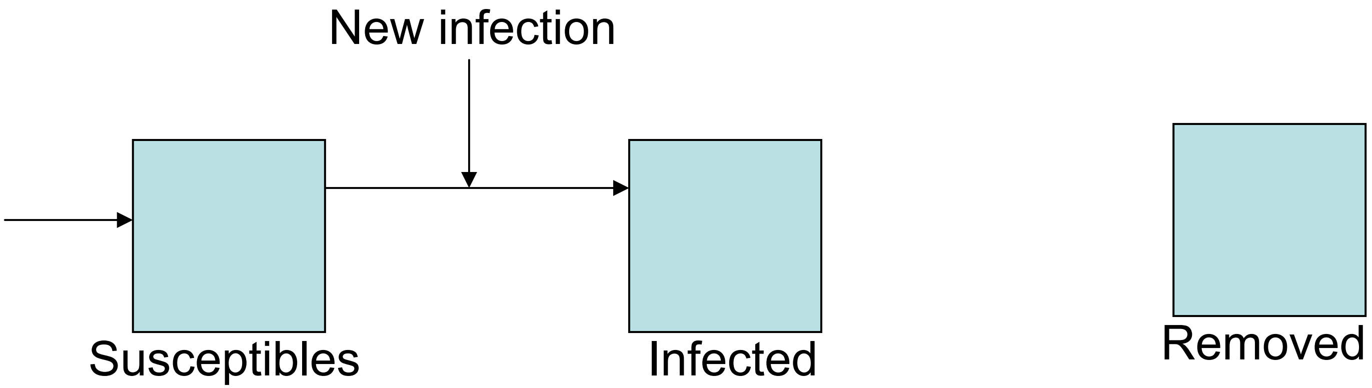
Start with *Simple Models*

- **K.I.S.S.** Principle
- Capture the **bare elements** of the system under study and its main components
- Make many **simplifying assumptions**
- **Three examples**

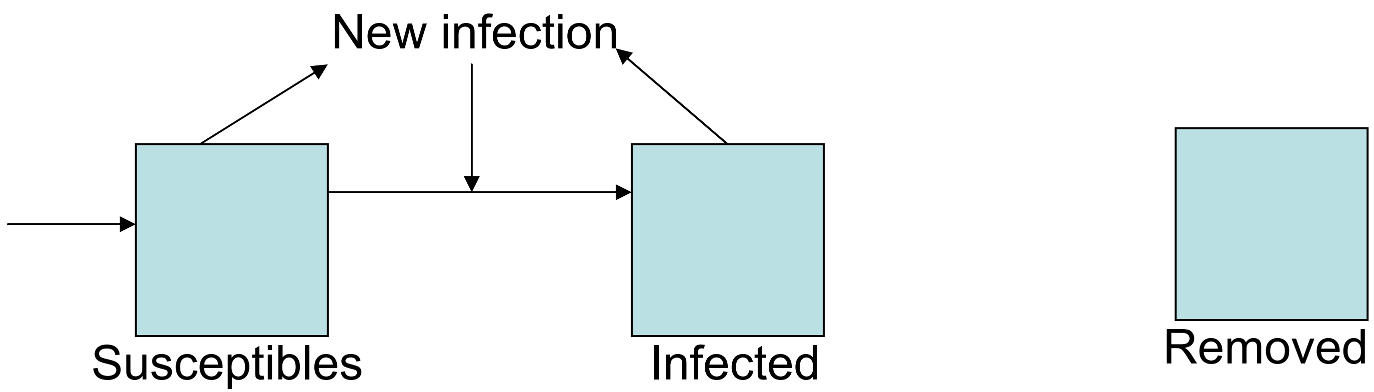
Simple system of disease spread



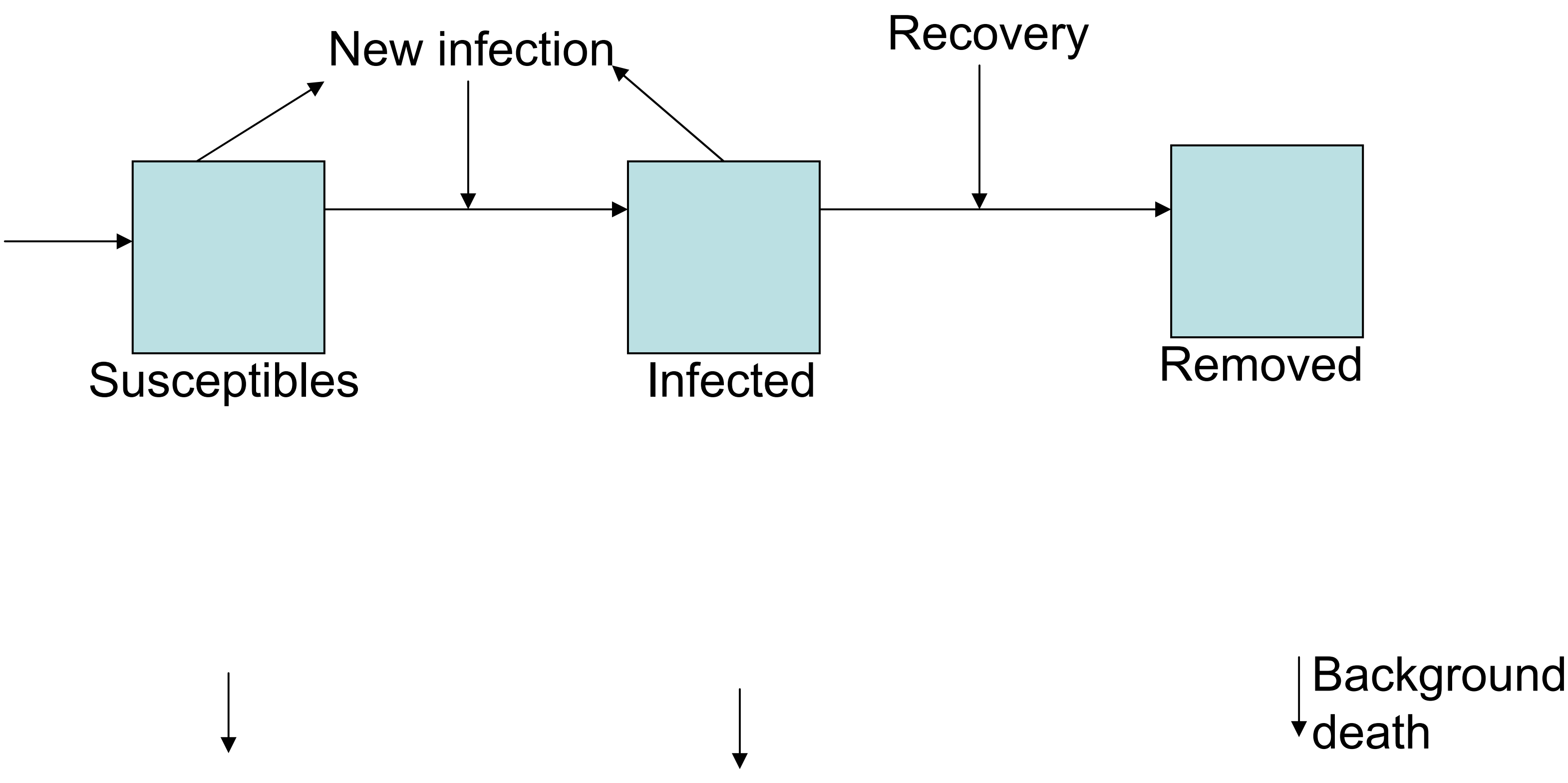
Simple system of disease spread



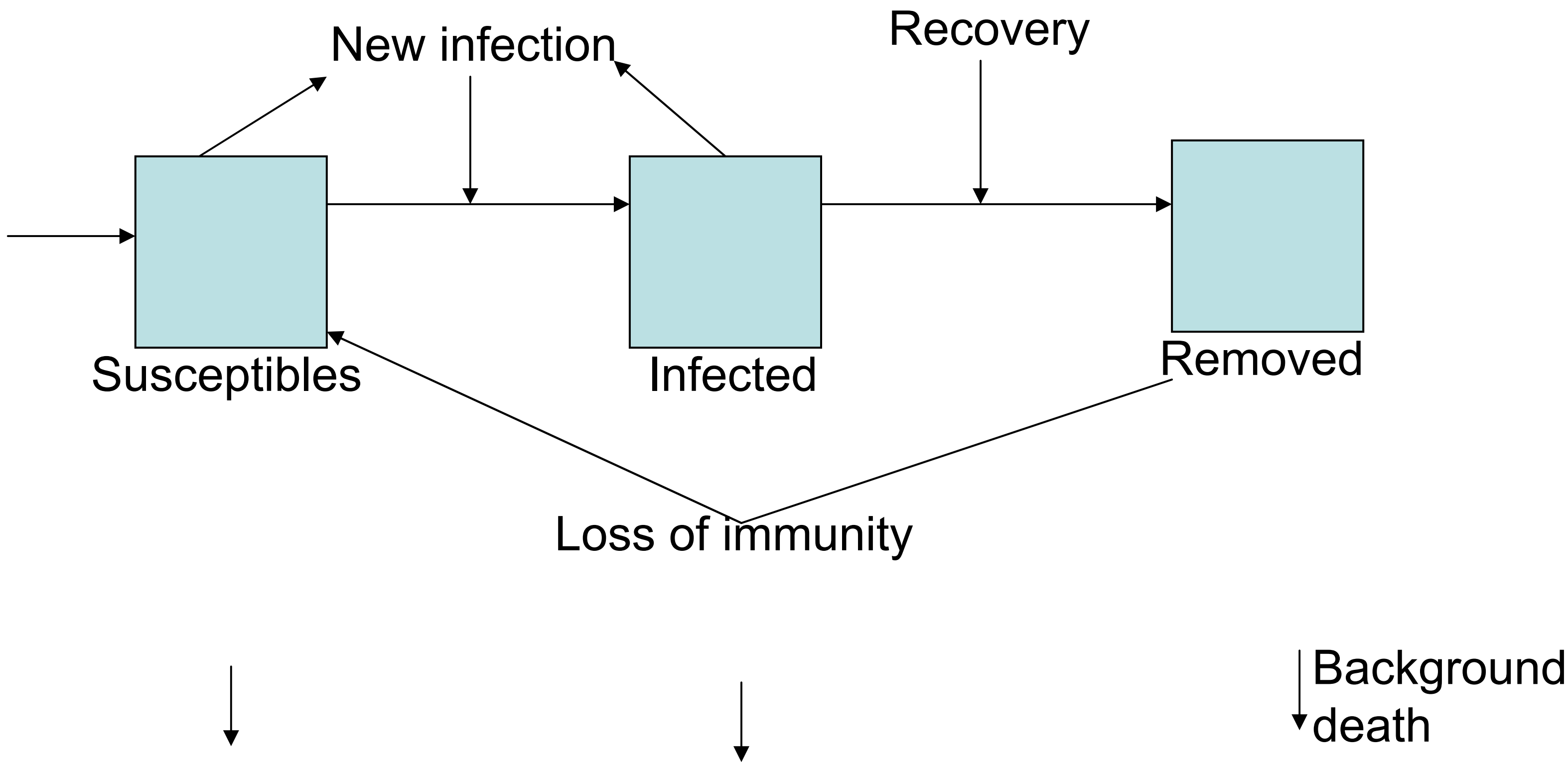
Simple system of disease spread



Simple system of disease spread



Simple system of disease spread



- Parameters that matter:

  c = contacts per person per year

  b = infection transmission probability

  a = recovery rate = 1/d

  m = background birth/death rate

Equation for new infections, Y.

$$\Delta Y = (c\,\Delta t)\,S\,(Y/N)\,b - (a\,\Delta t)\,Y - (m\,\Delta t)$$

- $(c\,\Delta t)$: Contacts per susceptible
- S: Number of susceptibles
- (Y/N): Probability contact with an infective
- b: Probability contact will transmit infection
- $(a\,\Delta t)\,Y$: recoveries
- $(m\,\Delta t)$: background death

$$\Delta Y = (c\ \Delta t)\ S\ (Y/N)\ b - (a\ \Delta t)\ Y - (m\ \Delta t)$$

Since S+Y=N, S=N-Y.

Rearrange and simplify

$$\Delta Y/\Delta t = c\ b\ Y\ [\ \{1 - (a+m)/cb\} - (Y/N)\ ]$$

Quadratic Logistic Equation in Y !!!

If $\{1 - (a+m)/cb\} < 0$, $\Delta Y/\Delta t < 0$
and $Y(t) \rightarrow 0$.

Disease dies out!

Basic Reproduction Number

- $(a+m)/cb > 1$ ➔ $dY/dt < 0$
  and disease dies out

- $(a+m)/cb < 1$ ➔ disease goes to endemic
  equilibrium

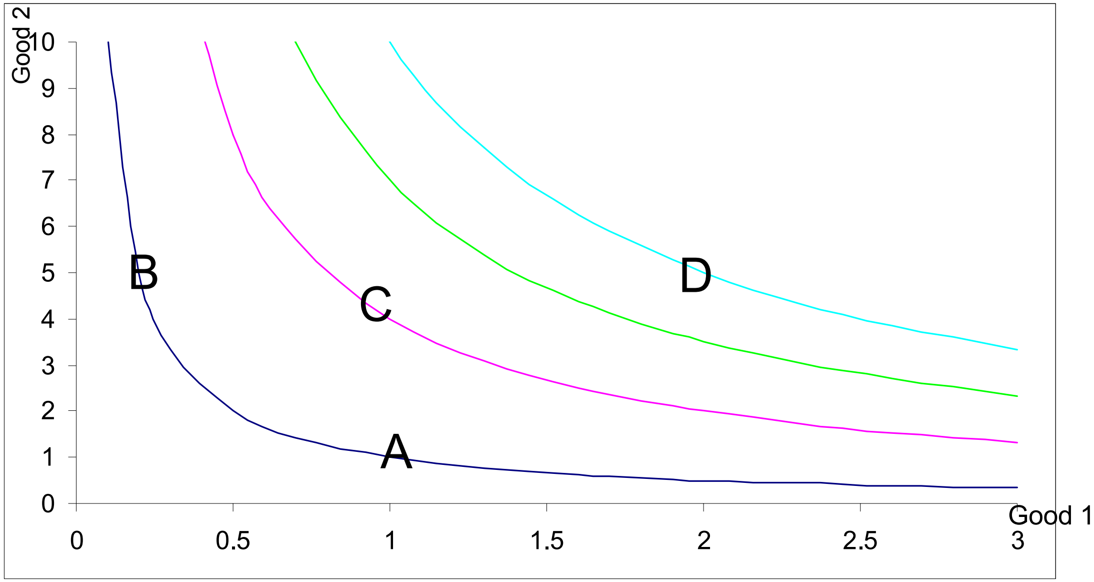
Threshold or tipping point

$R_0 = cb/(a+m)$,

basic reproduction number

Simple Economic Model of Consumer Choice

- Commodities
- Commodity bundles or baskets
- Consumers
- Preferences over commodity bundles
- Budgets
- Demand
- Production



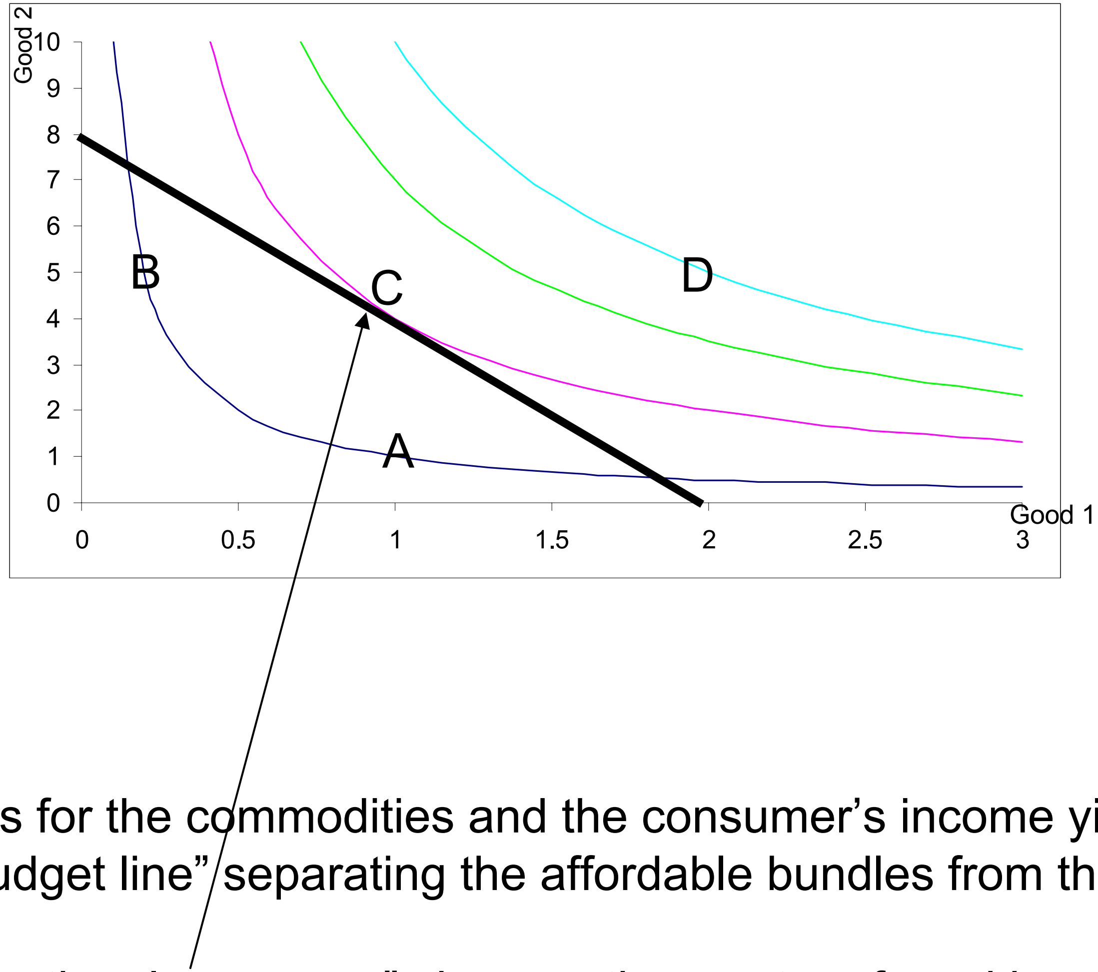
In a world of two commodities, commodity bundles can be represented by points in a two-dimensional space.

Point A represents the bundle (1,1).

Consumer preferences are represented by indifference curves.

The consumer is indifferent between bundles A and B.

Point D represents bundles (2,5), preferred to A, B, and C.

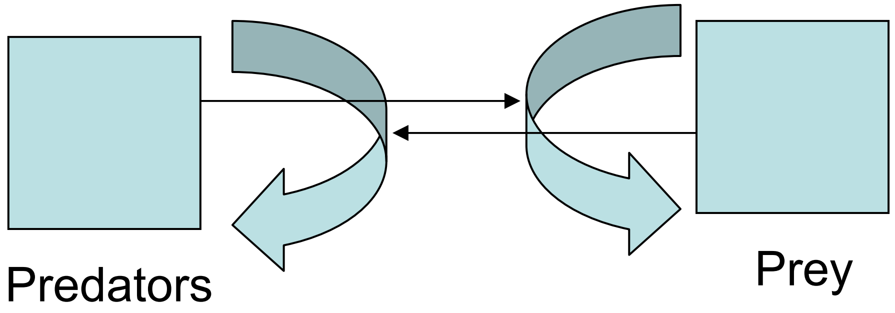


Prices for the commodities and the consumer’s income yield a “budget line” separating the affordable bundles from the others.

The “rational consumer” chooses the most preferred bundle he can afford – in this case bundle C.

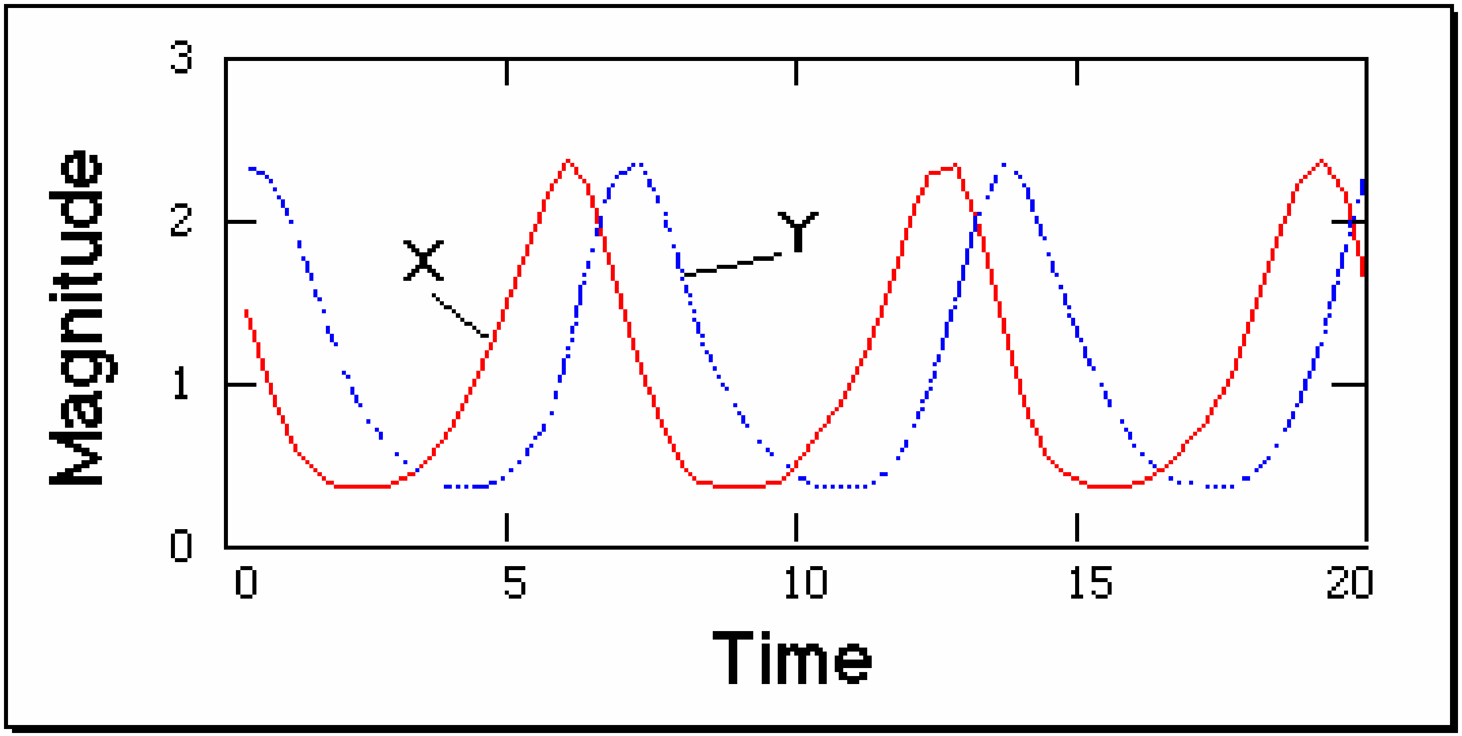
Different prices or different income would yield a different choice.

Simple Model of Predator-Prey



Growth rate of predators increases when they encounter prey, otherwise constant negative.

Growth rate of prey decreases when they meet predators, otherwise constant positive.



Result: regular oscillations/cycles.

Characteristics of "Simple" Systems

(economics, ecology, biology, business,…)

- **Homogeneity** ("representative agent")
- **Equilibrium** (no or simple dynamics)
- **Random mixing** (no structure or organization)
- **No feedback**; no learning/adaptation
- **Deterministic**
- **No connection** between micro and macro phenomena

What do we gain and what do we miss with these simple models?

Gain: insights into connections

e.g., R_0 (tipping points)

predictable ecological cycles,

consumer demand decreasing with price

Gain:

Simple solutions, heuristics, panacea

What do we gain and what do we miss with these simple models?

How much can we trust these insights?

The real world may be much more complex than these simple models suggest.

What do we miss?

Keep it simple, “but not too simple.” (Einstein)

Natural question: what happens when we relax these simplifying assumptions or add more realism?

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Complex System Approach

1. Heterogeneous agents/ diversity
2. Nonlinear dynamics
3. Contact structure; networks; organization
4. Feedback, adaptation, learning, evolution
5. Stochastic with concern for “tails”
6. Emergence

1. **Heterogeneity**

Simple Model: homogeneity

– “Representative consumer”

– No disease risk factors

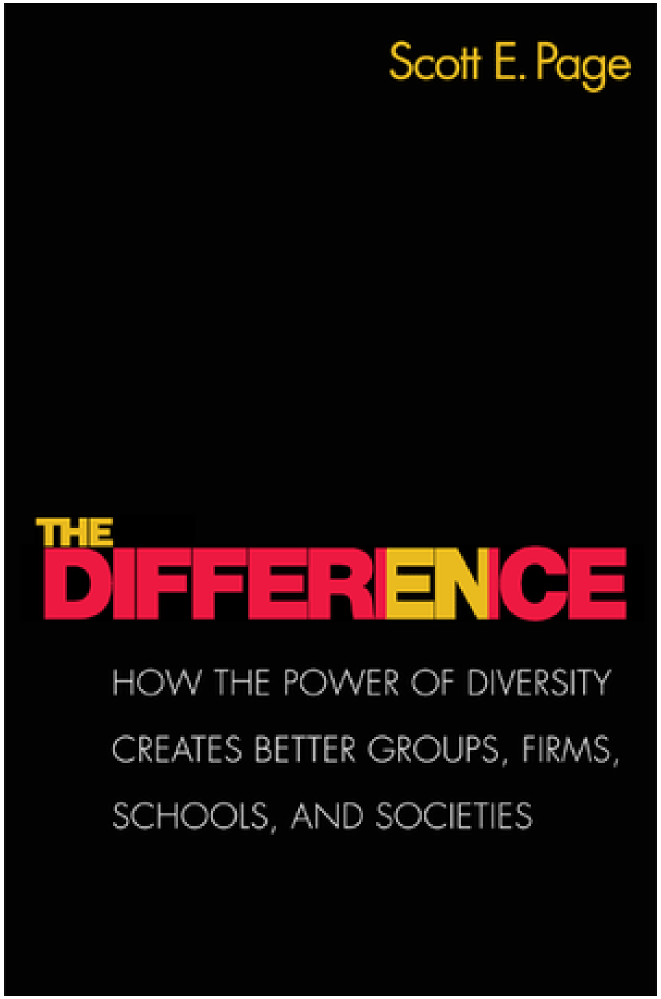
– See one predator, you’ve seen ‘em all.

Complex Systems Approach

People are different and those differences matter for outcomes and policy.

Scott Page

Left to Right: John Holland, Scott Page, Michael Cohen, Bob Axelrod, Rick Riolo, Mark Newman, Carl Simon, Mercedes Pascual



Putting a systems approach into UM’s concerns about diversity

Teams of diverse problem solvers do better than a team of narrow experts.

Heterogeneity critical in analysis of economic and health behaviors.

2. **Dynamics**

Simple Model: equilibrium-based

– Microeconomics = "general equilibrium theory"

Complex Systems Approach

– Often no equilibrium

– If there is one, it may be too late.

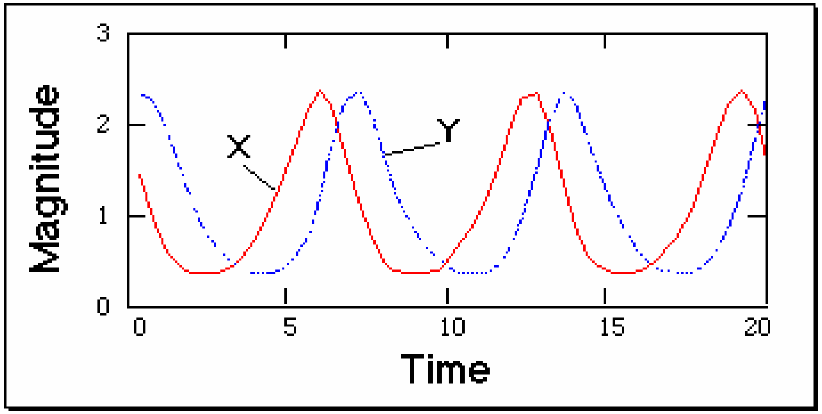
– If there is one, it's what happens on the way there that counts.

– Chaotic dynamics plays a role.

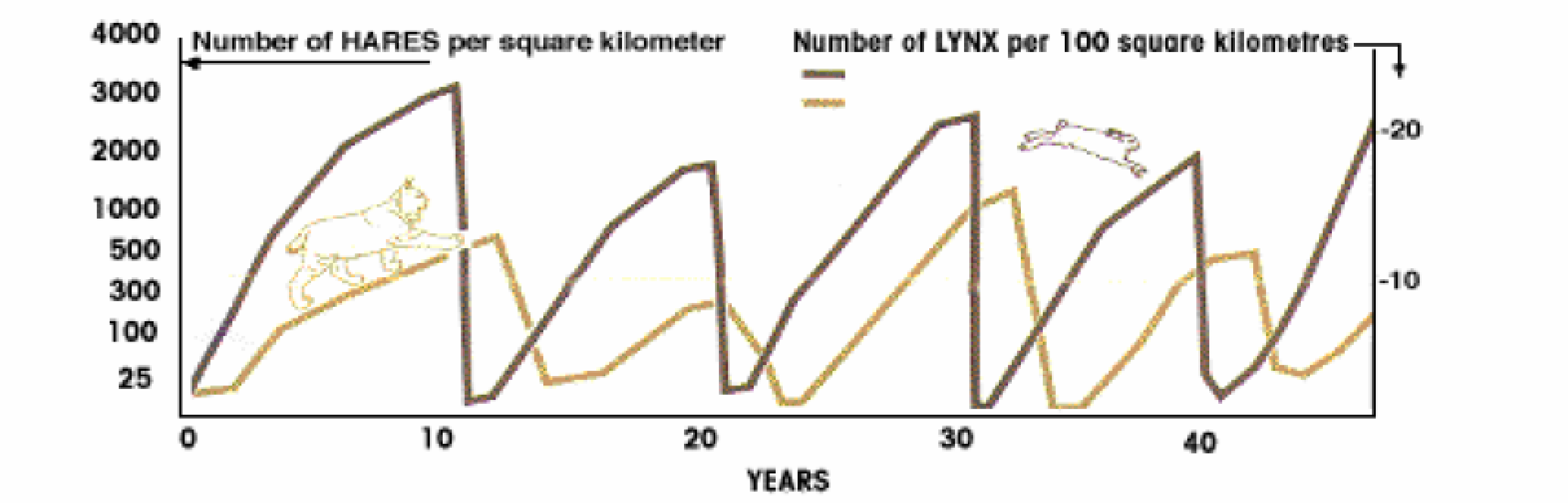
Carl Simon

Mercedes Pascual

Also: Len Sander (physics), Charlie Doering (math), John Vandermeer (EEB)

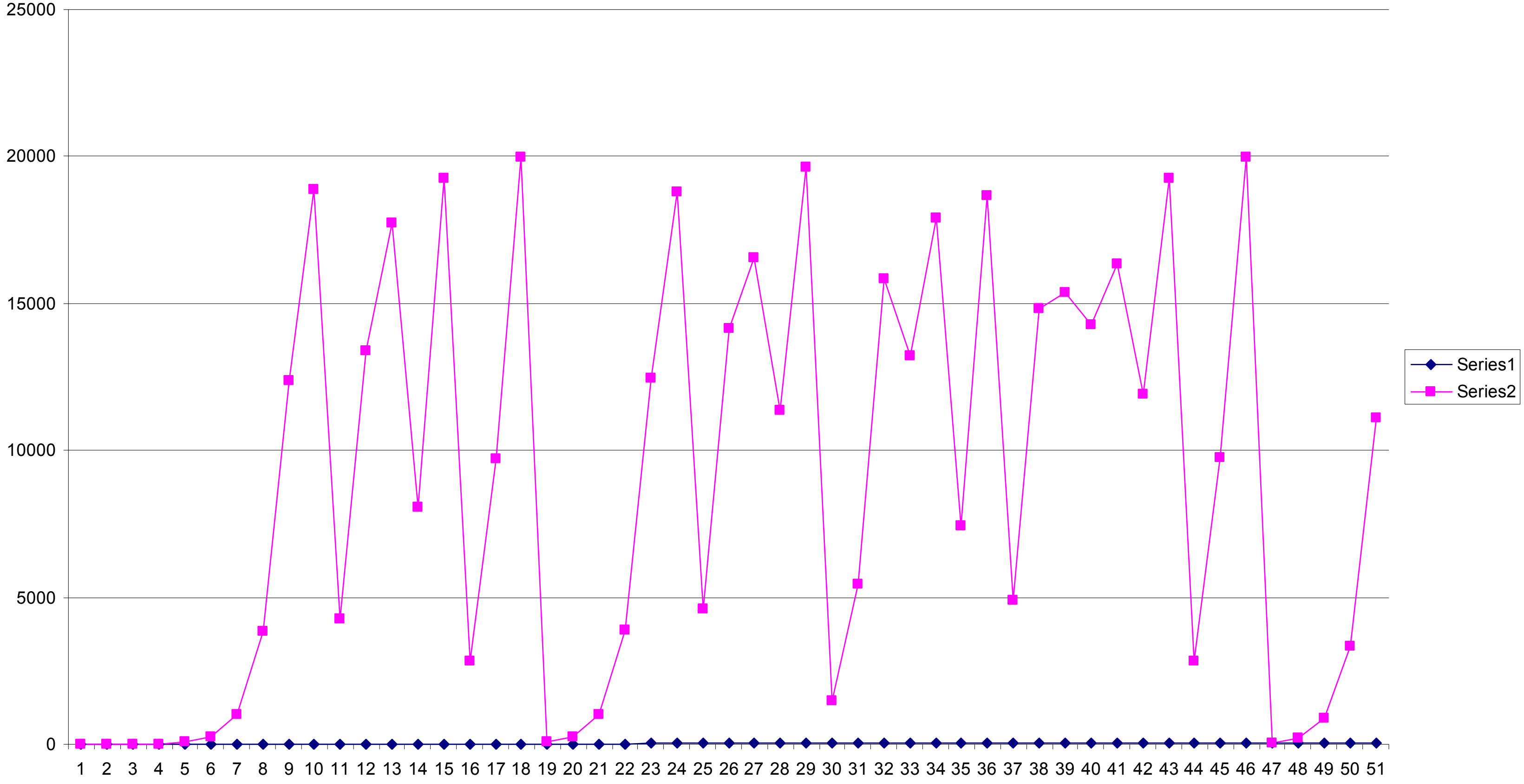


Regular oscillations/cycles of predator/prey system.



Actual data from lynx-hare trappings in Canada

Chaos vs Stochastic



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3. Contact Structure/Mixing

Simple Models: Random mixing

- Everyone has an equal chance of contacting any one else
- Economics, disease spread, ecology

Complex Systems Approach

- Meetings are not random
- Contacts have a structure that plays a role in outcomes
- Networks are appropriate technique

Michael Cohen

Mark Newman

Organizational structure

networks

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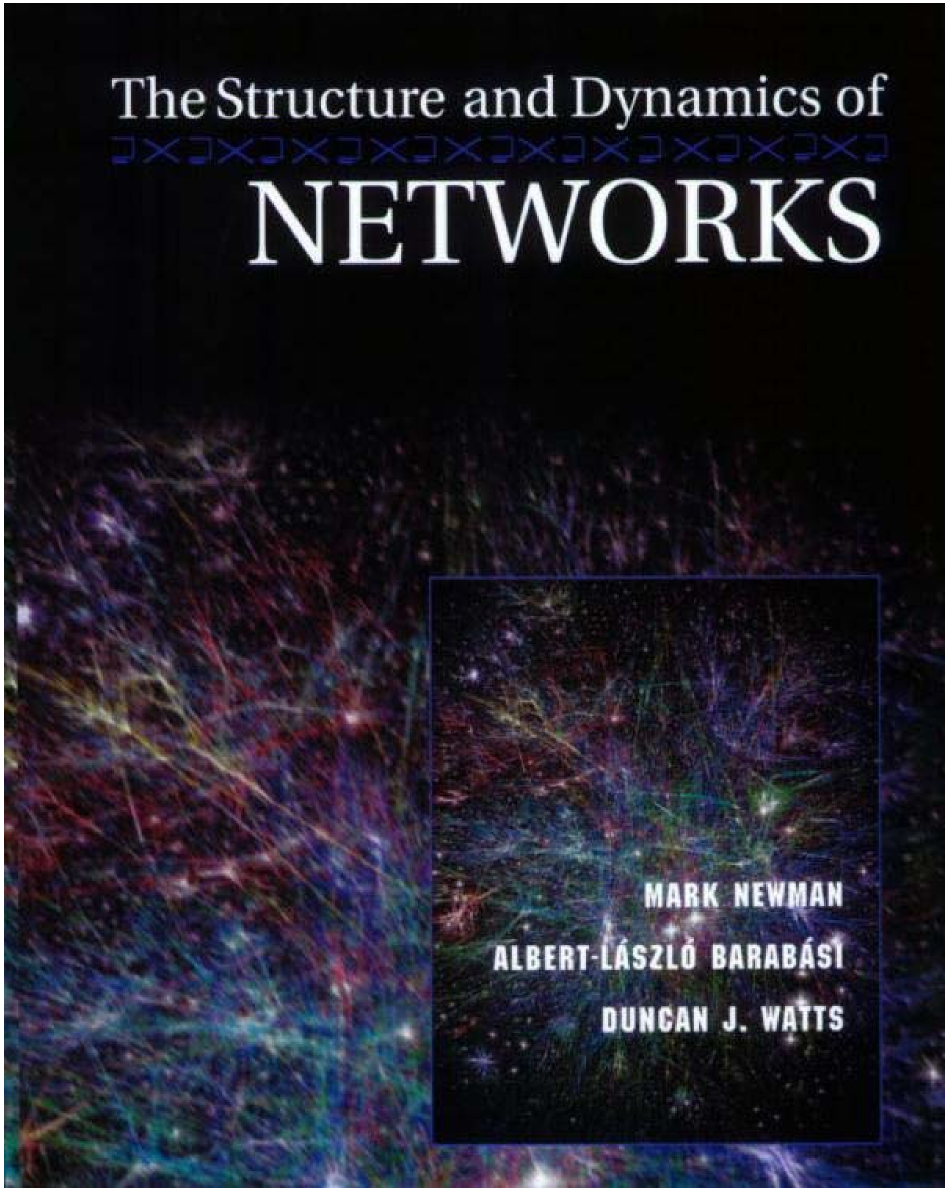
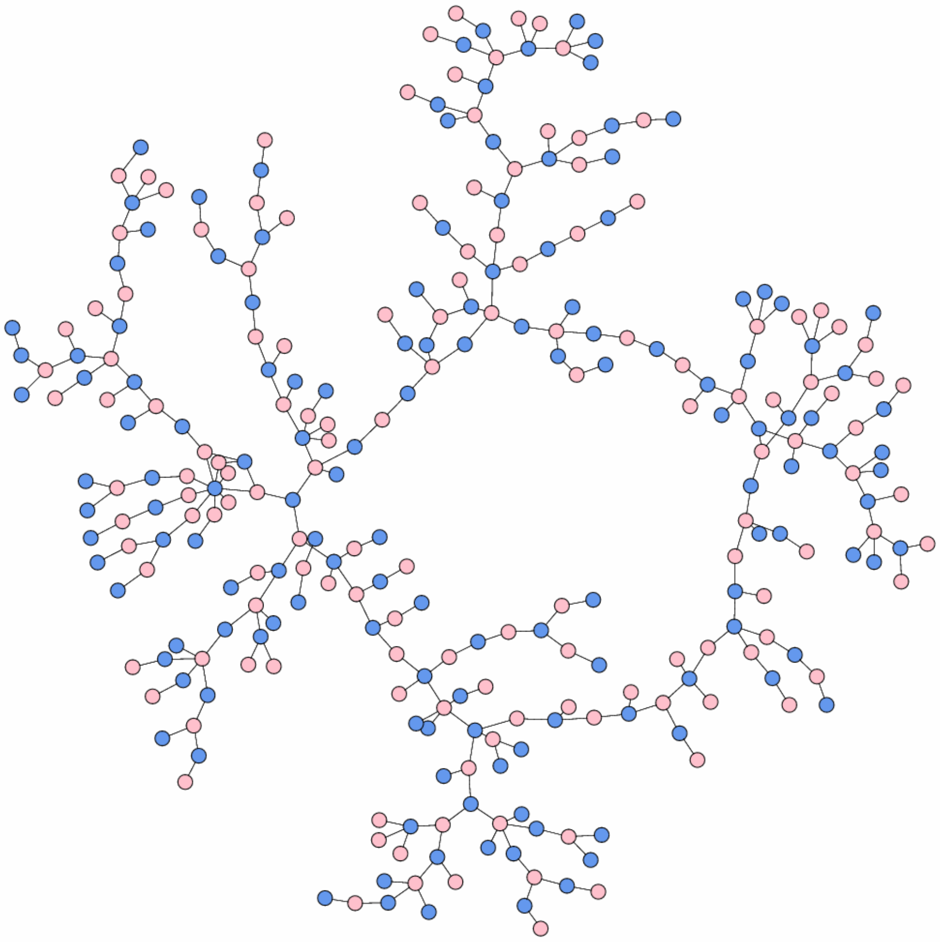


Computer optic cable network

Non-random mixing
Dating network at a US high school



Blue and pink dots are boys and girls respectively.
Lines are who dated whom. Only the largest connected group of nodes is shown.
NIH study: Jim Moody (Ohio State) and Peter Bearman (Columbia).
Diagram: Mark Newman

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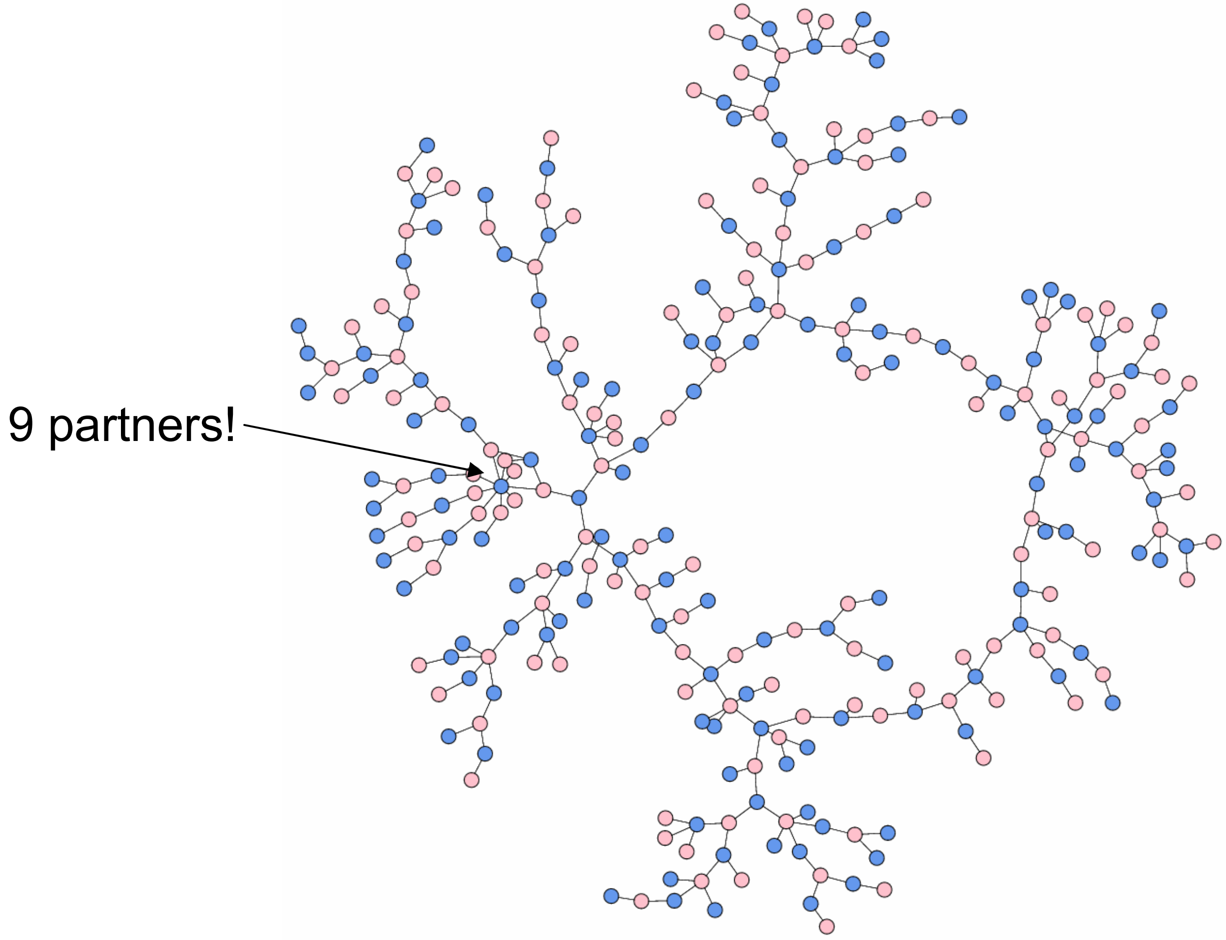
Dating network at a US high school



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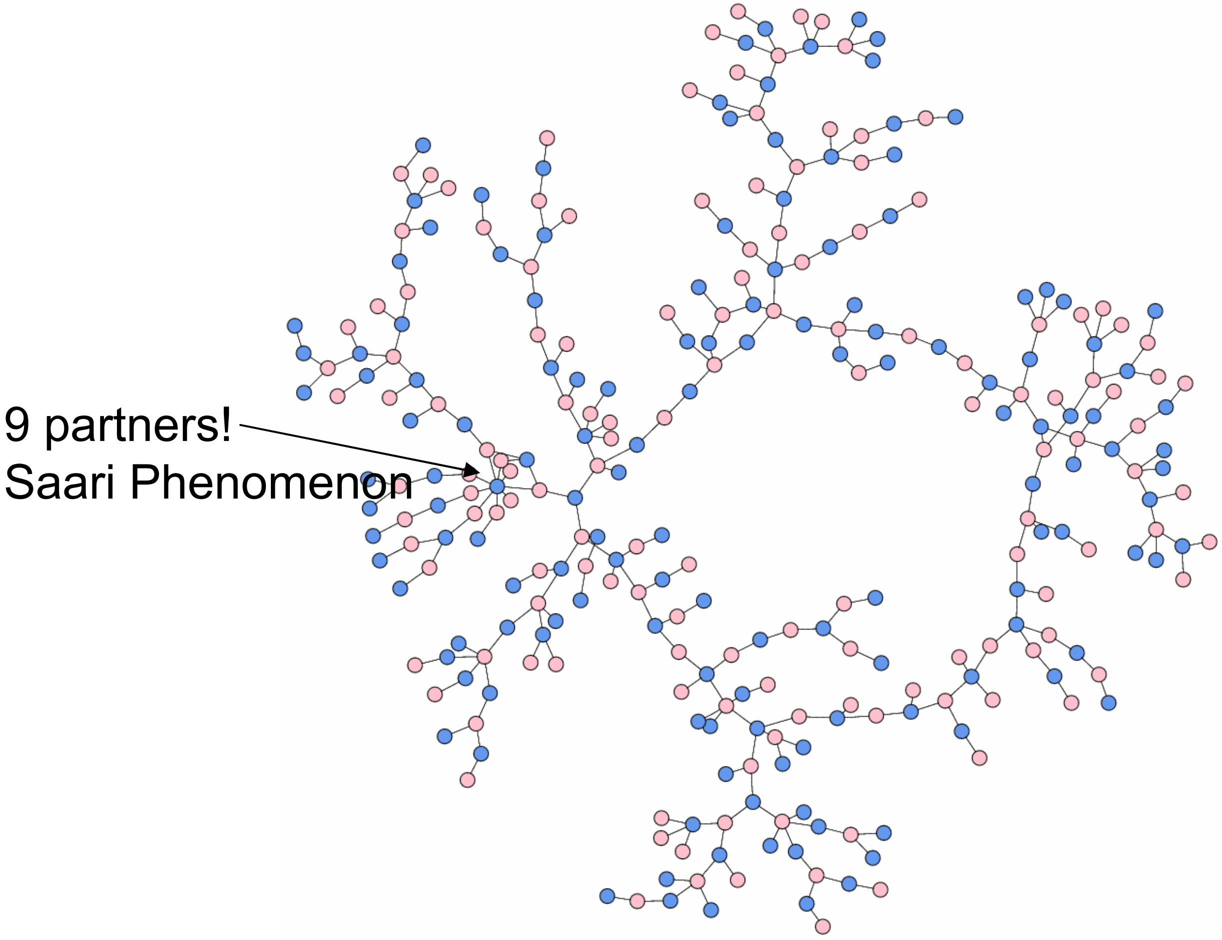

- Mark Newman:
  - Classify networks
  - Determine what class a given network is in.
  - Understand how the network class determines outcomes
  - Large tail distributions, power law networks:
    - R_0 doesn’t play a role anymore!

- Jim Koopman & CS:
  - How does the pattern of who meets whom affect disease spread?
  - Where are optimal places to intervene or vaccinate?
  - 2005 Kenneth Rothman Prize in *Epidemiology*

Complex Systems Networks Research

- Michael Cohen (SI)
  – organizational structure
- Jerry Davis (Business)
  – networks of boards of directors
- Lada Adamic (SI/CSCS)
  – the effects of local interactions on global properties
  – the Internet and the World Wide Web, peer-to-peer systems, social networks, and bioinformatics.
- Weekly networks seminar

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4. Adaptation to feedback

- Simple Models:
  - Preferences in economics do not change
    - No marketing, no education
    - No learning curve
    - No evolution
- Complex Systems Approach
  - Adaptation is central
  - Holland’s genetic algorithm

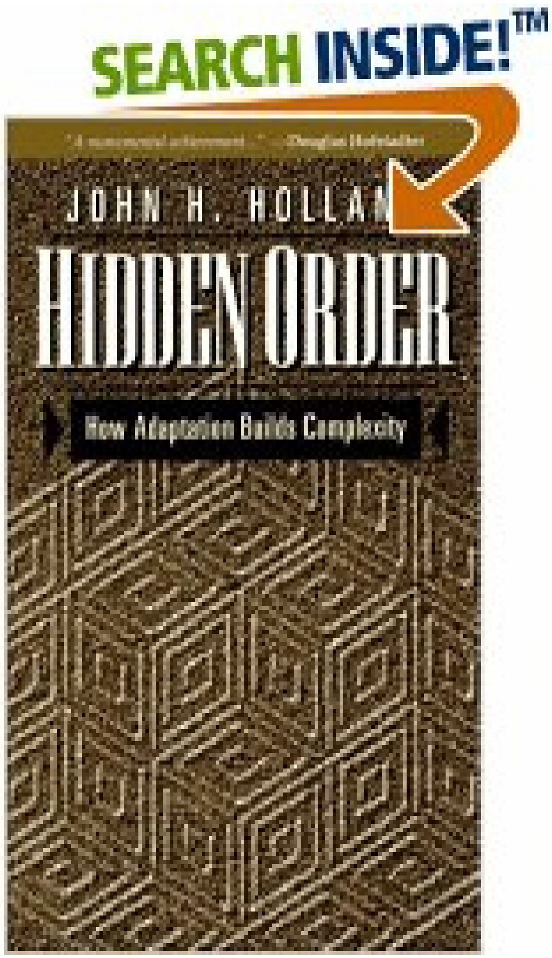
John Holland Robert Axelrod

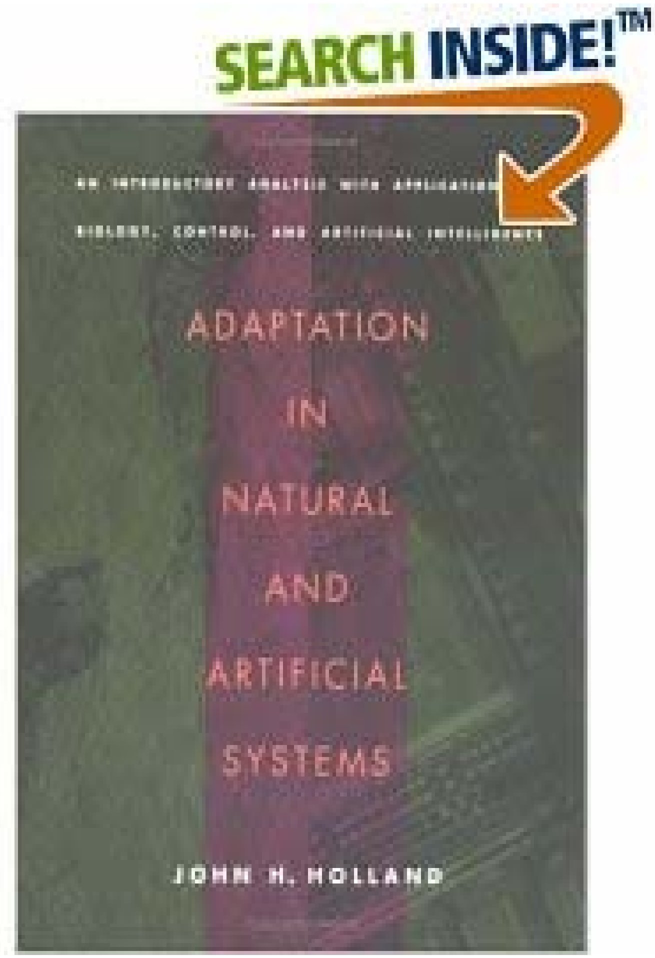
Both MacArthur Award Recipients

BACH way back

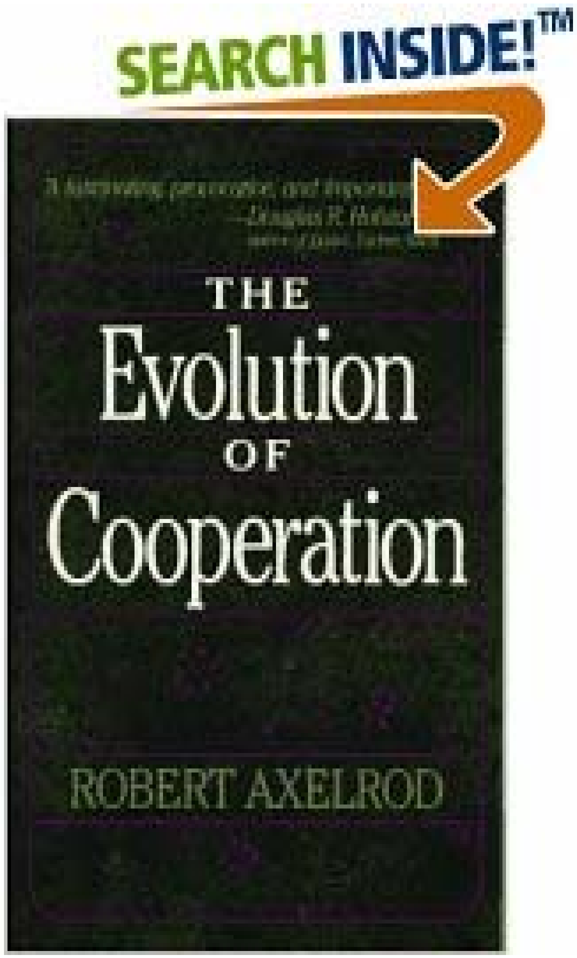
Bill Hamilton

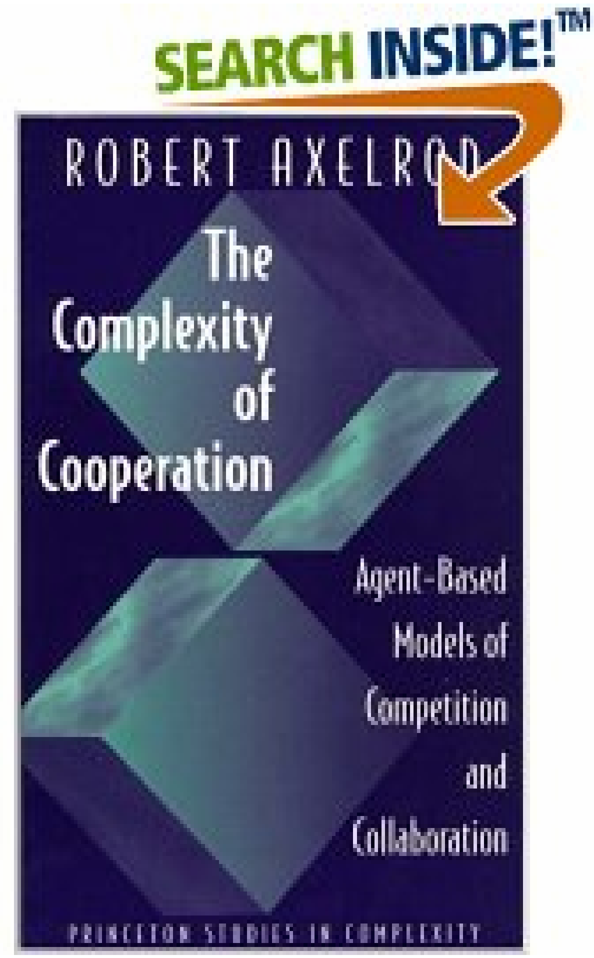
Two of Holland’s classics on adaptation





Two of Axelrod's classics on cooperation and feedback





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5. Stochasticity

- Some systems may be inherently deterministic
- Often stochastic models focus on the “mean”
- Complex systems approach cares about entire distributions, especially their tails.
- Variance often much more interesting than mean.

6. Emergence, Multi-scale

- Simple Models
  - No connection between micro and macro approaches
- Complex Systems Approach
  - Multi-scale
  - Emergence: assumptions at micro level lead to conclusions at macro-level
  - Agent-based modeling

John Holland Rick Riolo Mercedes Pascual

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6. Emergence

- Multiple scales
  - Study disease at genomic, cellular and population scales
    - Mercedes Pascual:
      - El Nino -> Climate Change -> Pathogens -> Disease
    - Denise Kirschner: TB
    - Betsy Foxman, Rick Riolo, CS:
      - commensal bacteria

Geoffrey West, SFI President (Time Mag)

6. Emergence

- Elizabeth Bruch (Soc/CSCS/RWJ)
  - Emergence of neighborhood patterns from characteristics of inhabitants

- Bottom-Up Approach

- Agent-based modeling
  - Rick Riolo: CSCS lab and courses

Why the complexity approach?

- Some systems are inherently complex
- Link between the composition and mechanics of the brain and behavior

Complex System Approach

- Heterogeneous agents/ diversity
- Nonlinear dynamics
- Role of networks
- Feedback, adaptation, learning, evolution
- Stochastic, “tails” matter
- Emergence

Why the complexity approach?

- How robust are the conclusions of the simple model approach to real world assumptions?

- Simple heuristics
- R_0 in epidemiology (Newman)
- Predictable periodicity in predator-prey ecologies (Pascual)
- Laissez-faire economics

Despite the extreme simplicity of microeconomic models,
they work fairly well in predicting and analyzing economic behavior.

This success has led to often complete (almost blind) reliance on the insights of simple microeconomics models.

Example: The invisible hand
“The ‘market’ can take care of all ills.”
Reagan, M. Friedman, WSJ

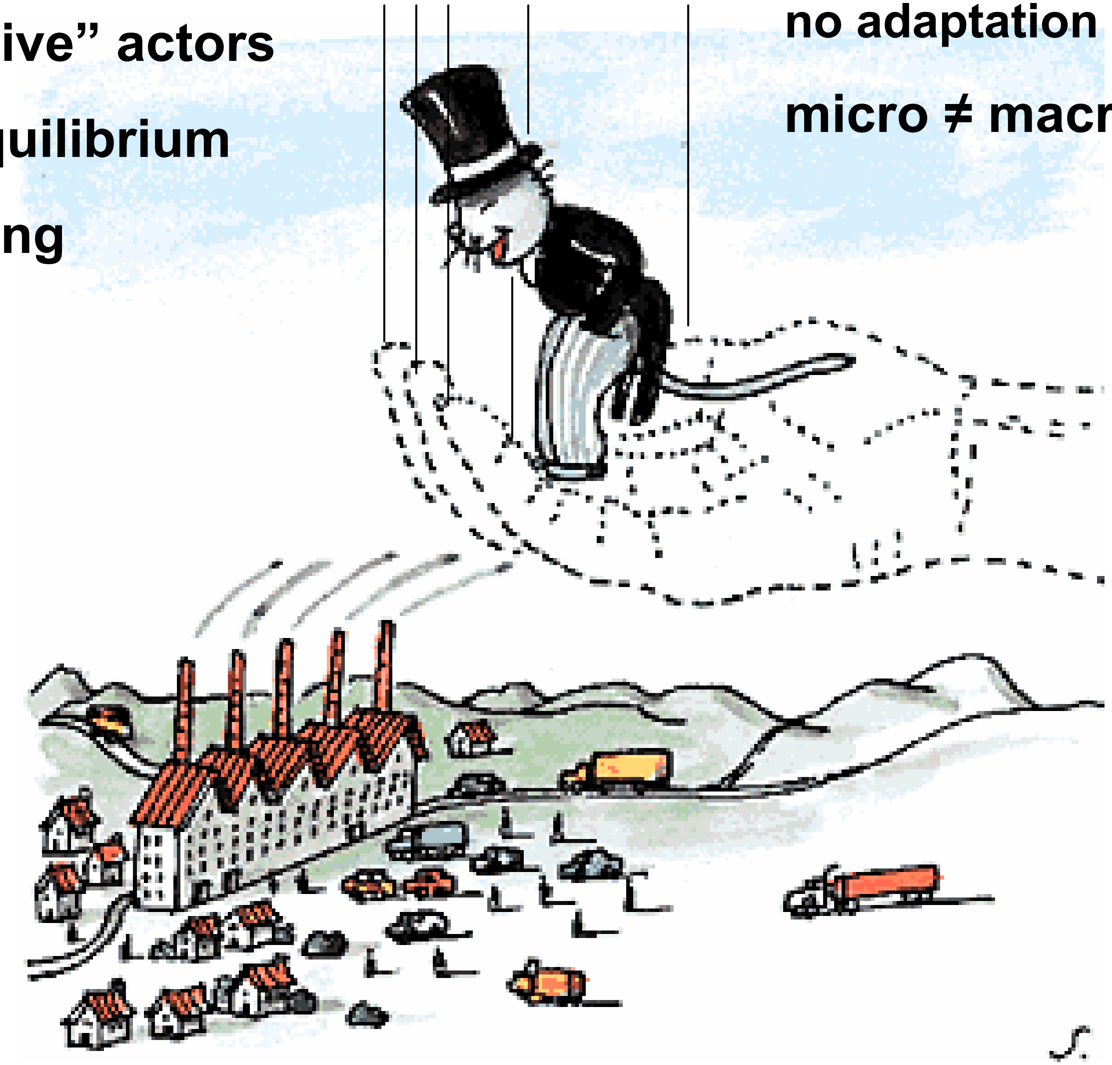
“representative” actors

system at equilibrium

random mixing

no adaptation to feedback

micro ≠ macro



- The Invisible Hand relies on assumptions

Bottom Line of Microeconomic Theory Courses:

"Fundamental Theorems"

1. Under reasonable hypotheses
   (convex preferences, no externalities, etc.),
   for any initial wealth,
   there is an equilibrium price system and distribution of goods.

At this price system,

- aggregate supply and demand balance
- all consumers are consuming their optimal bundle of goods.

“Fundamental Theorems”

2. Any such equilibrium is Pareto Optimal.
   (There is no reallocation of goods that will make every one better off.)

3. Any Pareto optimal allocation can be supported by a price system to form a competitive equilibrium.

(One can easily include more interesting supply details, such as the production processes of firms in a market of perfect competition.)

Basic assumptions

- Perfectly rational consumers
- Consumers motivated only by market forces
- Dynamics do not matter
- Perfectly divisible commodities
- Random trading
- Markets for everything and in all times

Basic assumptions that really matter

- No externalities
- No collective goods
- Perfect competition; no market power
- Perfect information
- Equity not a consideration

Opening for governmental role to catalyze successful markets

Government

• Collective Goods	• Taxation
• Equity	• Taxation
• Externalities	• Pollution fines Carbon markets

• Market power	• Antitrust laws, but
	firm size advantages
	    Efficiency
	    Innovation

• Asymmetric information	• Regulation Licensing market power

Governments and Asymmetric Information

- Investment safety
  - Enron
  - Savings and Loan Scandal
- Consumer Safety
  - Airplanes
    - Mechanical safety
    - Pilots
- Food and drug safety
  - Pet food crisis
  - Bacteria tainted food
  - Drug safety and effectiveness

Roles of government

- Umpire
  - protecting rights
  - enforcing contracts
  - law and order
- Rescuer of last resort
  - moral hazard problems
- Market catalyst
  - Time inconsistencies
  - Rent-seeking (pursuit of private benefit with public authority)
  - Blandishments of interest groups
- Constitutional justification for this role

CSCS Projects

- Sustainable Mobility
  - T. Gladwin, J. Levine, D. Kelbaugh, S. Zielinski, D. Featherman (CARSS), CS
- Genre Evolution
  - Eric Rabkin, CS
- Salmon Life History
  - B. Low, J. Breck, E. Rutherford, PJ Lamberson, CS
- Evolution of Antibiotic Resistance
  - B. Foxman, R. Riolo, B. Percha, CS

Book in Progress

- Can you shake an invisible hand?
- Markets and Government
- WSJ vs NYT editorial pages
- Enlightened Libertarianism

COAUTHORS:

- William Keech, Social and Decision Sciences, Carnegie Mellon
  - Home of Herbert Simon ("bounded rationality" Nobelist)
- Michael Munger, Political Science, Duke
  - Libertarian candidate for Governor of North Carolina

CSCS affiliated (primary) faculty I

- Lada Adamic, Information
- Bob Axelrod, Poli Sci, Public Policy
- James Breck, Nat. Resources
- Dan Brown, Nat. Resources
- Michael Cohen, Information
- Jerry Davis, Business
- Charles Doering, Math
- Ed Durfee, Comp.Sci.
- Dan Forger, Math
- Betsy Foxman, Epidemiology
- Tom Gladwin, Business and Nat. Resources
- Phillip Hanlon, Math
- John Holland, Psych and Computer Sci.
- George Kaplan, Social Epidemiology

CSCS affiliated (primary) faculty II

- Denise Kirschner, Immunology
- James Koopman, Epidemiology
- Jay Lemke, Education
- Bobbi Low, Nat. Resources
- Scott Moore, Business
- Harris McClamroch, Aero. Engin.
- Franco Nori, Physics
- Mark Newman, Physics
- Scott Page, Poli Sci/Econ
- Mercedes Pascual, Ecology
- Eric Rabkin, English
- Bob Reynolds, WSU

CSCS affiliated (primary) faculty III

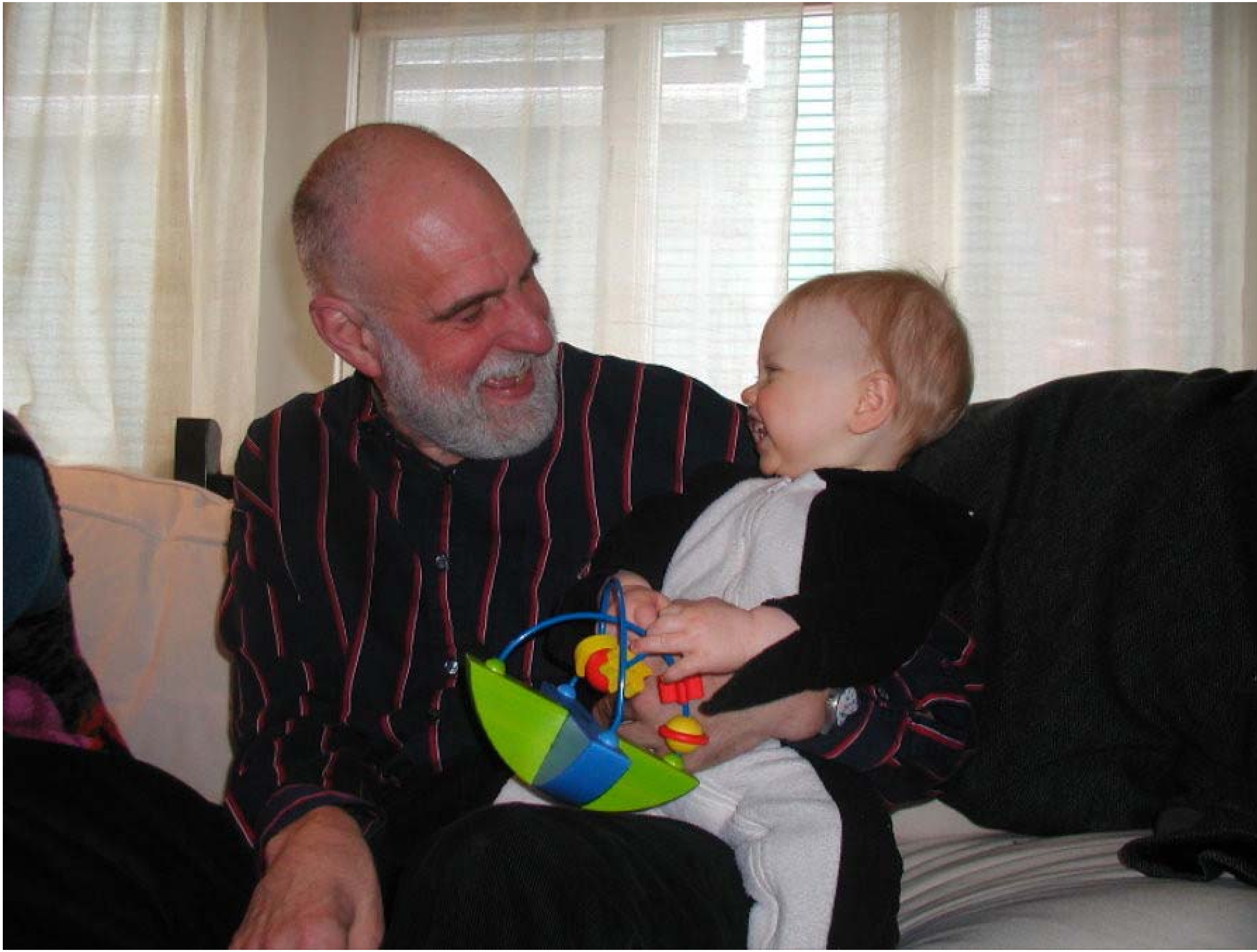
- Rick Riolo, CSCS
- Len Sander, Physics
- Teresa Satterfield, Romance Languages
- Bob Savit, Physics
- Larry Seiford, Industrial Engin
- Carl Simon, Math/Econ/Pub Policy
- John Vandermeer, Ecology
- Michael Wellman, Computer Sci
- Henry Wright, Anthropology
- Jun Zhang, Psych

Some Complex Systems Techniques

- Networks
- Genetic algorithms
- Agent-based modeling
- Dynamical systems; game theory
- Cellular automata
- Computational social and decision science
- Thresholds, Tipping Points

- The sustainable mobility/accessibility challenge:

- **Ensure that future generations have *access to adequate resources* to meet their mobility needs and aspirations**
- **while maintaining the *integrity and resilience* of supporting environmental and social systems**



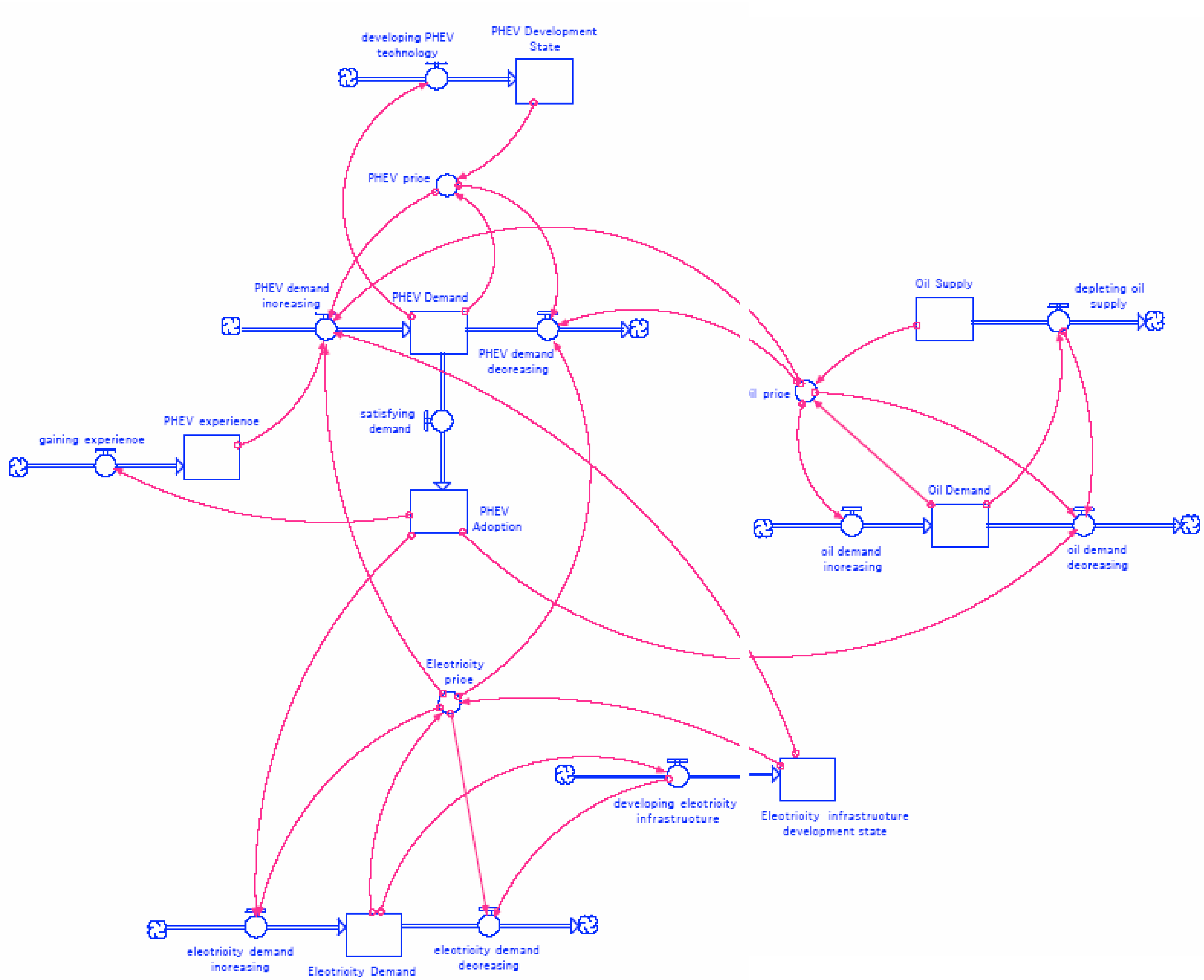
- **This is *not* only a technological or a fuel-oriented problem.**

- **It involves important social dilemmas:**
  - **consumers and producers focus on short-run private costs and benefits,**
  - **while ignoring the long run and societal consequences in decision-making about mobility options**

- **We must consider**
  - **land use**
  - **city design**

Consider Congestion

- Build new roads?
- Add lanes to existing roads?
- Charge user fees? Tax extra cars?
- Dedicated rapid-bus lanes?
- Build/expand elevated rapid transit, subways?
- Encourage bicycles? Ban them?
- Car pool lanes on highways?

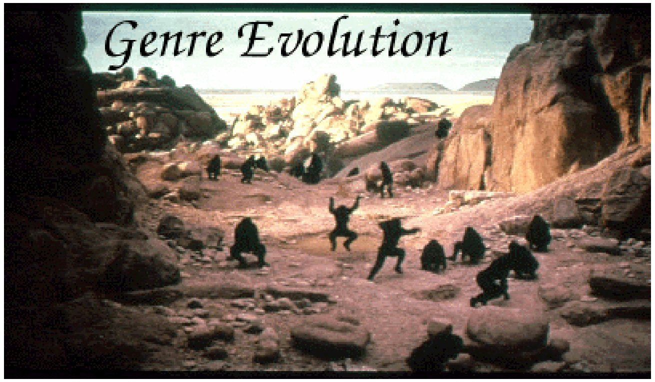

developing PHEV technology
PHEV Development State
PHEV price
PHEV demand increasing
PHEV Demand
PHEV demand decreasing
satisfying demand
PHEV experience
gaining experience
PHEV Adoption
Oil Supply
depleting oil supply
oil price
Oil Demand
oil demand increasing
oil demand decreasing
Electricity price
developing electricity infrastructure
Electricity infrastructure development state
electricity demand increasing
Electricity Demand
electricity demand decreasing

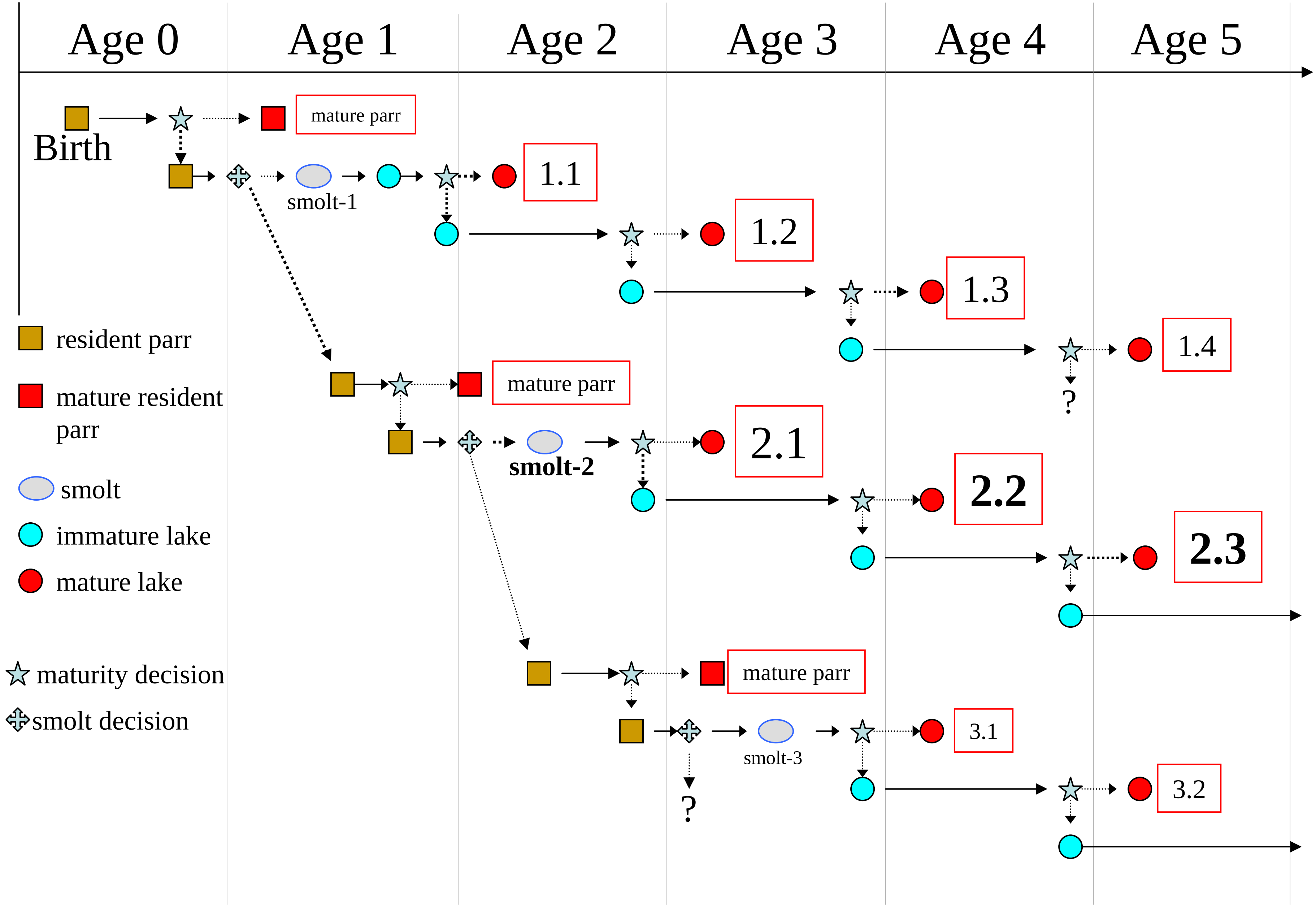
Genre Evolution Project

- Innovations in literature are not merely caused by randomness, or sporadic acts of genius.
- Cultural phenomena do not occur in a vacuum.
- The culture can change because of literature, and literature can change because of the culture.

- Cultural phenomena evolve in the same way as do biological systems. . .

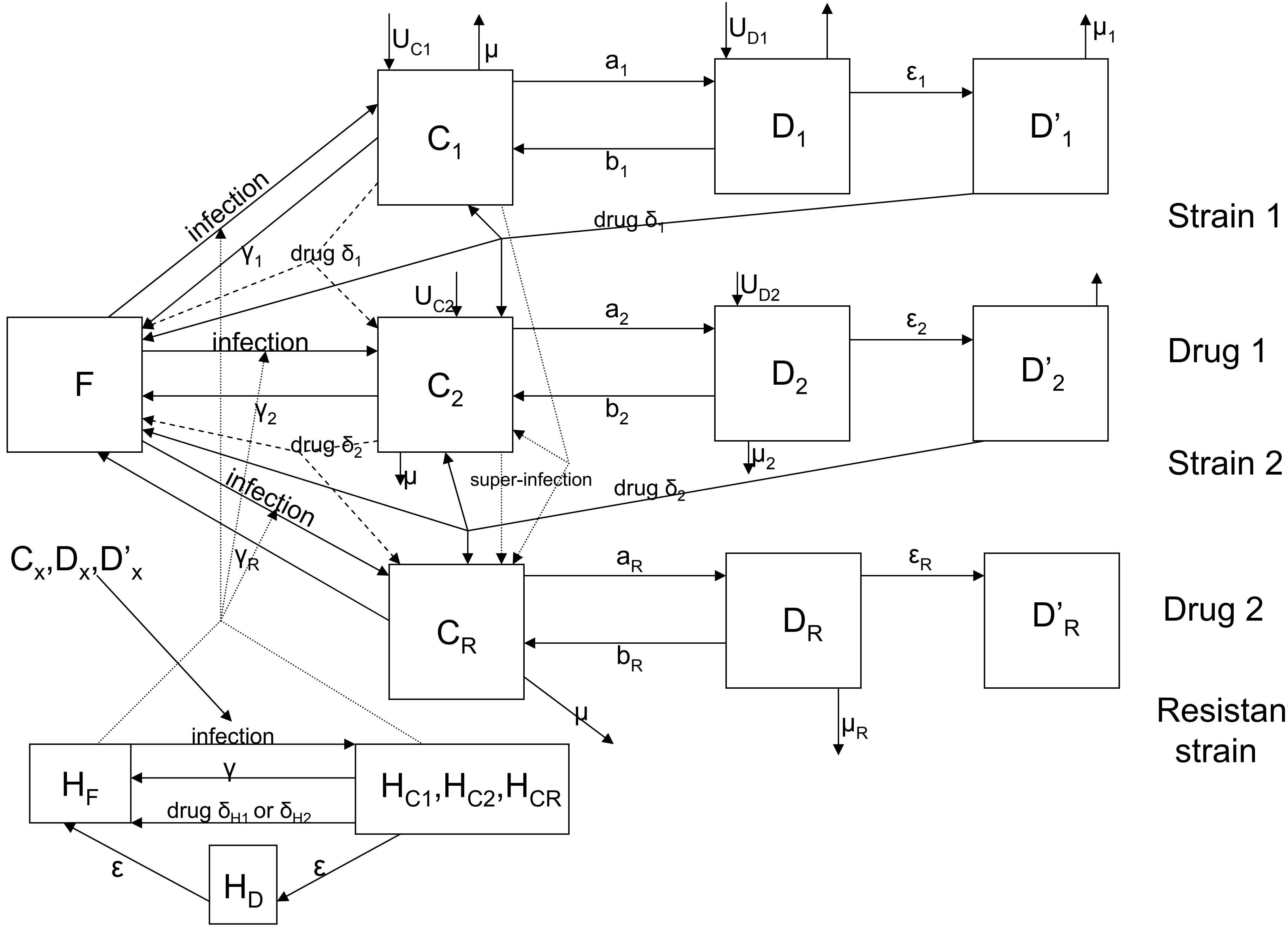
. . . that is, as ***complex adaptive systems***.





Age 0
Age 1
Age 2
Age 3
Age 4
Age 5
Birth
mature parr
1.1
smolt-1
1.2
1.3
1.4
?
resident parr
mature resident parr
mature parr
smolt
2.1
smolt-2
2.2
immature lake
2.3
mature lake
maturity decision
mature parr
smolt decision
3.1
smolt-3
?
3.2

Three strains, two drugs, drug resistance, health workers



Our students

- Ross Hammond (Brookings)
  - Bob Axelrod
  - Agent-based models of corruption, migration, prejudice

- Kristin Hassmiller (UNC)
  - David Mendez (SPH)
  - When you take into consideration systems effects (contact structure), smoking is twice as big a factor in the spread of TB than previously estimated.

Our Students

- Katia Koella (Penn State)
  - Mercedes Pascual (EEB)
  - Multi-scale approach
  - Incorporate information on how influenza evolves with knowledge abut the epidemiology of the disease
  - Aid in predicting and controlling influenza outbreaks
  - *Science, Nature, PNAS*

NSF Press Release on their 2008 Budget

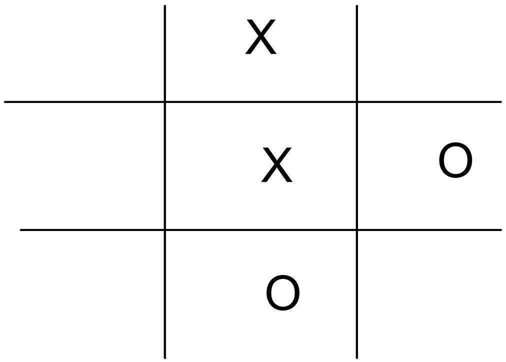
- Natural systems, for example, provide stunning examples of effective communication, complex computation, efficient signaling, adaptive self-organization, and multimodal sensing using small but complex chemical and physical networks.
- Studies of such biophysical systems will engage physical and computer scientists, engineers, biologists and social scientists.
- All will demand creative approaches in the ultimate convergence of the physical, bio-, nano-, info-, neuro-, and cognitive sciences.

Genetic Algorithms

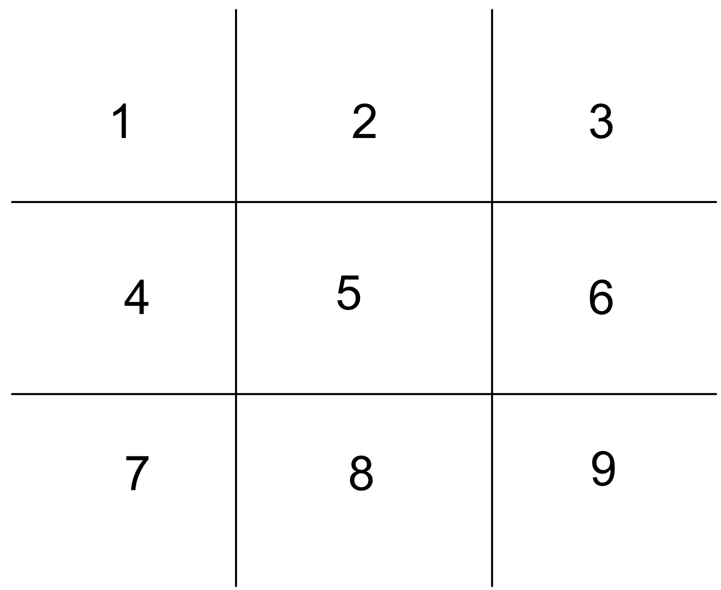
John Holland

- Rule-based system
- Rule or “classifier” is an if-then statement:
  - Hypothesis → Conclusion
  - Business strategy, behavioral rule, etc.

Example: Tic-Tac-Toe



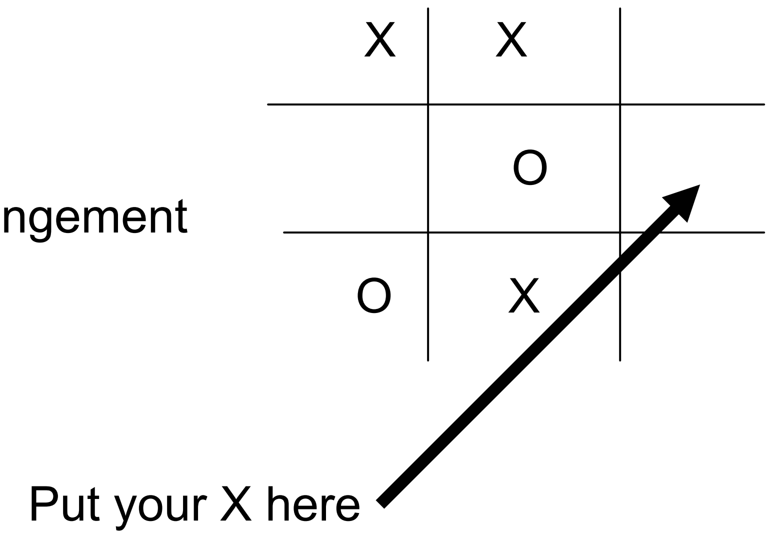
Label the nine locations:



Tic-Tac-Toe (cont)

- Write 0 for “O”.
- Write 1 for “X”
- Write 2 for empty
- Write # for “don’t care”

The rule that says: given board arrangement



would be written: 1 1 2 2 0 2 0 1 2 , 6.

Tic-Tac-Toe (cont)

- The rule that says “if the center spot is open, take it” would be written:

  ### #2# ###, 5.

Each rule has a *strength*, a rough measure of how well it has done in the past,

And a *specificity*, a fraction of loci in the hypthesis that are not #s.

Genetic Algorithm Process

1. Input from the environment the current state of the board.
2. List all classifiers whose hypotheses are consistent with that current state.
3. Stochastically, “choose” the one of these with highest strength, giving higher weight to higher specificity.
4. Carry out this move. Output to the environment.
5. Next time it is your move, go to step 1.

Genetic Algorithm Process

6. If the game was successful, increase the strength of all the rules use.
7. If unsuccessful, decrease their strengths.
8. Tax all rules.

Now add "genetics"

- Every so often (mutation rate), choose rule(s) of high strength.
- Mutate at a random locus, or
- Crossover two successful rules at a random locus:

abcd|efg		abcdEFG
ABCD|EFG	➔	ABCDefg

Give the new rules average strength.

Remove some low strength rules.

Examples of Genetic Algorithm Success

- Art Samuel’s checker player
- Goldberg’s oil pipeline repair
- Smith’s poker player
- Bean’s production optimizer

- GA works especially well in finding global max in “rugged landscape”.

Example: Repeated Prisoner's Dilemma

- Two players, two strategies, symmetric game:

	Cooperate	Defect
Cooperate	5, 5	0, 6
Defect	6, 0	3, 3

Optimal Strategy:

One-iterate game: defect
Two-iterate game: defect, defect
?-iterate game: ????

RPD Strategies

- Axelrod's computer tournament
- Tit-for-Tat
  - If opener, cooperate,
  - Do to your opponent this move what your opponent did to you last move.

RPD as a GA

- Classifiers:
  – Hypothesis: last 3 moves of you and your opponent
  – Conclusion: your next move

0=cooperate, 1=defect, #= don't care

CDD?
DCD   is 011011?

Tit-for-Tat: #####0,0 and #####1,1.

RPD as GA (cont)

- Start with a sequence of random rules.
- Play representative algorithms from the tournament.
- See what strategies move to the top.

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RPD as GA (cont)

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- After 1000 moves, even more successful strategies took over.