Cellular Automata and Complexity

Philosophy.

Natural Systems

- Suppose we want to study a natural system.
  - Galaxy, ecosystem, brain, snowflake, running athlete...
- Most systems are composed of many, many components.
  - Many, many, many, many, many...
  - Complex!

How Study Many Components?

- Simplify!
  - Consider components alone.
    - Brain is composed of neurons. So study neurons.
    - Legs of athletes are dashpots and springs (suspension systems). So study springs and dashpots.
    - Ecosystem is wolves and moose and grass and... So study wolves. Study moose. Study grass.
  - Reassemble when possible.
    - Predator-prey relationships for wolves and moose.
- Reductionist approach!

Reductionist Philosophy of Science

- Reductionist
  - Take a complex object and break it down into its components.
  - Study the individual components.
  - Sometimes re-assemble the parts to create a whole.
  - Historically, has been wildly successful.
    - Example: Physics – study atoms to understand materials.

Alternative Holistic Approach

- Holistic
  - Don’t attempt to break into parts.
  - Usually have many interacting or weakly interacting parts.
  - Study the whole.
  - Historically, not widely applicable until computers could keep track of the many parts.
    - Example: Statistical Mechanics – study large numbers of atoms to create an “ideal gas”.
      - Didn’t initially require computer, used probability theory.
    - Example: Sociology – large numbers of people rioting.
      - Did require computer. Also uses probability theory.
- Includes “complex systems theory”.

Holistic Science Danger

- Holistic approaches risk phenomenological or “classification” analyses.
  - Always useful to describe/classify phenomena.
    - But not predictive.
    - Nor an explanation of observations.
  - Science at its best is predictive.
    - Or at least explains observations.

Complex Systems Theory

- Complex Systems Theory
  - A holistic approach.
    - Does its best to be predictive/explain observations.
    - When fails, can explain why!
      - Example: “It is theoretically impossible to do the following and this is why...”
      - Kind of like Turing’s halting problem and Godel’s theorem.
- We will do some phenomenology in this class.
- But we will also do heavy duty math proofs and predictions!

How Study Many Components (Revisited)

- Option 1: Reductionist
  - Simplify to a minimum number of complex components.
    - The complexity of the system is retained in each component.
- Option 2: Complex systems theory
  - Simplify each component until no longer complex.
  - Keep the large number of components.
    - The complexity of the system is retained in the large numbers.

How Simple Should Each Component Get?

- Reeeeally simple. Almost stupidly simple.
  - At the level of “Duh”.
- Treat each component as a 1 or 0.
  - That’s it!
  - Sometimes treat as a vector of 1’s and 0’s.
  - Sometimes treat as 0, 1, and 2.
  - But you get the idea.

How Can That Work?

- Can a 1 and 0 adequately describe the complexities of the human brain?
  - Or galaxy? Ecosystem? Bird flock? Rioting football fans? Flowing glaciers?

- Yes! Stay tuned!
  - Complexity theory has created some of the most interesting science (and computer science) of the last century.
    - Artificial life.
    - Artificial intelligence.
    - Parallel computing.
    - Cellular automata.

  - With applications in
    - Climate change
    - Glacier flow
    - Social interactions
    - Sea shell designs
    - Physics of magnets
    - Etc!

Complex System: Definition

- Definition: A Complex System is a system composed of a large number of separate interacting components.
    - Note: The interactions are important!
        - If no interactions, then are "just" dealing with *statistics* of large numbers of objects.
            - Called statistical physics (e.g., thermodynamics, statistical mechanics).
            - Very cool stuff, but not complexity theory.

Complex System Examples

- NOT complex systems:
  - Ideal gasses – large numbers of atomic components, but not interacting (or weakly).
  - Group of people that must be quiet and can't communicate with each other – may be large numbers, but not interacting.
  - Your dog chasing your cat -- not a large number, even though interacting.
- Complex systems:
  - Your brain – large numbers of neurons, interacting with neighboring neurons.
  - Large group of people in a football stadium, each talking to their neighbors.
  - Rivers – large numbers of water molecules bumping into their neighbors as they flow.

Cellular Automata As Complex Systems

- We will spend the semester looking at Cellular Automata (CA).
  - Large sets of 0’s and 1’s (the cells).
    - Sometimes 0’s, 1’s, and 2’s, or vectors of 0’s and 1’s, or etc.
  - Put them on a grid...
    - 00100101
    - 10010011
    - 00100000
    - 01010101
  - Each 0 and/or 1 interacts with neighboring 1’s and 0’s.

CA Time Evolution

- Interactions cause each cell to update.
  - Cells evolve with time.
    - In real world, time is (or appears) continuous.
    - For simplicity, we break time into intervals – discretize.
      - Time 1
      - Time 2
      - Time 3
      - ...
      - Time n

      - Like generations.
    - Computers like discrete time intervals. That's how they work.
      - Computer clocks run at x.xx Ghz, which means the computer updates its state that many times per second.

CA Interactions

- Ok, so 0's and 1's interact. How?
  - Sum modulo 2.
  - Product.
  - XOR.
    - If have 0 and 1 (or 1 and 0), then 1. Otherwise 0.
  - Etc.
- Notice we keep the interactions ("rules") simple.
  - So we have large numbers of 0's and 1's with stupidly simple rules of interaction.
  - Complexity theory permits complex rules.
  - Beauty of CA is that simple rules are sufficient. Stay tuned!

Ensemble Behavior

- Frequently, to get back “real-world” behavior we will average together lots of 0’s and 1’s.
  - Averages in time. Or averages in space.
  - Called ensemble average.
  - Note: Sometimes we will consider smaller sets and/or weak or non-existent interactions. This will help us understand the ensemble (large group) behavior.
    - Remember, reductionism isn’t bad. Just different.

So Why Is This Computer Science?

- Complexity Theory is used in physics, sociology, geology, biology, and modern art.
- So why is it computer science?
  - Reason 1: Everything gets reduced to simple 0's and 1's.
    - Computer Science is all about 0's and 1's.
  - Reason 2: Modeling large numbers of objects requires a computer.
  - Reason 3: Prototypical complex system is a cellular automata.
    - Automata are computer science constructs.

A Little CA History

- CA’s and complexity are relatively new sciences.
  - von Neumann and Ulam created CA concept in 1940’s.
    - Were trying to build self-replicating patterns and hence self-reproducing robots – hey, they worked at Los Alamos.
  - In 1960’s Zuse proposed that universe is a cellular automata (CA).
    - New branch of physics.
  - Conway invented “game of life” in late 60’s.
    - Became popular pastime for math/computer folks.
  - Many others contributed – Moore, Toffoli, Margolus, etc.

- But didn’t take off until computers made CA simulations simple.
  - Studied in detail and championed by Wolfram in 1980’s.
    - In 2002 wrote pop-science tome *A new Kind Of Science* to mixed reviews.
  - Now CA studied by many in many different disciplines.
    - research related to glaciers, bird behavior, riots, etc.

Next…

- CA!
- We'll do an overview of basic CA.
- Then we'll jump into the nitty-gritty of the complex deep theory of a *supposedly* simple CA.
  - Yeah, right. Simple to describe, but very complex behavior!