CSCU9YM: Modelling for Complex Systems

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Lecture 1: Introduction to Complex Systems

Complex Systems

- What is a complex system?

  "a system composed of interconnected parts that as a whole exhibit one or more properties [...] not obvious from the properties of the individual parts" - Wikipedia (http://en.wikipedia.org/wiki/Complex_system)

- Complex systems arise in many areas of study:
  - Systems biology (a holistic, not reductionist approach to studying systems like metabolic networks, cell signalling networks)
  - Geophysics (e.g., climate modelling)
  - Economics (e.g., the Artificial Stock Market)
  - Social Science (e.g., Schelling's Tipping Point, Artificial Anasazi)
  - Systems Ecology (a holistic approach to studying the natural world)

Emergence

- A key feature of complex systems is that they exhibit emergent behaviour.
  - This is behaviour that cannot be predicted from studying the constituent parts of the system individually. The behaviour arises or emerges as a result of interactions amongst the part.
  - "The whole is more than the sum of its parts"

- Illustration: the Aggressor Defender Game

- Examples of emergent phenomena:
  - In natural systems: wetness, friction, temperatures, weather, bird swarms
  - In social systems: stock market crashes, tipping points, traffic jams

Modelling methods

- In this module we will study two techniques for modelling complex systems and studying their emergent behaviour:

- Agent-based Modelling
  - uses the NetLogo modelling environment (http://ccl.northwestern.edu/netlogo/)

- Process algebra and stochastic simulation
  - uses the Bio-PEPA language and associated tools
  - taught by Carron Shankland

Agent-based modelling

“Art is a lie that helps us see the truth”

– Pablo Picasso (artist)

“Agent based modeling is also a lie that helps us see reality”

– George Gumerman (agent-based modeller)

Agent-based modelling

- In agent-based modelling (ABM), a system is modelled as a collection of autonomous decision-making entities called agents.
- Agents represent individual entities in the system being modelled.
- Agents may be all the same or may be of different types.
- Each agent assesses its situation and decides what to do on the basis of a set of rules.
- The behaviours of an agent depend upon what is being modelled.
- Some possible behaviours are:
  - movement
    - e.g., road traffic simulation; bird flocking
  - interaction / communication
    - e.g. epidemics, spread of rumours, computer viruses
  - birth / death / production / consumption
    - e.g., epidemics, predator-prey interaction, ...

A brief history of agent-based modeling

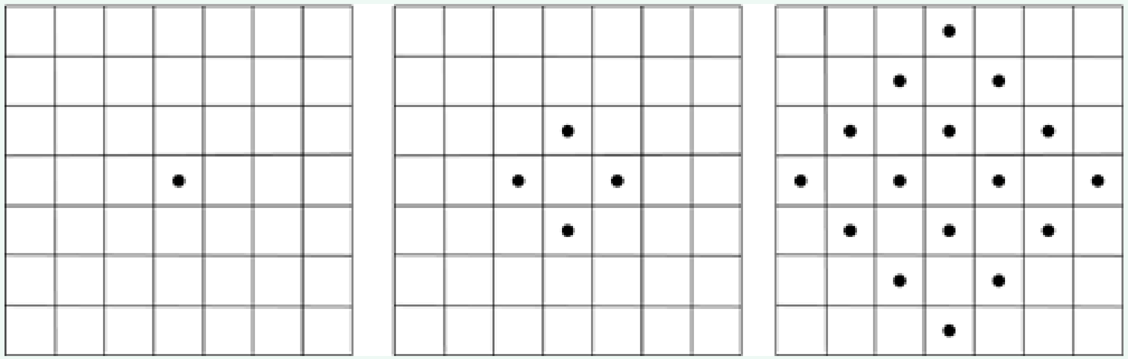
- In agent-based modeling *(ABM)*, a complex system is modeled as a collection of individual agents which follow simple behavioural rules which govern their actions and interactions.
- The basic idea goes back to the 1940s and predates computers.
  - However, it was hard to model anything non-trivial without computers.
  - ABM did not become popular until the 1990s, when sufficiently powerful computers become available.
- Today there is increasing interest in using ABM to understand complex systems in a wide variety of fields:
  - Economics (Agent-Based Computational Economics)
  - Social Sciences (Agent-Based Social Simulation)
  - Biology, Ecology, Physics, Mathematics, Computing Science,...

Early ABMs: Self reproducing Automata

- In the 1940s, John von Neumann tried to model self-reproducing non-biological systems, e.g., robots for building robots.
  - Given technology at the time, this was a thought experiment only!
- Neumann's initial model was too complex to analyse.
- Stanislaw Ulam suggested a simpler model inspired by crystal growth on a two-dimensional lattice.
- The resulting model was the first example of a type of ABM now called cellular automata

Rules:
- 4 neighbours per cell (above, below, left, right)
- Cells are full or empty
- full cell with even number of full neighbours → empty
- empty cell with odd number of full neighbours → full

Generation 1 Generation 2 Generation 3



- (Conway's Game of Life is a famous similar example we will meet later.)

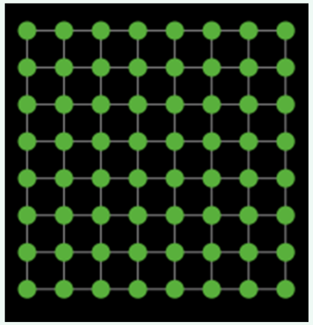
Early ABMs: Evolution of segregation

- One of the earliest applications of ABM in the social sciences was by economist Thomas Schelling (1969).
- Schelling was interested in how communities might evolve to become racially segregated, not because they were planned that way, but because of (slight) individual preferences for having neighbours of the same colour.
- The model used tokens of two colours placed on a two dimensional lattice.
  - Simple rule: if a token was surrounded by “too many” neighbours of the other colour, it would move to some randomly chosen cell.
  - After a few steps, clusters containing only one colour emerge.
- Schelling had no computers. He “simulated” his model using graph paper and coins.
- (This work is widely referred to in computational economics.)

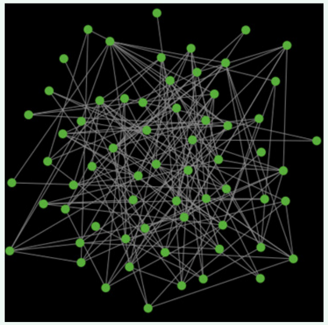
Spatiality and Networks

- Early ABMs such as cellular automata generally arranged agents on a simple square lattice.
- Nowadays, there are many other kinds of network that are studied. We will look at these in more detail in later lectures:
  - Erdős-Rényi (random) networks (1959)
  - Small world networks (Watts and Strogatz, 1988)
  - Scale-free networks (Barabási, 1999)
- Networks may be static or may evolve dynamically through time.

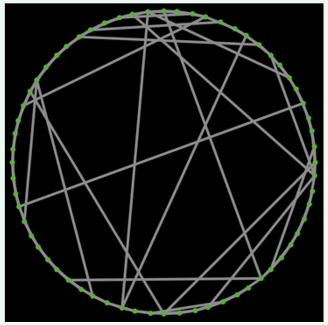
lattice



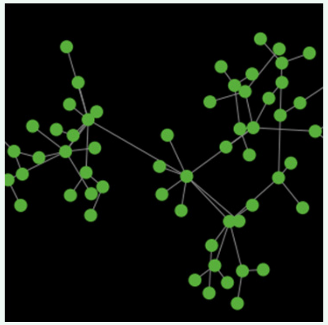
random



small-world



scale-free



Tools for ABM

- The earliest ABMs were developed with minimal tool support:
  - Von Neumann may have used the ENIAC – one of the earliest computers (1946), which he helped create.
  - Schelling used graph paper and coins in his racial segregation model
- Conway's Game of Life (a cellular automata model) was introduced just as minicomputers were coming into existence (1970s). It became popular with hobbyists and was implemented in many of the new programming languages of the time (e.g. BASIC).
- Today, there are specialist tools using domain-specific languages that make it easy to construct ABM. Popular tools include
  - Repast (Collier et al, 2003)
  - Swarm (Santa Fe Institute, mid-1990s)
  - NetLogo (Wilensky, 1999)
    - » Derived from the Logo language for teaching children to program
    - » Widely considered the easiest ABM tool to use

Example: Predator-prey model

- Ecology: exploring the long term stability of predator-prey ecosystems (wolves, sheep and grass in this example).
  - A stable ecosystem maintains its population over time (perhaps with some fluctuations.
  - In an unstable ecosystem, one or more species eventually becomes extinct.
  - Question: what factors make a population stable?
- Agents: wolves, sheep and grass
- Rules:
  - Wolves and sheep both wander around randomly.
  - Movement costs energy. If energy drops to zero, the animal dies. Energy is replenished by eating (wolves eat sheep, sheep eat grass).
  - Animals can reproduce (with a fixed probability). Grass regrows after a fixed time.

Example: The Game of Life

- A classic example of a type of agent-based model known as cellular automata.
- The universe is a two-dimensional grid of cells.
- A cell is either alive or dead.
- Each cell has 8 neighbours.
- The system evolves through time. The state of a cell in the next time step depends on the state of its neighbours in the current step:
  - A live cell with less than 2 live neighbours dies (loneliness).
  - A live cell with 2 or 3 live neighbours remains alive
  - A live cell with more than 3 live neighbours dies (overcrowding)
  - A dead cell with 3 live neighbours comes to live (reproduction)
- Invented by Conway in 1970, Life was hugely popular among the users of the first minicomputers and was much studied.
- [See http://en.wikipedia.org/wiki/Conway's_Game_of_Life]

Example: Fire escape design

- How do people behave in a life-threatening crowd situation like escaping from a burning building? How can we avoid people being crushed or trampled and maximize the number who escape?
- Agents: people
- Environment: enclosed space with exit(s) and obstacles
- Rules: a complex model of human movement,
  - based partly on the physics of motion
  - and partly on socio-psychological aspects (e.g., people try to avoid getting too close to others).
- Some interesting (and counter-intuitive) results!
- [video]

- [Helbing, Farkas and Vicsek (2000), Simulating dynamical features of escape panic, Nature 407, pp 487-490]

Overview of ABM part of course

7 Lectures:

- Introduction to ABM (this lecture)
- Model design and the ODD protocol
- Doing experiments with simulation (design, results analysis)
- Network structures
- Catch-up and assignment Q&A

6 practical classes

- Introduction to NetLogo
- Designing and studying a first model
- Performing experiments with BehaviorSpace
- Network models
- Catch-up and assignment help

Assessment: NetLogo modelling exercise and report; checkpoints

Textbooks:

- Agent-Based and Individual-Based Modeling, Railback and Grimm,2012
- An introduction to Agent-Based modeling, Wilensky and Rand, 2015

End of lecture