Agent-based modelling of complex systems

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Lecture #2: Introduction

Outlook

- Learning objectives (again)
- Why ABM?
- Understanding emergence
- ABM as tool for knowledge restructuration

Learning objectives

1. Why does ABM provide us with a unique and powerful insight into complex systems?
2. What is ABM and how is it used?
3. What are some simple ABM models that we can create?
4. How do I create my own agent-based models?
5. What are the basic components of agent-based modeling?
6. How do I analyze the results of an agent-based model?
7. How can I tell if the implemented model corresponds to the concept of the model I developed in worlds?
8. How can I use the output of an agent-based model?

Why agent-based modeling?

- **ABM** – a form of computational modeling whereby a phenomenon is modeled in terms of agents and their interactions
- **Agent** – an autonomous computational entity with particular properties and actions:
  - state variables and values (position, velocity, age, wealth etc.)
  - a graphical component to be presented on screen
  - rules of behavior (including interactions with other agents)
  - information on environment (including contact network topology)

Why agent-based modeling?

- goal of ABM is to create agents and rules that will generate a target behavior
- sometimes rules are not well known → ABM used for understanding a phenomenon through experimentation with rules and properties
- “anything that is perceived as difficult to understand can be made more understandable by a suitable representation” → a methodology suitable for complex systems
- complex system restructuration through ABM:

  a) understanding of complex systems can be democratized

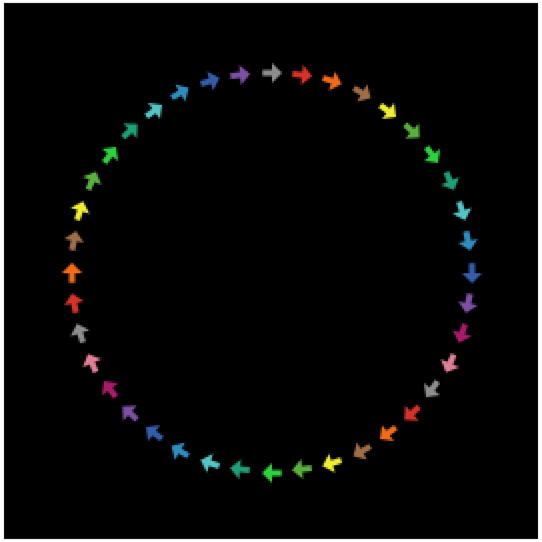
  b) the science of complex systems can be advanced

Understanding complex systems and emergence

- usually very hard for people
- two challenges:
  - trying to figure out the aggregate pattern when one knows how individual elements behave (**integrative understanding**)
  - trying to find the behavior of individual elements that could generate a known pattern (**differential** or **compositional understanding**)

Integrative understanding

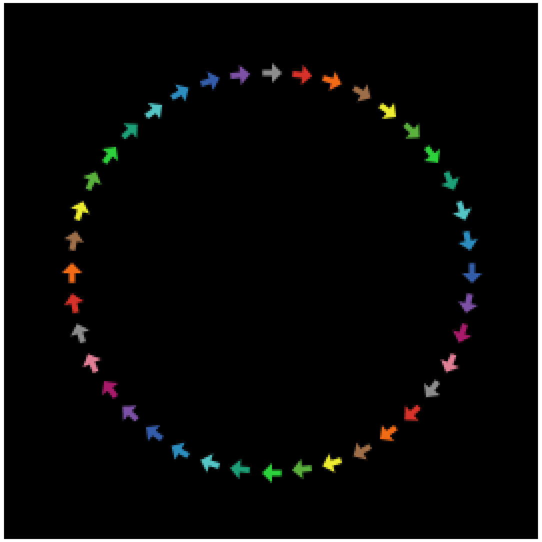
- consider a system composed of few arrows (**agents**)
- imagine a clock ticking
- at every click of the clock, each arrow moves forward by 0.35 units and the turns right one degree (**rule**)
- start with arrows facing clockwise on a circle (of radius 20 units)



What is the resulting pattern?

Integrative understanding

- now we slightly alter the rule:
  - at every click of the clock, each arrow moves forward by 0.5 (instead of 0.35) units and the turns right one degree



What will be the aggregate pattern in this case?

Integrative understanding

- most people do not predict the correct pattern even in this simple example
- typical predictions:
  - a larger circle
  - a smaller circle
  - a flower shape

Differential understanding

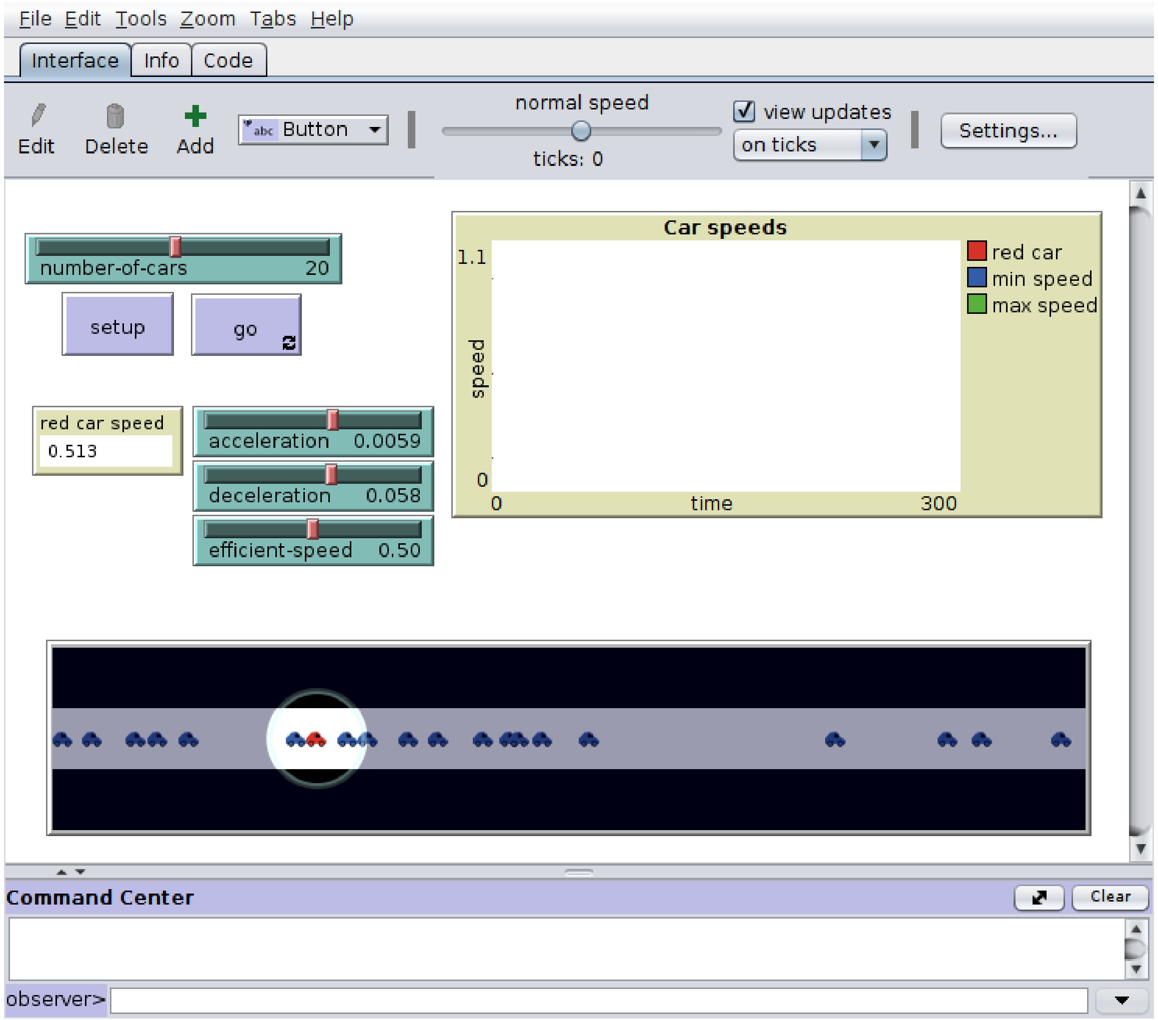
- flip side of the previous difficulties
- many coherent, beautiful or powerful patterns observed in the world

How do they originate?

Differential understanding

- traffic jams observed in most industrial societies with individually driven vehicles
- we tend to think of traffic jams as being composed of thousands of individual cars
- from a bird’s eye perspective, traffic jams appear as a single object moving backward against the flow of traffic

Differential understanding



Differential understanding

- secret to understanding of the patterns → they are emergent, arising from the interactions of distributed individual elements
- in case of the traffic jam model:
  - highway is divided into cells
  - cars are the agents
  - in each step, they conduct following actions (the rules):
    - acceleration: all cars not at the maximum velocity accelerate
    - slowing down: if there is another car in the cell ahead, slow down to avoid a collision
    - motion: all cars are moved forward the number of cells equal to their velocity

Is it a reasonable model?

Differential understanding

Differential understanding

- most of the traffic jams arise from the statistical distribution of cars and speeds
- the model explains that!!!
- of course, accidents and radar traps cause some traffic jams too
  - they could be taken into account in an extended version of the model
- in general, using an emergent lens is a vital need for our understanding of many phenomena observed in real world

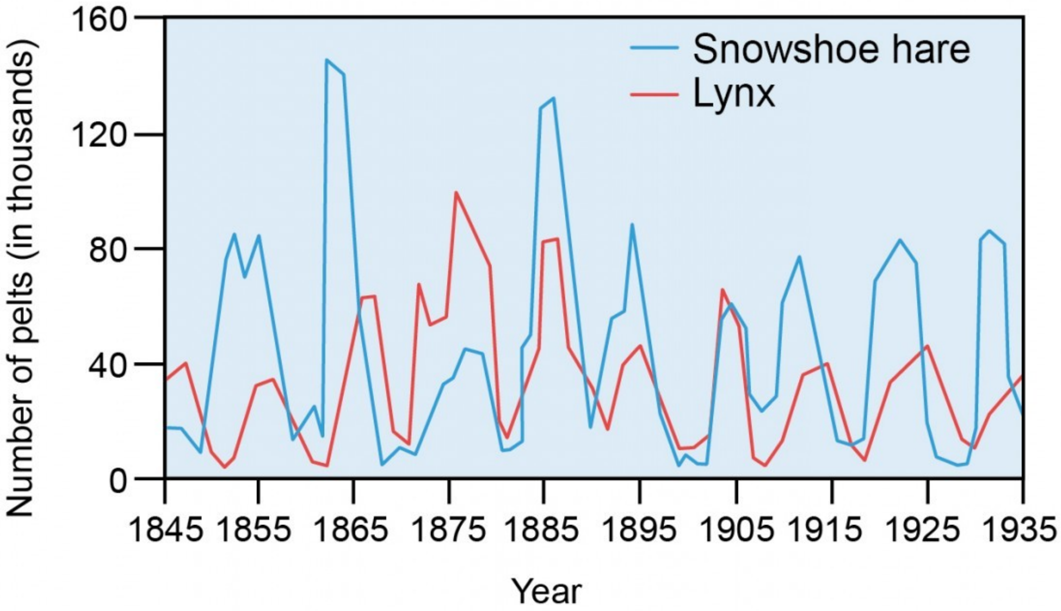
ABM as a tool for knowledge restructuration

- new computer-based representations of complex systems can help restructurate our knowledge in many domains
- in many areas we have relied on simplified description of complexity, often using advanced mathematical techniques that are tractable
- with ABM we can simulate thousands of individual system elements
- more accessible ways to study complex phenomena
- virtually every university subject can benefit from basic familiarity with ABM
- chemistry, biology and material science have embraced ABM from start
- disciplines like psychology, sociology, physics, business and medicine embraced it in a second wave
- recently we observe the growth of ABM in economics, anthropology, philosophy, history and law

ABM as a tool for knowledge restructuration

- as for the complex systems, we expect following restructuration due to ABM:
  - understanding of complex systems can be **democratized**
  - the science of complex systems can be **advanced**

Case study: predator-prey interactions



Case study: predator-prey interactions

- first model proposed by A. J. Lotka (1925) and V. Volterra (1926)

$$\frac{dx}{dt} = \alpha x - \beta x y$$

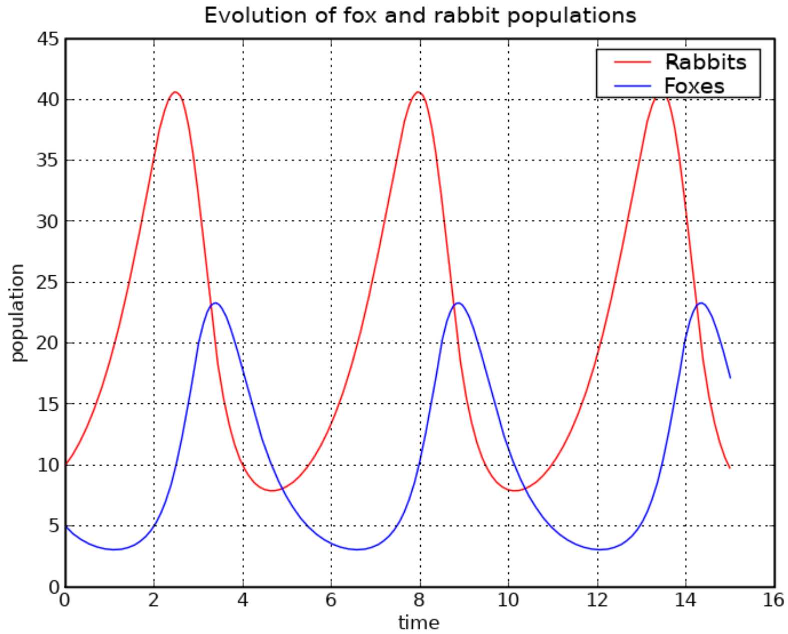
$$\frac{dy}{dt} = \delta x y - \gamma y$$

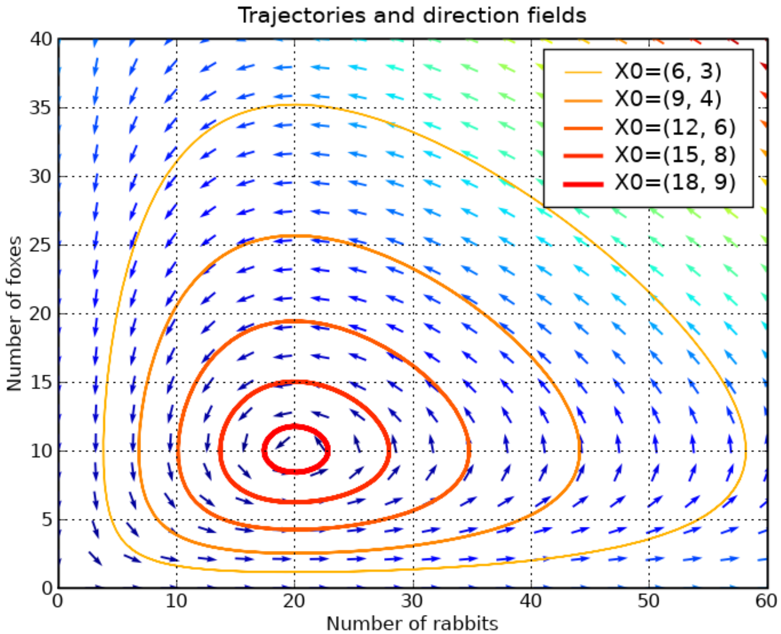
- x is the number of prey
- y is the number of predators
- t represents time
- α, β, γ and δ are positive real parameters describing the interaction of the two species

Case study: predator-prey interactions

- assumptions (not necessarily realizable in nature):
  - prey population finds ample food at all times
  - food supply of the predator population depends entirely on the size of the prey population
  - rate of change of population is proportional to its size
  - environment does not change in favour of one species and genetic adaptation is inconsequential.
  - predators have limitless appetite
- solution deterministic and continuous

Case study: predator-prey interactions

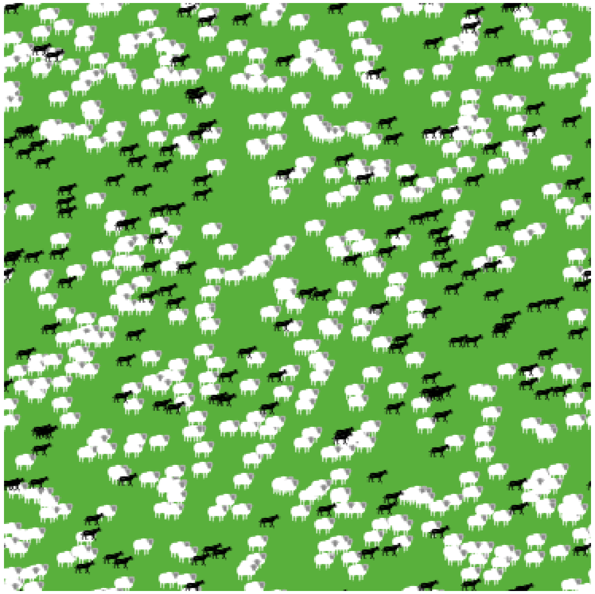




Case study: predator-prey interactions

- the solution shows cycles of growth and decline in each population
- model requires familiarity with differential equations and numerical methods of solving them
- mechanisms that cause these cycles are not readily apparent from the equations
- **mechanisms are not explicit**
- it is not clear why the increase happens at a constant rate δ

Case study: predator-prey interactions



- an agent-based representation of the system involves simple algorithmic models, e.g.:
  - each individual has a store of energy
  - energy is depleted when they move and increased when they eat
  - if energy dips too low, they die
  - if energy is high enough, they reproduce
  - if the encounter food while moving, they eat

Case study: predator-prey interactions

- compared to the initial model, the rules are explicitly stated at individual level
- stochasticity may be included in a natural and easy way
- rules instruct each agent, how to behave
- they are understandable by even young children
- they can be challanged more easily and tested
- calculus is not required (**lower entry threshold**!!!)
- but still, for an expert an equation can sometimes represent a phenomenon more compactly than ABM