Complex Systems 530: Computer Modeling of Complex Systems

Lecture 1: Introduction and overview

Welcome!

- Today
  - Class logistics & introductions
  - Why model? How to choose what kind of model to use?
  - Agent-based models (ABMs)
  - ABM exploration

Course Info

- Instructor: Prof. Marisa Eisenberg
- Office Hours - TBD
- Course website & syllabus
  https://epimath.github.io/cscs-530-materials/
  (Go through this together & talk about the plan for the class)
- Course Structure
  - Homework/Labs & Project
- Course Goals & Philosophy

Course overview

- Focus of course: how to design, build, simulate, visualize, analyze, document, and compare agent-based models & other models

- Along the way, we will also explore:
  - A bit of philosophy of modeling/complex systems
  - Intro/intermediate programming
  - Some probability, statistics
  - Cellular automata
  - Some network (graph) theory & data analysis
  - A bit of collective behavior, pattern formation, & game theory
  - Models in social, biological, and physical systems

Course overview

- We will not focus as much on equation-based models (e.g. ODE's, PDE's)—these are also super useful! But there are a lot of existing courses covering these topics (e.g. CSCS 511)
  - (That said, if math is your jam, we will have some of that too!)
  - If you are curious whether your question is better addressed with ABMs vs. other kinds of models, we will discuss some & can talk more as we go

Goals for the course

- Learn about models and model-building—how and why to build models for a given problem
- Become a sophisticated consumer of articles involving ABM and gain a solid grounding in some of the key models in the field
- Develop familiarity and competencies in two programming languages, NetLogo and Python
- Leave this class with an ABM you have designed, built, and analyzed that will (hopefully) be useful to you in your future research!

Languages for Coding

- Example code and HW files will be mostly in NetLogo & Python 3
    - See website for more information on how to install
    - Anaconda
- However, for much of the class you can code in whatever language is comfy for you (e.g. R, MATLAB) (within reason…)

Prior Background

- A background in complex systems is not required, but hopefully you have a strong interest!
- Some basic programming and basic math/stats background is **strongly** encouraged.

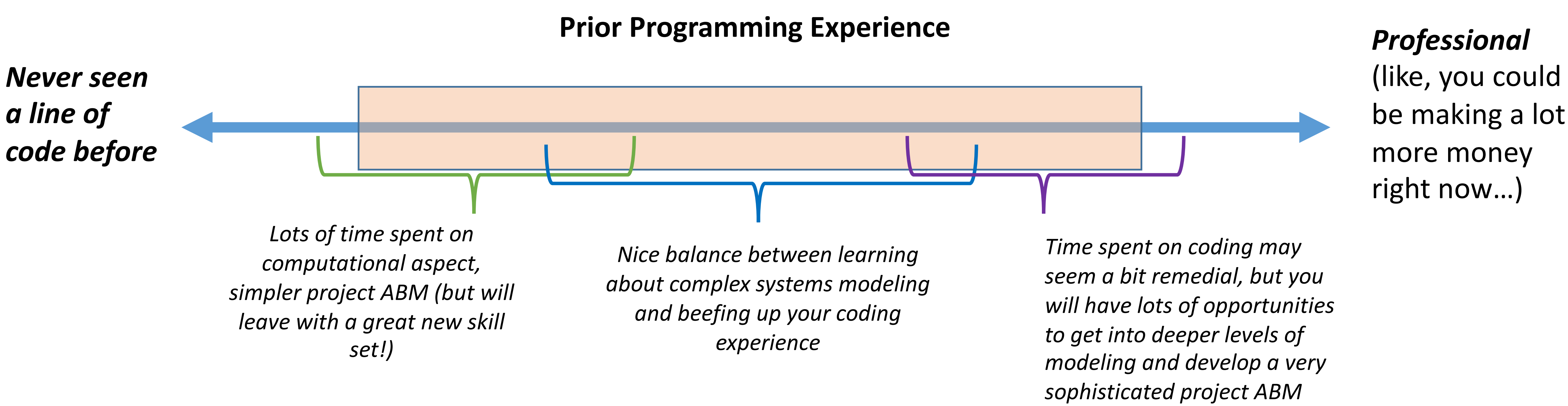
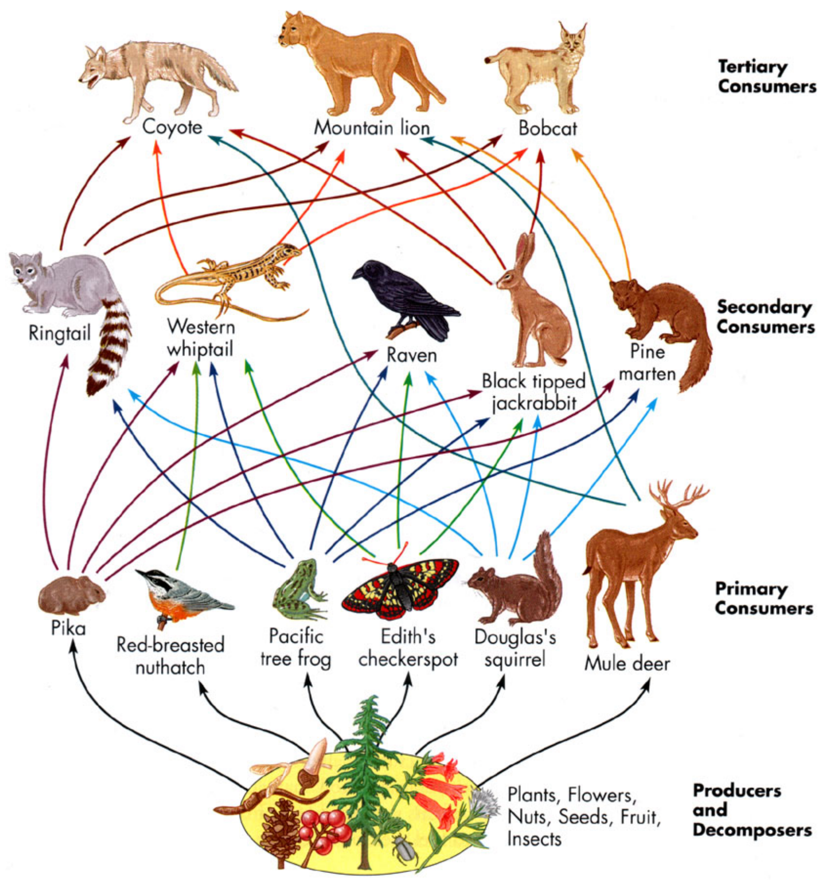


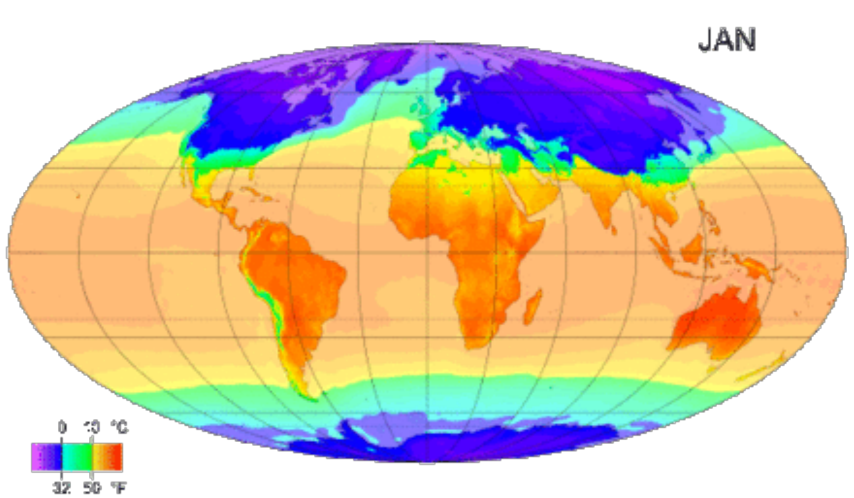
diagram borrowed from Lynette Shaw!

Introduction

What is a complex system?




© Daniel Biber, Germany, Shortlist, Professional, Natural World & Wildlife, 2018 Sony World Photography Awards

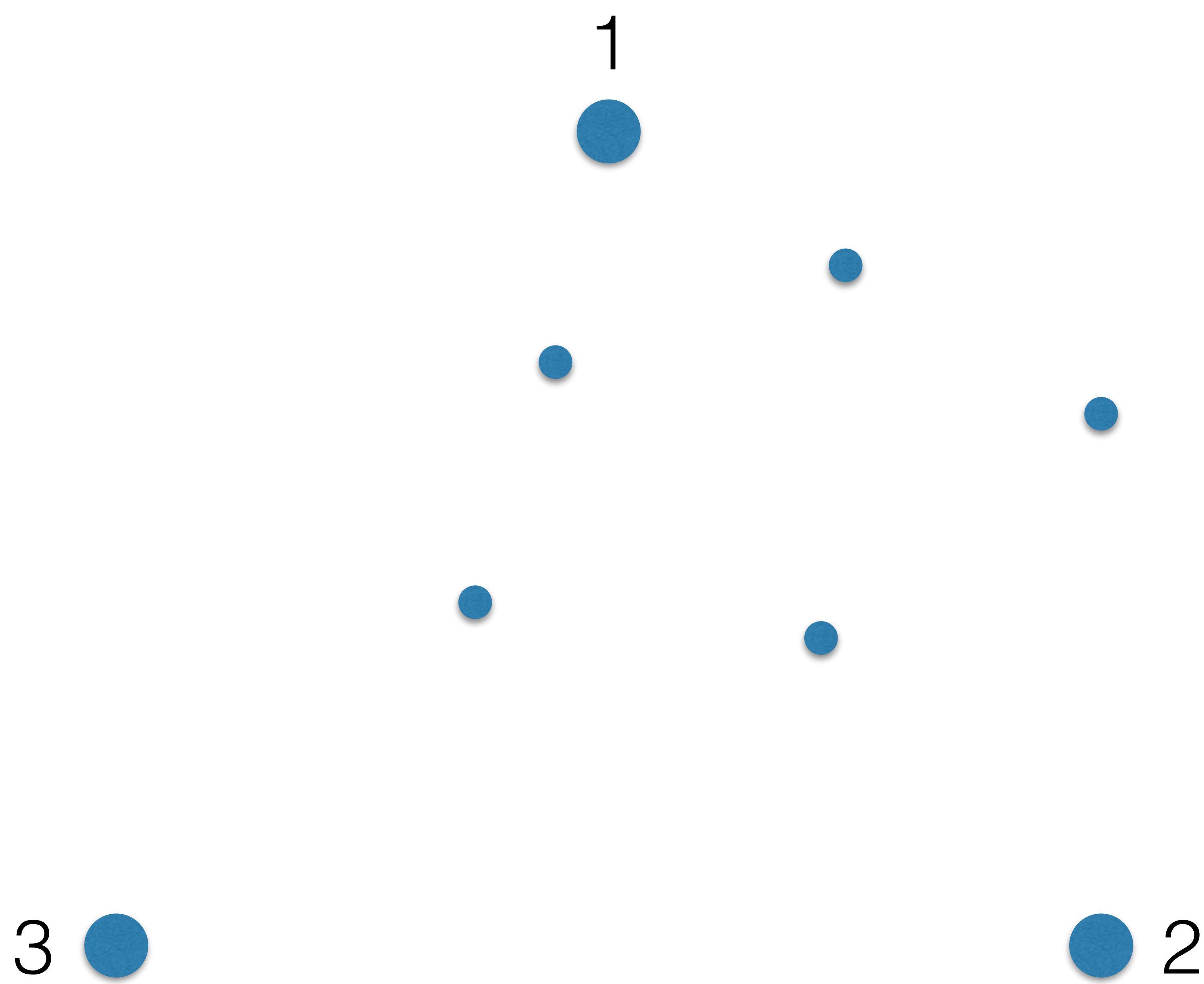


What is a complex system?

- **A collection of components that interact, often in nonlinear ways**

- Sayama: "Complex systems are networks made of a number of components that interact with each other, typically in a nonlinear fashion. Complex systems may arise and evolve through self-organization, such that they are neither completely regular nor completely random, permitting the development of **emergent behavior at macroscopic scales**."

Interactive Example!



Interactive example

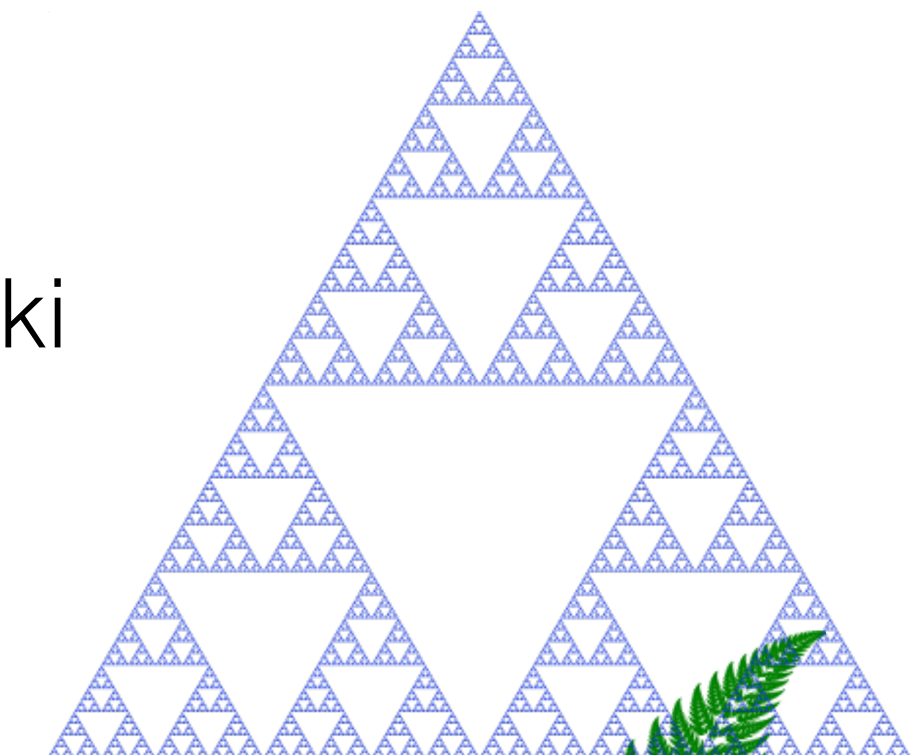
- 1) Mark a point at random within the triangle (can really be anywhere but this is simpler)
- 2) Randomly pick a vertex
- 3) Mark your next point: the point halfway between your current point and the vertex you chose
- Repeat steps 2) and 3)

The chaos game!

- Generates a fractal! This is called the **Sierpiński gasket** or Sierpiński triangle

- Fractals are objects that exhibit self-similarity (ferns, trees, snowflakes, rivers, & more)

- Simple rules can generate surprising emergent patterns!



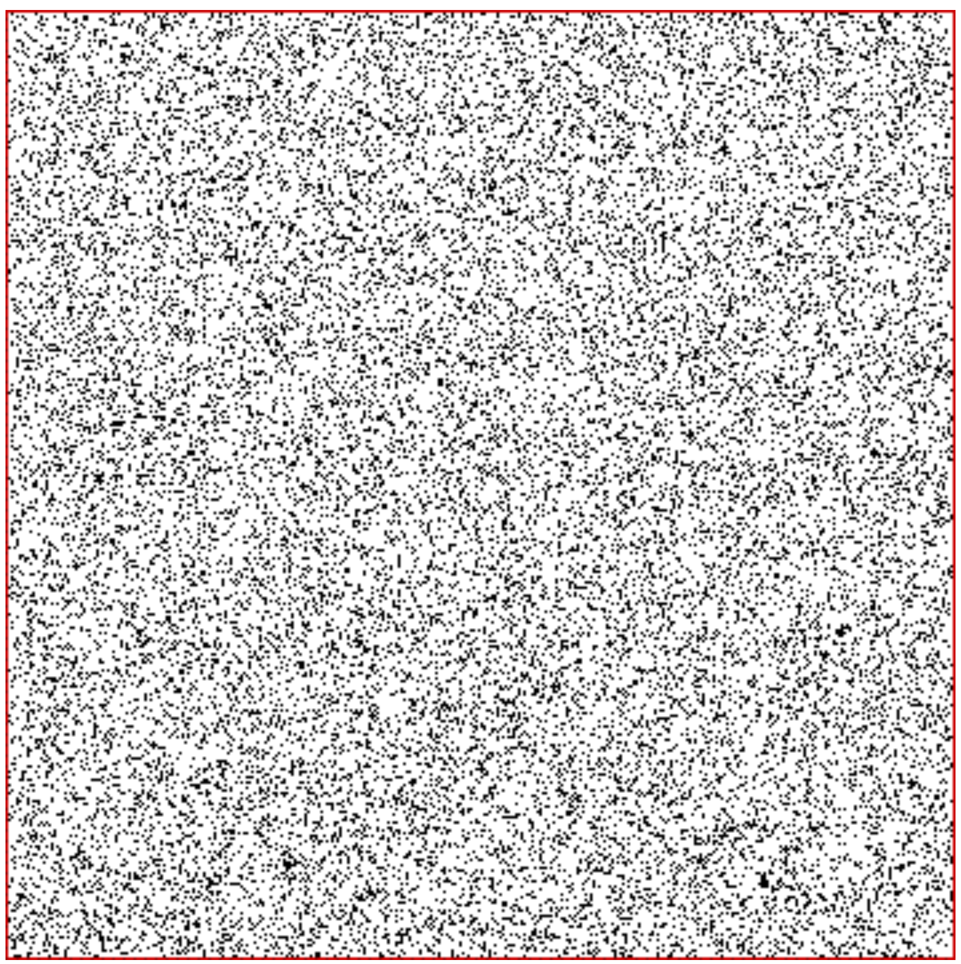
Interactive game is from: http://math.bu.edu/DYSYS/chaos-game/node4.html

The chaos game

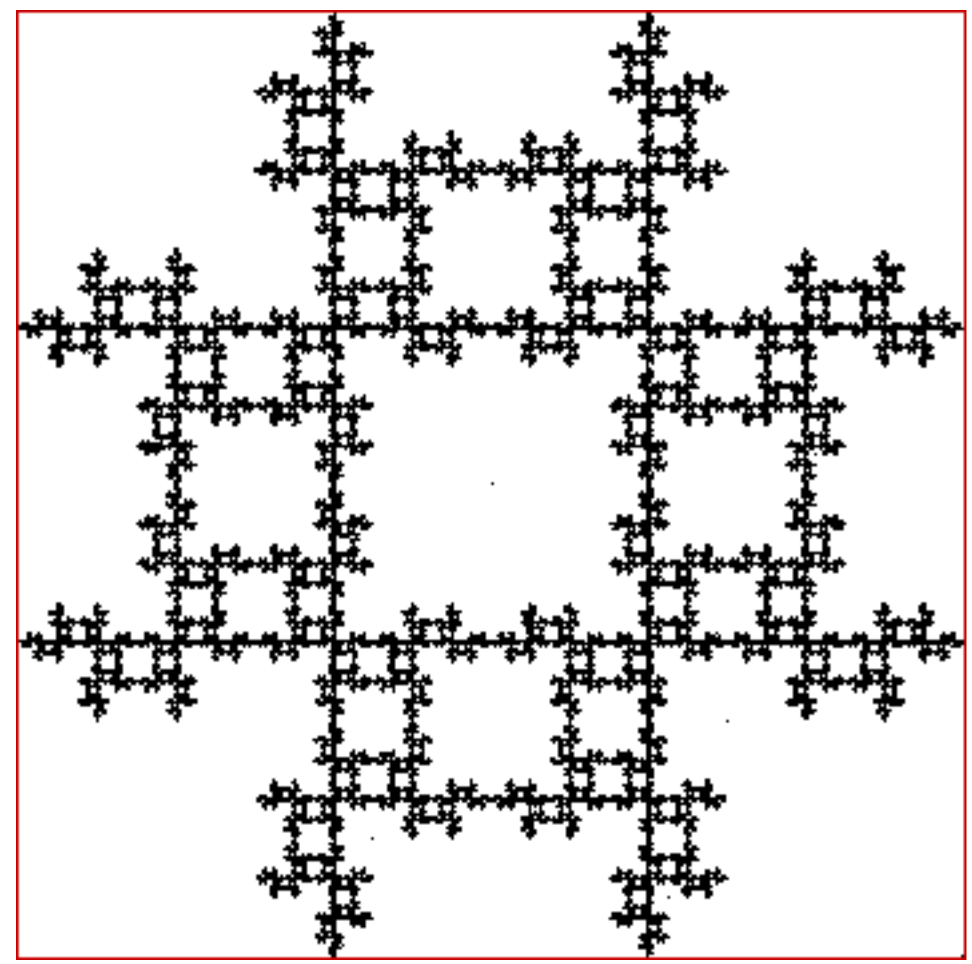
- The Sierpinski gasket is an attractor for this process
- Why does this work? A little intuition—think about transformations—discuss
- We will do more with this later
- Does it work with other shapes?

The chaos game

Try it with a square?



Use a square but don't choose the same vertex twice



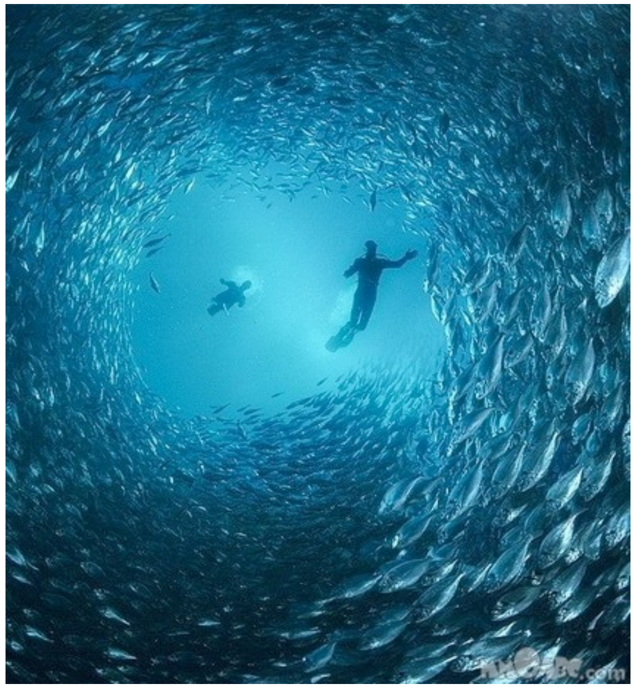
Many other variations!

Complex Systems

- Emergent behavior
- Self-organization
- Adaptive interactions
- “Fat-Tail” Behavior
- Chaos
- Nonlinearity, tipping points, etc.

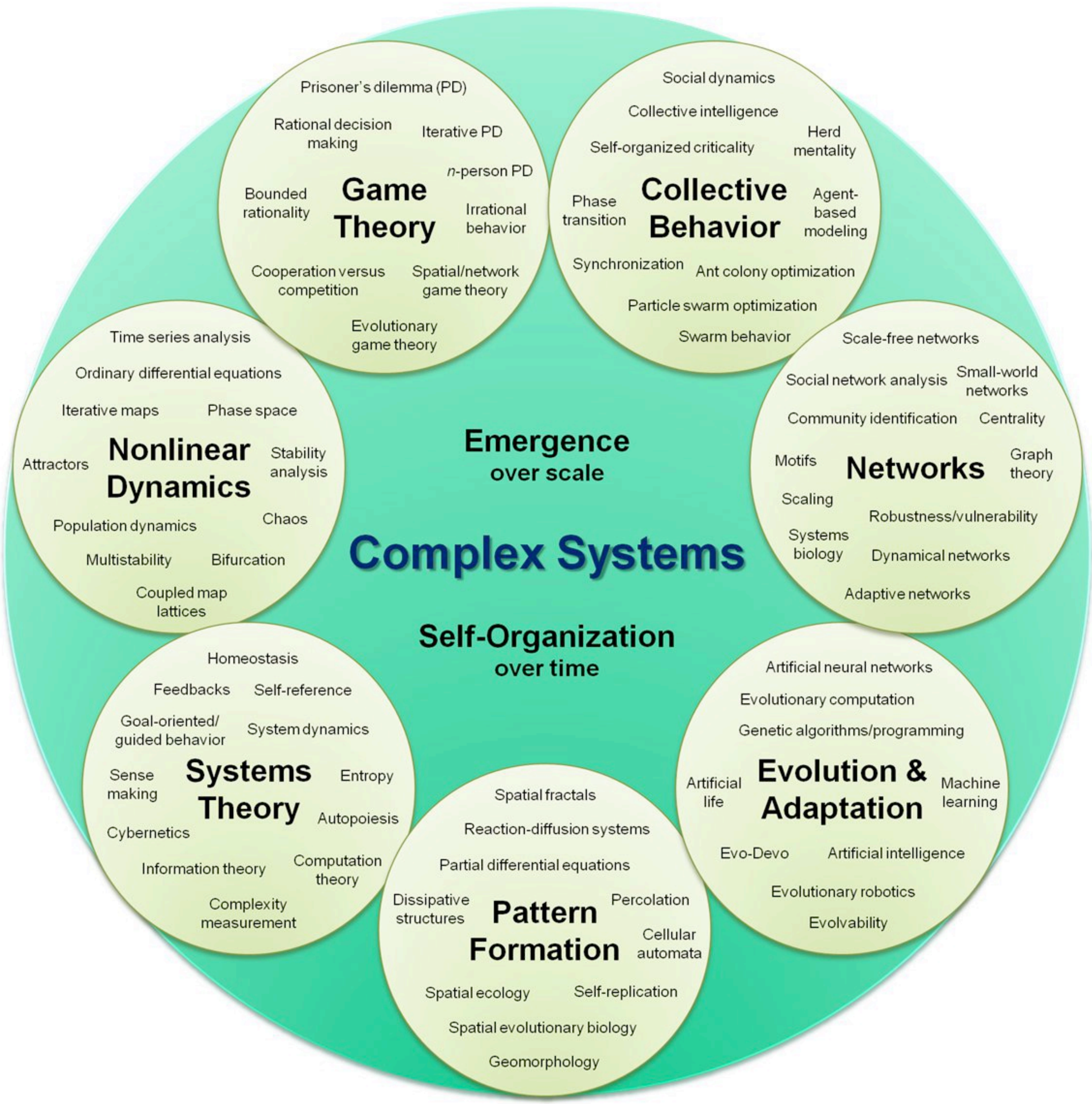
Example: flocking!

- Flock of geese/school of fish
  - Forms a large, organized pattern
  - But no 'group mind' or leader
  - Birds follow local rules
  - Result is emergent, organized behavior



https://www.youtube.com/watch?v=e8Prw9AZ9jw

Complex Systems Science



Introduction to the Modeling and Analysis of Complex Systems by Hiroki Sayama

What is a model?

- In a few words, what does a model mean to you?

What is a model?

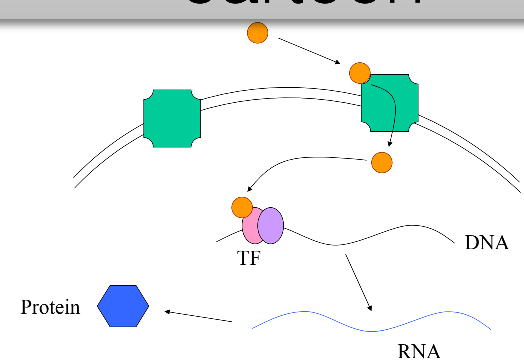
Reality

↕

Abstraction of Reality

Physical
e.g. miniature, animal model

Diagram
e.g. schematic, map, cartoon



Math/computational
e.g. equations, code

$$\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

```
for i in range(1,10):
    print(i)
```

Models are abstractions

- They are **simplifications**—and so they are **wrong**!
- But they are also often **useful**
- Abstraction is both their strength & weakness
- The trick is, how much to simplify? What details to keep, which ones to remove?
- Even “simple” systems can be complex

Why model?

- Discuss

Why model?

- You already model all the time! All of us build mental models, pictures, etc. of the world and the systems we’re interested in.

- Really, we are asking: why build explicit models, where we lay out the mechanisms, assumptions, parameters, etc. as equations/code?

    - If we make our models explicit, we can test, interrogate, explore them—can make sure they are self-consistent, explore more complex scenarios, etc.

Why model?

- Understand mechanisms, causality
- Help to guide & test control, treatment, intervention strategies,
- Test alternative scenarios (counterfactuals)
- Forecast/predict

Why model?

From Epstein 2008:

- Explain
- Guide data collection
- Illuminate core dynamics
- Suggest dynamical analogies
- Discover new questions
- Promote a scientific habit of mind
- Bound (bracket) outcomes to plausible ranges
- Illuminate core uncertainties
- Offer crisis options in near-real time
- Illuminate core dynamics
- Demonstrate tradeoffs / suggest efficiencies
- Challenge the robustness of prevailing theories
- Expose prevailing wisdom as incompatible with data
- Train practitioners
- Discipline the policy dialogue
- Educate the general public
- Reveal the apparently simple (complex) to be complex (simple)

Why model?

Known knowns	Known unknowns
Unknown knowns	Unknown unknowns

Why model?

Known knowns	Known unknowns
Unknown knowns	Unknown unknowns

Words of caution

- How to know if you have the right mechanism?
- How much do our assumptions and simplifications affect our outcome?
- May not be possible to, for example, predict certain things from the data/understanding that we have! (e.g. early epidemic curve)
- *Importance of understanding/testing assumptions, uncertainty quantification, model comparison, etc.*

How to choose a modeling framework?

- Differential equations, stochastic population-based models, agent-based models, many others!
- Deterministic vs. stochastic?
- Discrete vs. continuous?
- Population-based or individual-based?
- Spatial/non-spatial?
- Different frameworks will have different analytical and computational tractability, interpretability, and assumptions

How to choose a modeling framework?

- Often can model the same process with many different frameworks (ABMs, ODEs, Markov models, etc.)

- Can also sometimes implement the same or equivalent model in different frameworks

- Discuss for:
  - Epidemics
  - Swarming/flocking (e.g. murmuration, fish schooling)
  - Population growth (e.g. birth/death processes)

How to choose a modeling framework?

- Depends on the problem/question of interest!
- ABMs often particularly advantageous for questions where individual heterogeneity is key (e.g. spatial position of individuals, individuals with varying properties, etc.)
- May also just be more illustrative/clear/interpretable in one framework or another even if equivalent

How to choose a modeling framework?

- What if the modeling framework you choose affects your results?
- More generally, how to decide how realistic/ simplified to make your model?
- Model comparison & inference robustness assessment—more on this later

Koopman JS. Infection transmission science and models. Japanese journal of infectious diseases. 2005 Dec 1;58(6):S.
Pollock KH. Inference robustness vs. criterion robustness: an example. The American Statistician. 1978 Nov 1;32(4):133-6.

Agent-based models (ABMs)

Agent-based models!

- Agents - independent “agents” move, interact, explore environment, etc.
- Environment - agents exist in a non-agent environment (can be static or dynamic)
- Rules/interactions - to govern agent behavior, how they interact with the environment, etc.

Motivating example: video games!

Agent-based models

- Advantages
  - Can handle situations where population cannot be viewed as aggregates
    - Heterogeneity
  - Often a natural description of system - think in terms of individuals & their decisions/actions
    - Builds from micro (individual process) to macro (overall emergent behavior)
  - Flexible, can account for more complexity/detail

Agent-based models

- Disadvantages
  - Often harder to develop, document, and validate
  - Less of an existing analytical framework for understanding dynamics, doing parameter estimation, etc.
  - Flexibility towards complexity/complicatedness is both a strength & weakness
  - Can be tempting to make highly complicated & realistic—can make it difficult to know what's going on. Be careful to keep it 'as simple as possible (but not simpler)'

We will explore

- Designing, building, and simulating ABMS
- Parameter exploration & sampling - exploring the model behavior
- Interpreting results
- Documenting ABMs!
- Alternative models & inference robustness - how do the inferences/predictions/outcomes/explanatory power of our model change as we add realism?

Let's try out an ABM!

- Forest fire model: https://ncase.me/simulating/model/

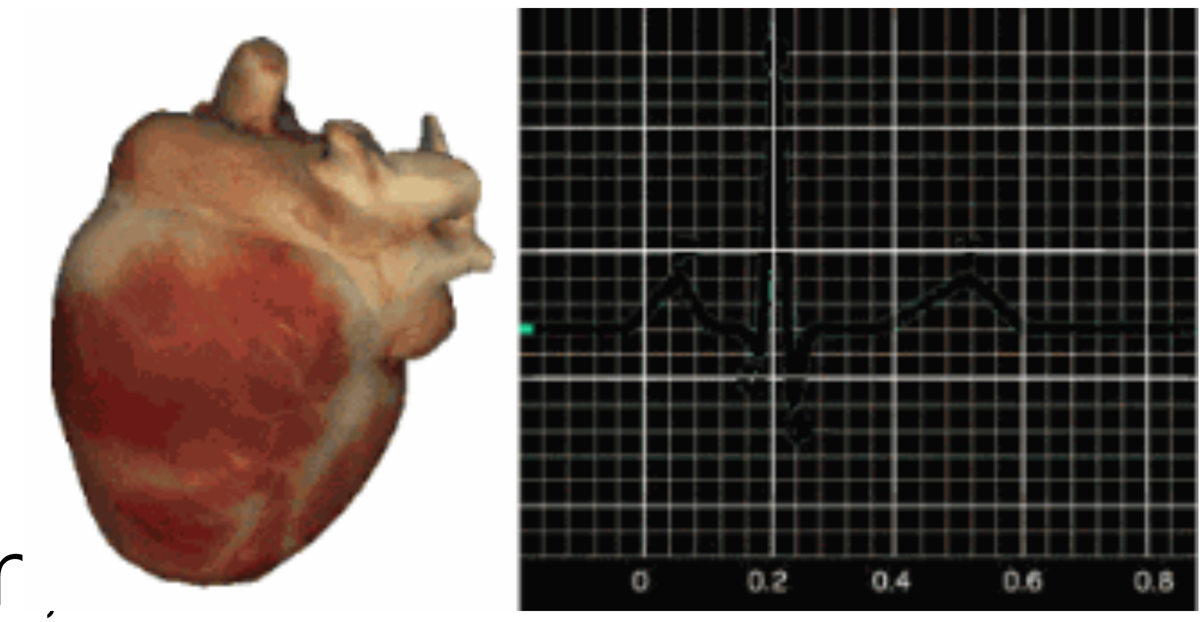
- What do you notice?

- Any interesting behaviors as you adjust things? You can also add other agent types into the mix!

- What happens if we increase tree growth to 5% and start with all trees?

- Modeling by analogy: what else could this model (or similar) be used for?

Cardiac dynamics & heart muscle tissue

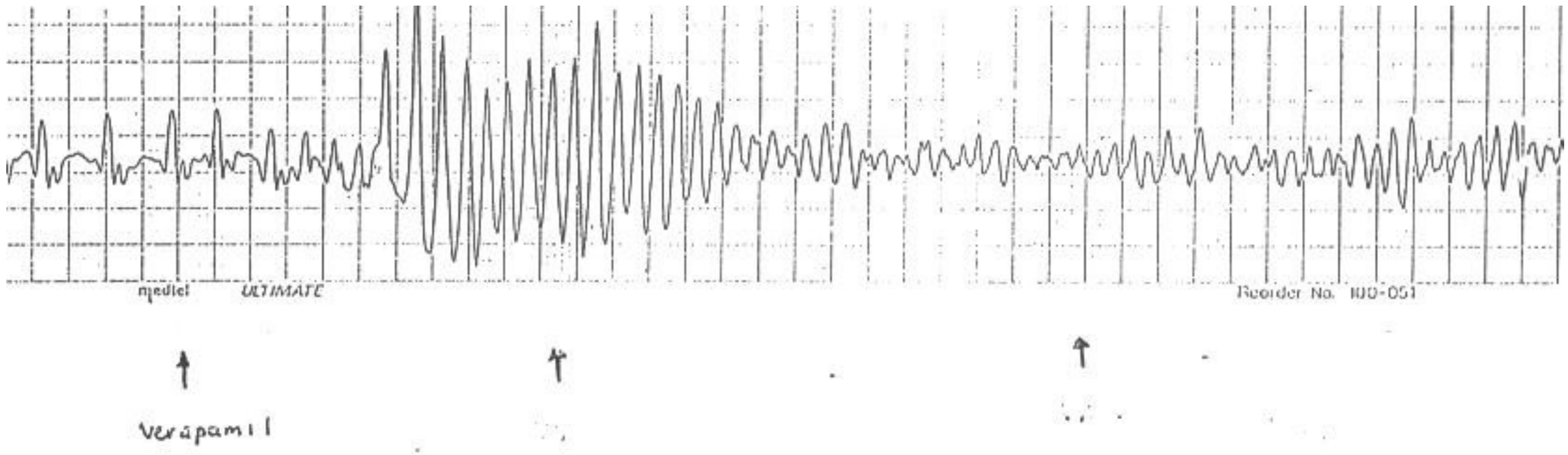


http://www.scholarpedia.org/article/Cardiac_arrhythmia

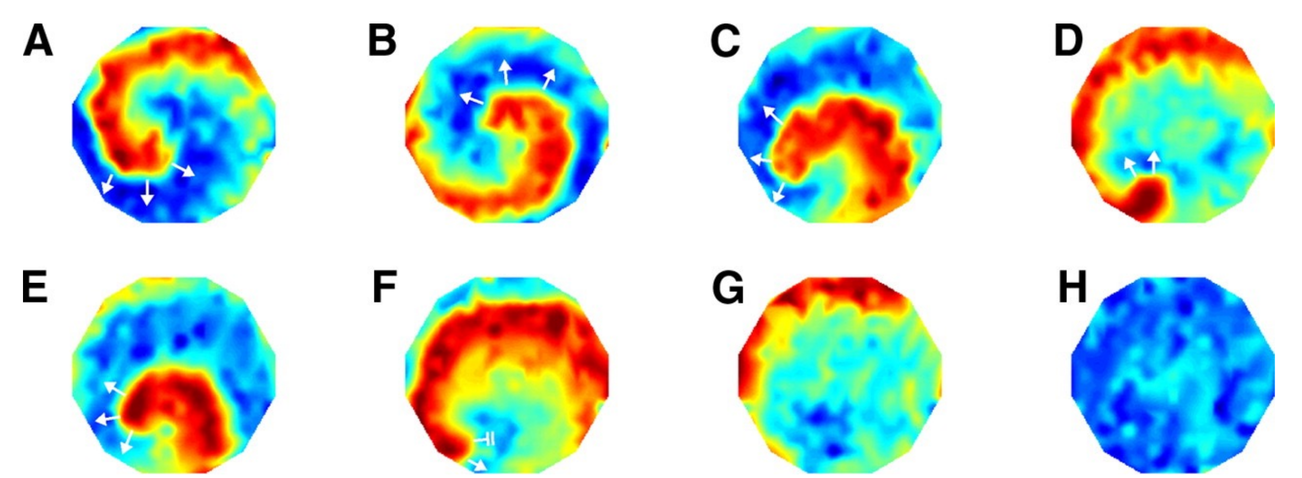
- Normal rhythm: depolarization wave contracts atrium and ventricle in a regular rhythm, originating at sinoatrial node & traveling to atrioventricular node

- However, heart can undergo bifurcation to other behaviors—arrhythmias

Cardiac arrhythmias

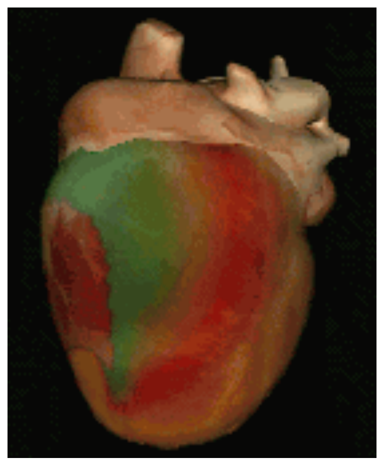


- Tachycardia—>ventricular flutter—>ventricular fibrillation
- These bifurcations can often be understood in terms of spiral waves, period doubling bifurcations, and other spatiotemporal dynamics

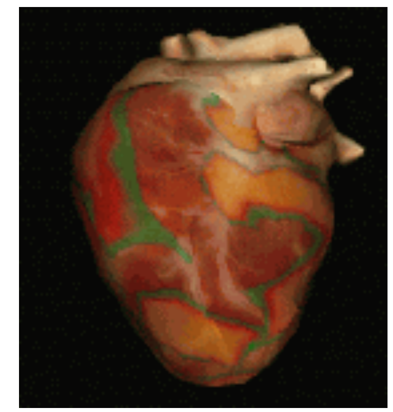


http://ajpheart.physiology.org/content/294/1/H58.figures-only

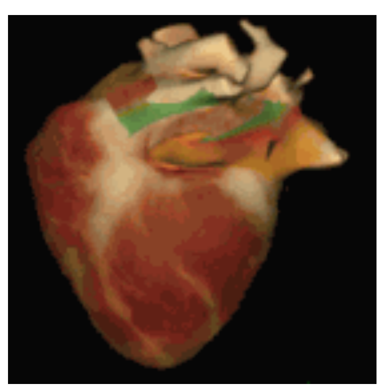
Spiral/scroll waves in heart arrhythmias



Ventricular tachycardia



Ventricular fibrillation



Atrial flutter

Atrial fibrillation

http://www.scholarpedia.org/article/Cardiac_arrhythmia

Now let's make one from scratch

- https://ncase.me/sim/?s=blank
- Simple voting model!
- Everyone starts with some random initial preference
- They tally the planned votes of their neighbors and if more than half of neighbors are voting the other way, they switch
- What happens?

Wilensky, U. (1998). NetLogo Voting model. http://ccl.northwestern.edu/netlogo/models/Voting. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Voting model

- Things to try:
  - Award ties differently (e.g. switch if exactly half of neighbors vote the other way)
  - Different initial percentages of each party
- Try with 3 parties
  - What happens? Same patterns?

More emoji ABMs

- https://ncase.me/sim/
- Explore!

For next time…

- Read
  - “Why Model?”, Epstein 2008
  - Sayama, Chp. 1-2
  - “More is Different,” Anderson 1987
  - Wilensky, Chp. 0-1
- Do
  - Download and Install NetLogo and Python (e.g. Anaconda)