Lecture 11
Applications

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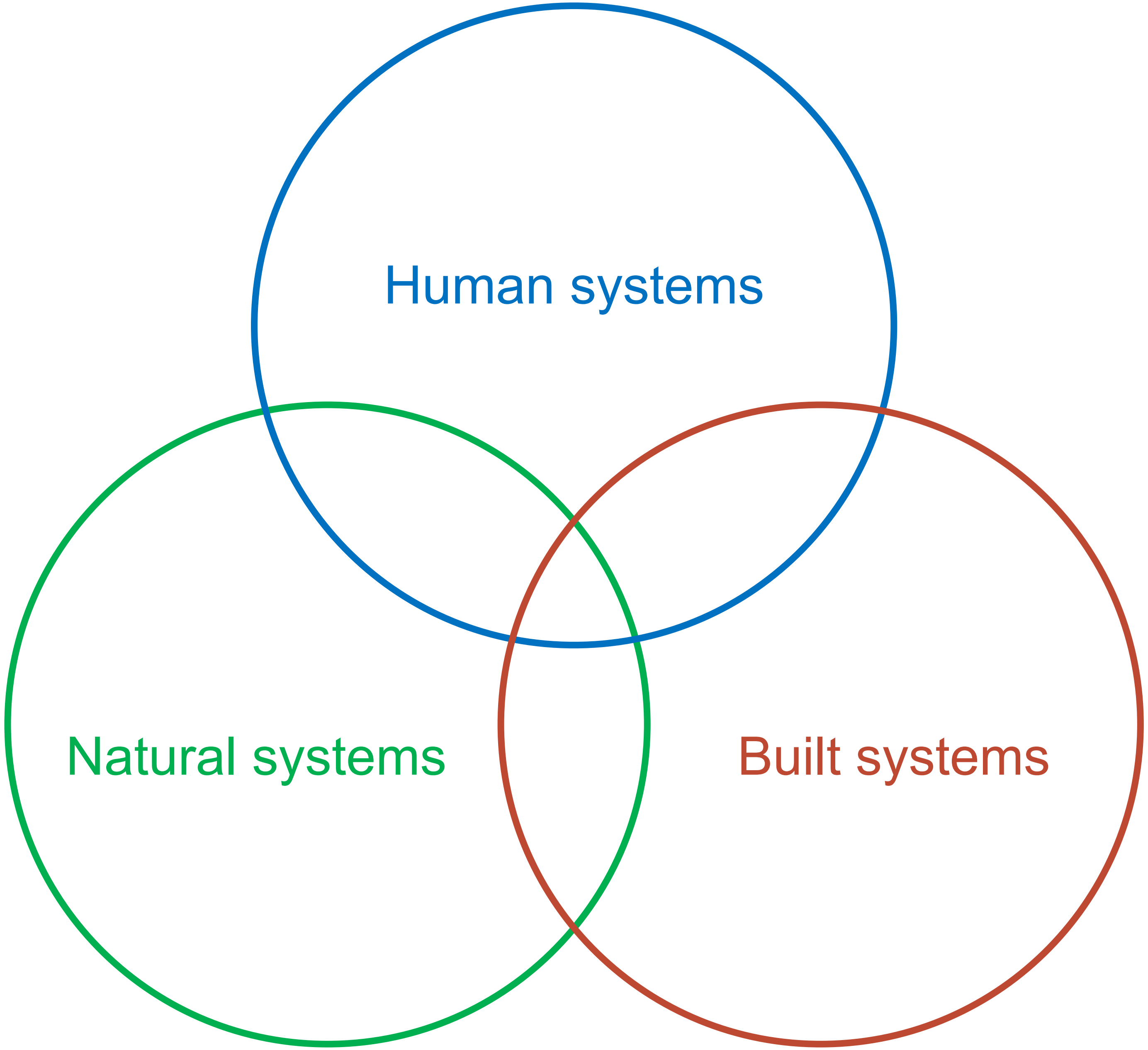
CIVIL 534: Computational systems thinking for sustainable engineering

21 May 2025

Outline

- Sustainability indicators
- Application example: Epidemic spread
  - Network model
  - Systems thinking model
  - Data-driven decision-making and sensitivity analysis
- Course wrap-up
- Project final presentation next week
  - Consultations after class today
- My office hours today are cancelled - email me if you would like to meet

Urban systems definitions



Measuring sustainability of urban systems

- Human systems
  - Gross domestic product
  - Human development index
  - Happiness index
  - …
- Natural systems
  - Biodiversity
  - Ecological footprint
- Built systems
  - ?

Human development index

Need a **simple** composite measures of human development that goes beyond economic advances and captures **human well-being**
Per capita GDP isn't enough!!!

Human development index

HDI = healthy life + education + standard of living

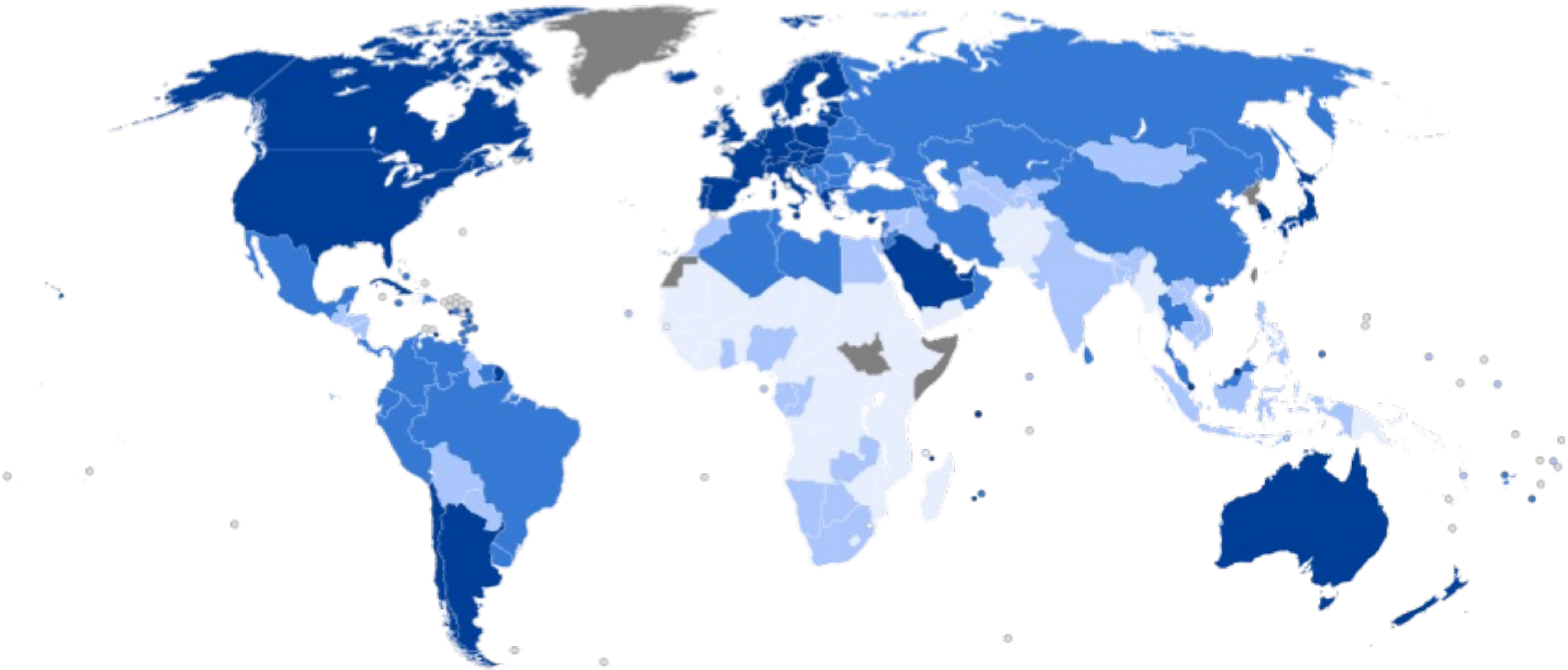
Life expectancy index = $\frac{LE-20}{85-20}$

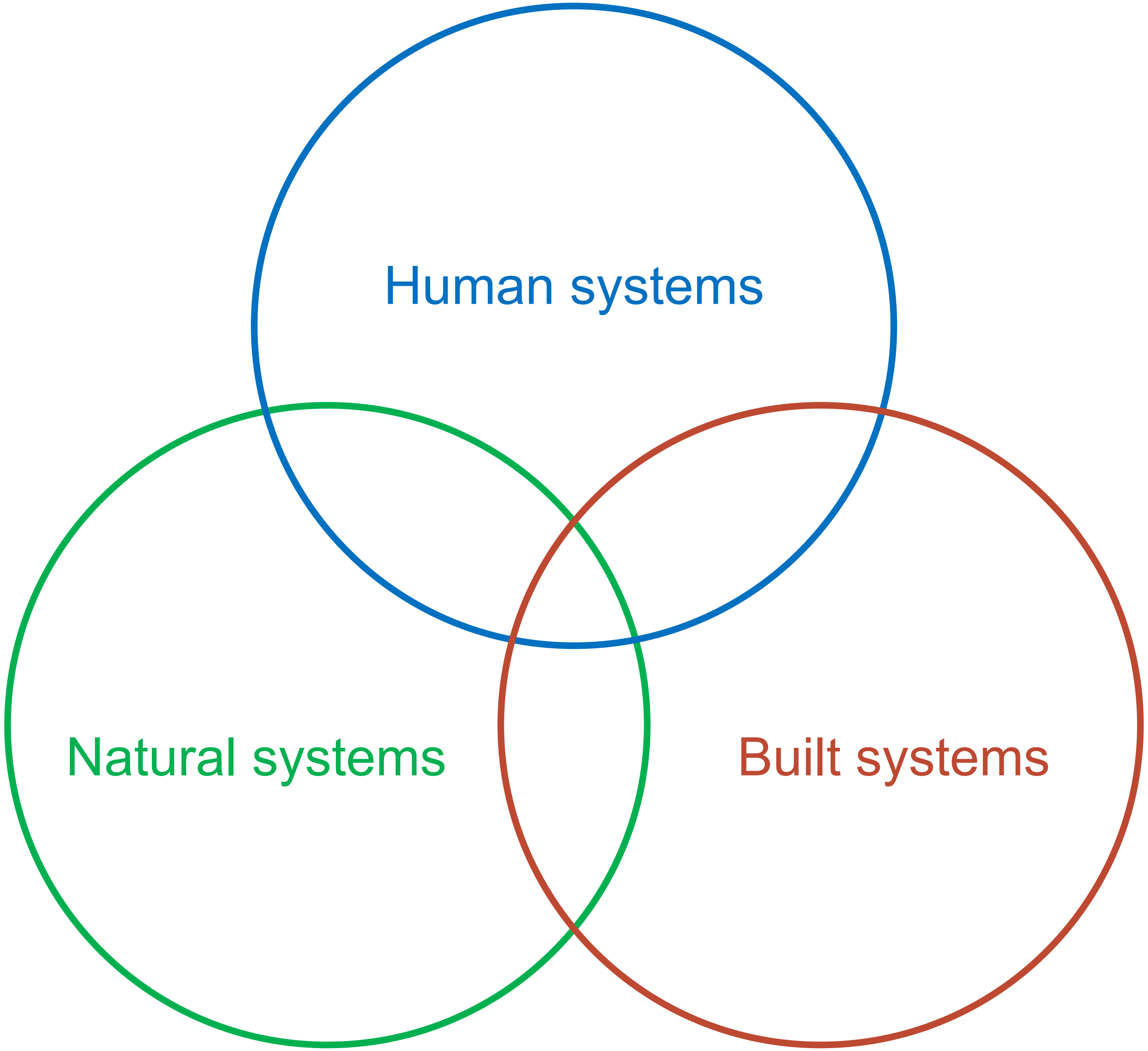
Education index = $\frac{\frac{MYS}{15}+\frac{EYS}{18}}{2}$

Income index = $\frac{\ln(GNI_{pc})-\ln(100)}{\ln(75{,}000)-\ln(100)}$

HDI = $(LEI * EI * II)^{1/3}$

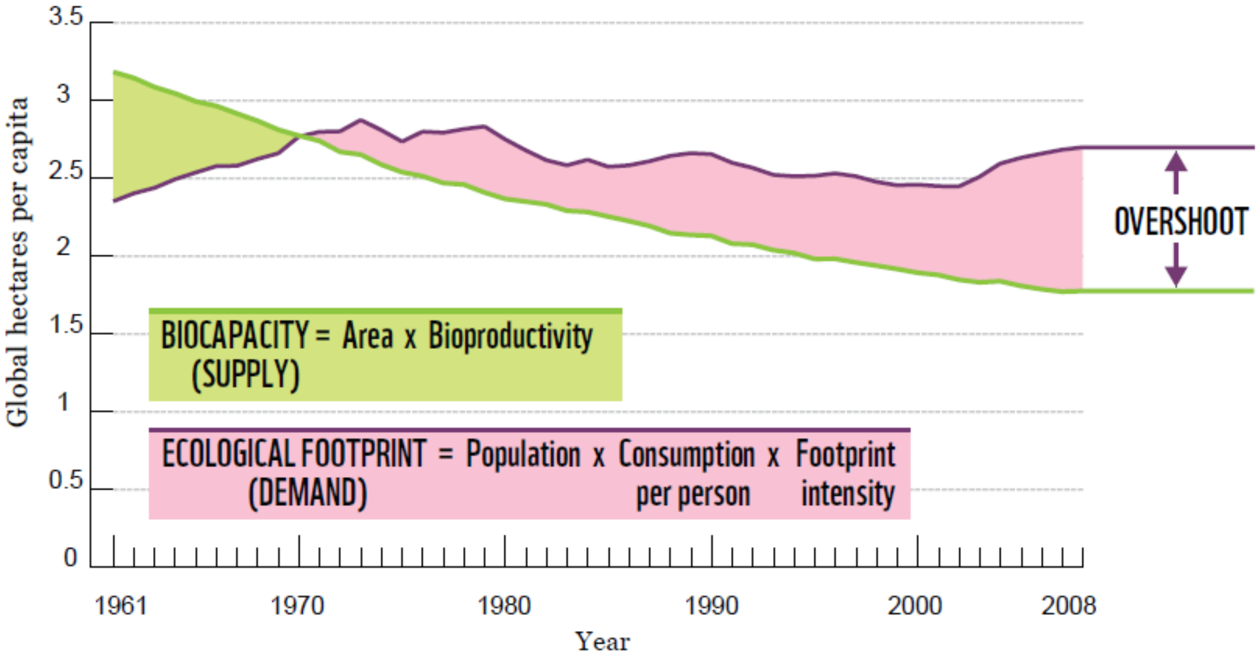
Human development index




Human systems
Natural systems
Built systems

Ecological footprint

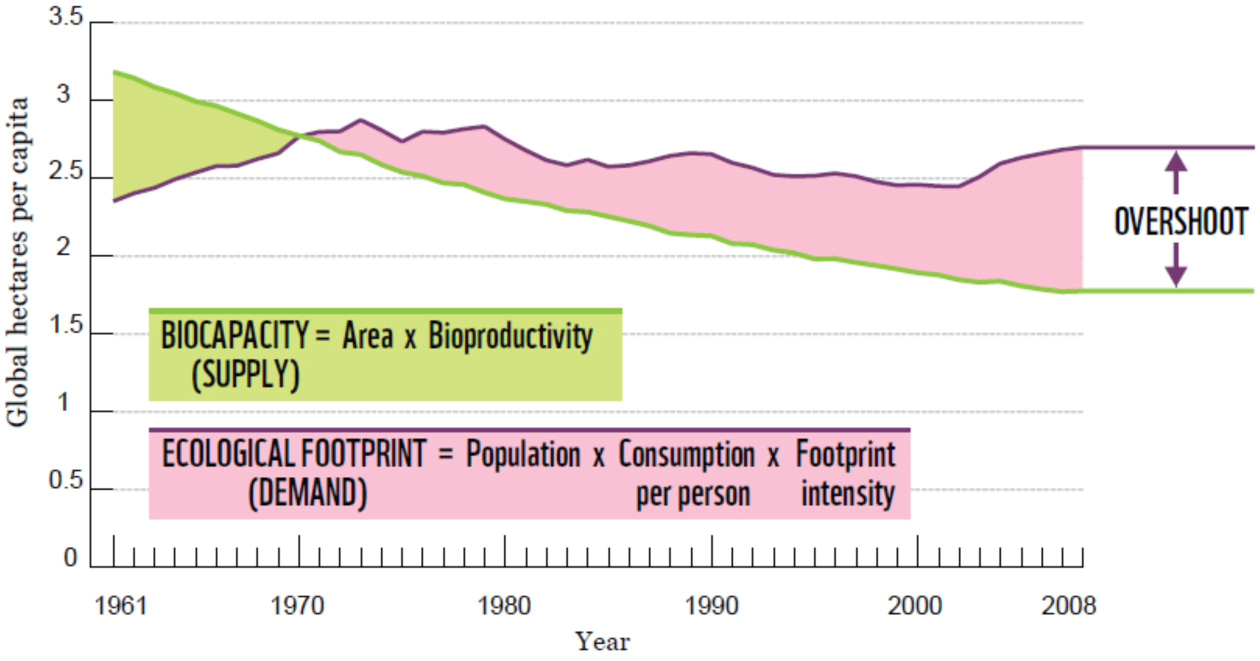
- The Ecological Footprint tracks the area of biologically productive land and water required to provide the renewable resources people use, and includes the space needed for infrastructure and vegetation to absorb waste carbon dioxide (CO_2)
- The Ecological Footprint has 6 components (carbon, forest, grazing, fishing, cropland, built-up environment)



Sources: Prof. Eloi Laurent & WWF

Ecological footprint

- Biocapacity is the total regenerative capacity available to serve the demand represented by the Footprint
- Both are expressed in units called global hectares (gha), with 1gha representing the productive capacity of 1ha of land at world average productivity.



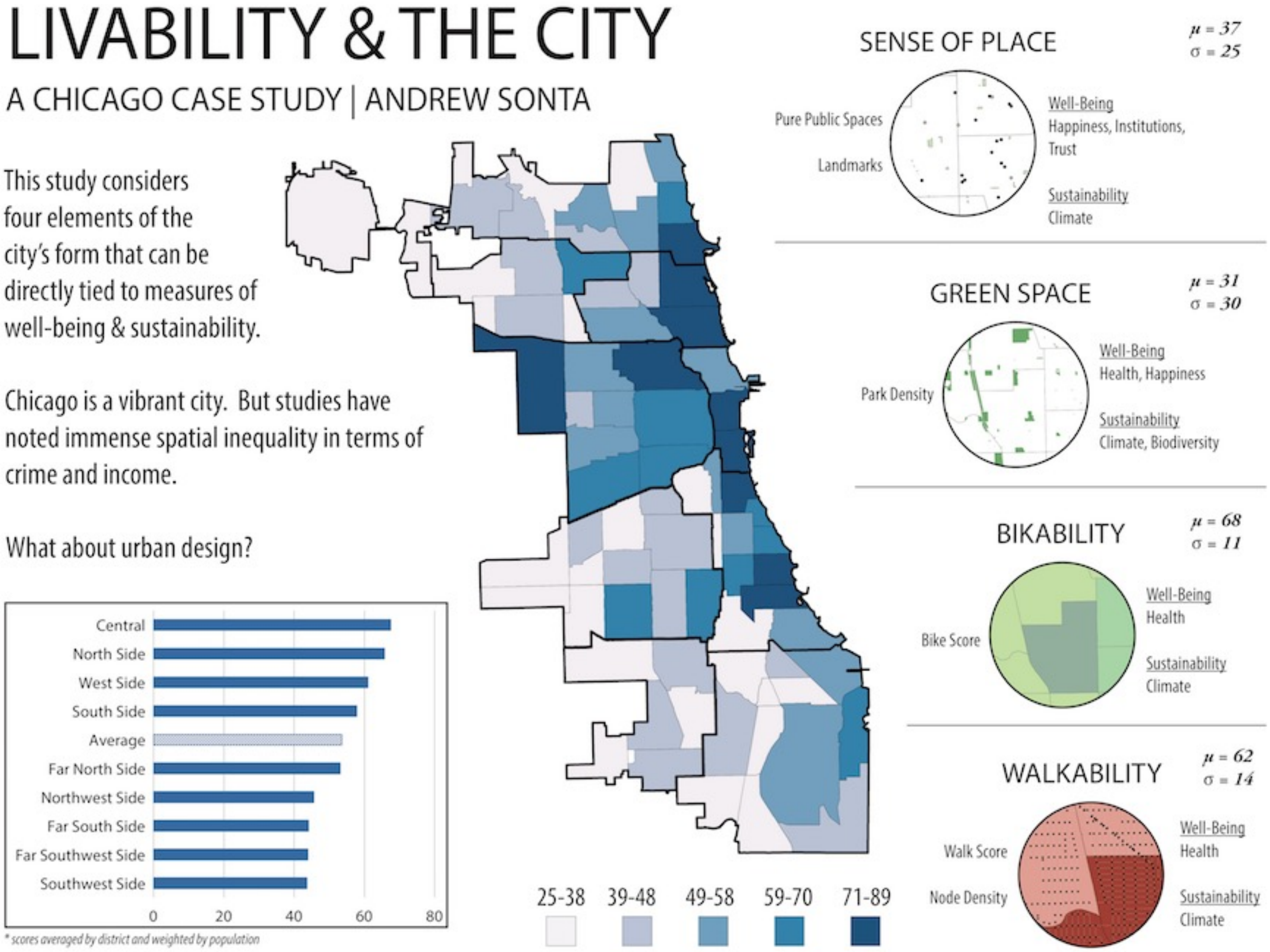
Sources: Prof. Eloi Laurent & WWF

Ecological footprint

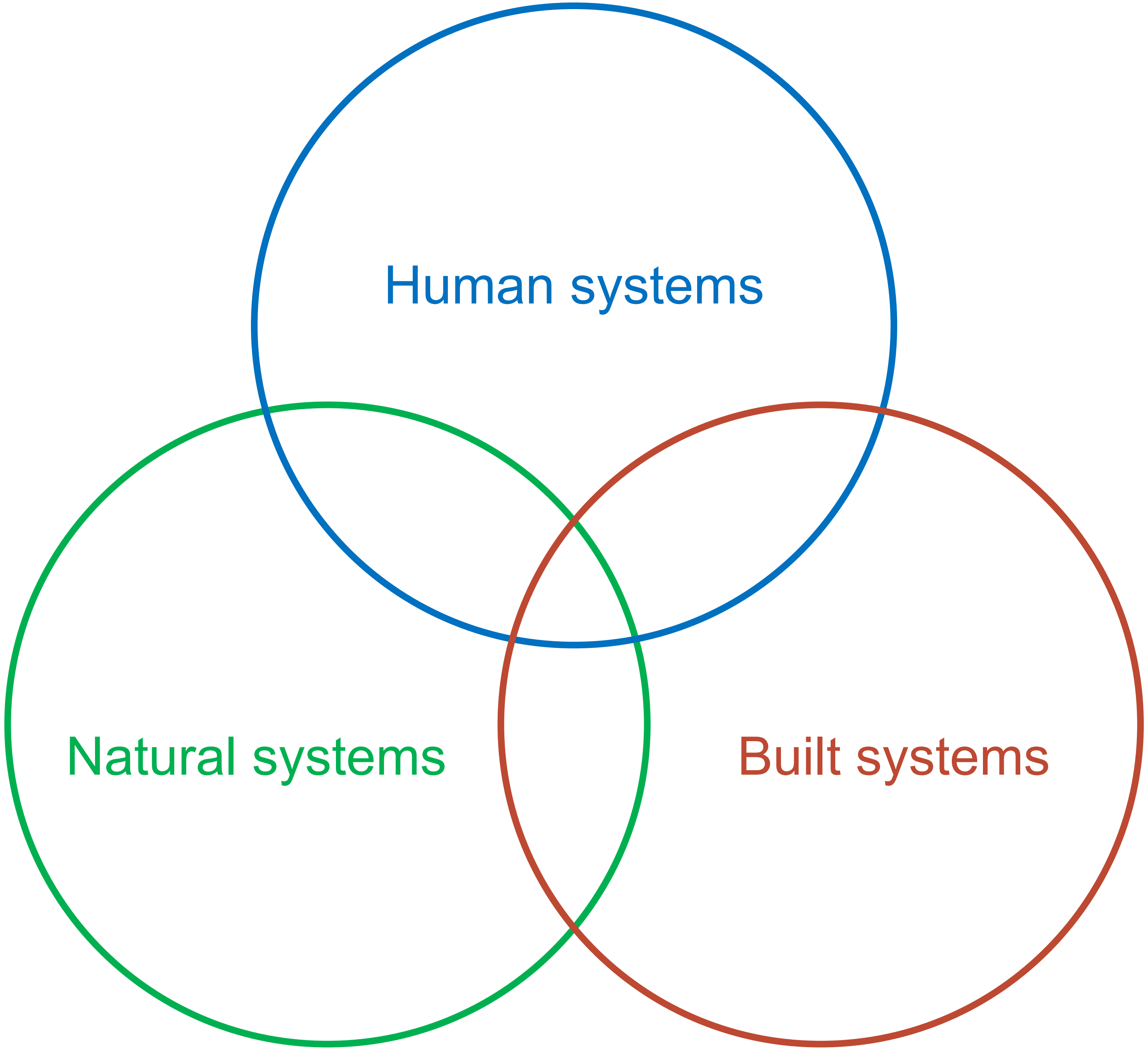
- Many online tools
- I did my own rough calculation on: https://www.footprintcalculator.org/en

Built environment indicators

- Some of my research from graduate school…



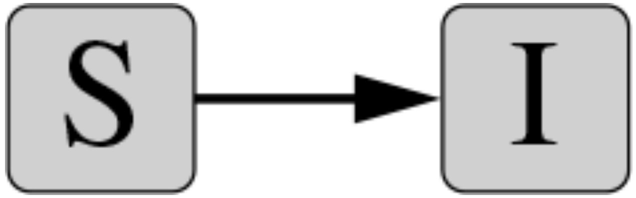
Intersections?



Cascading behavior on networks

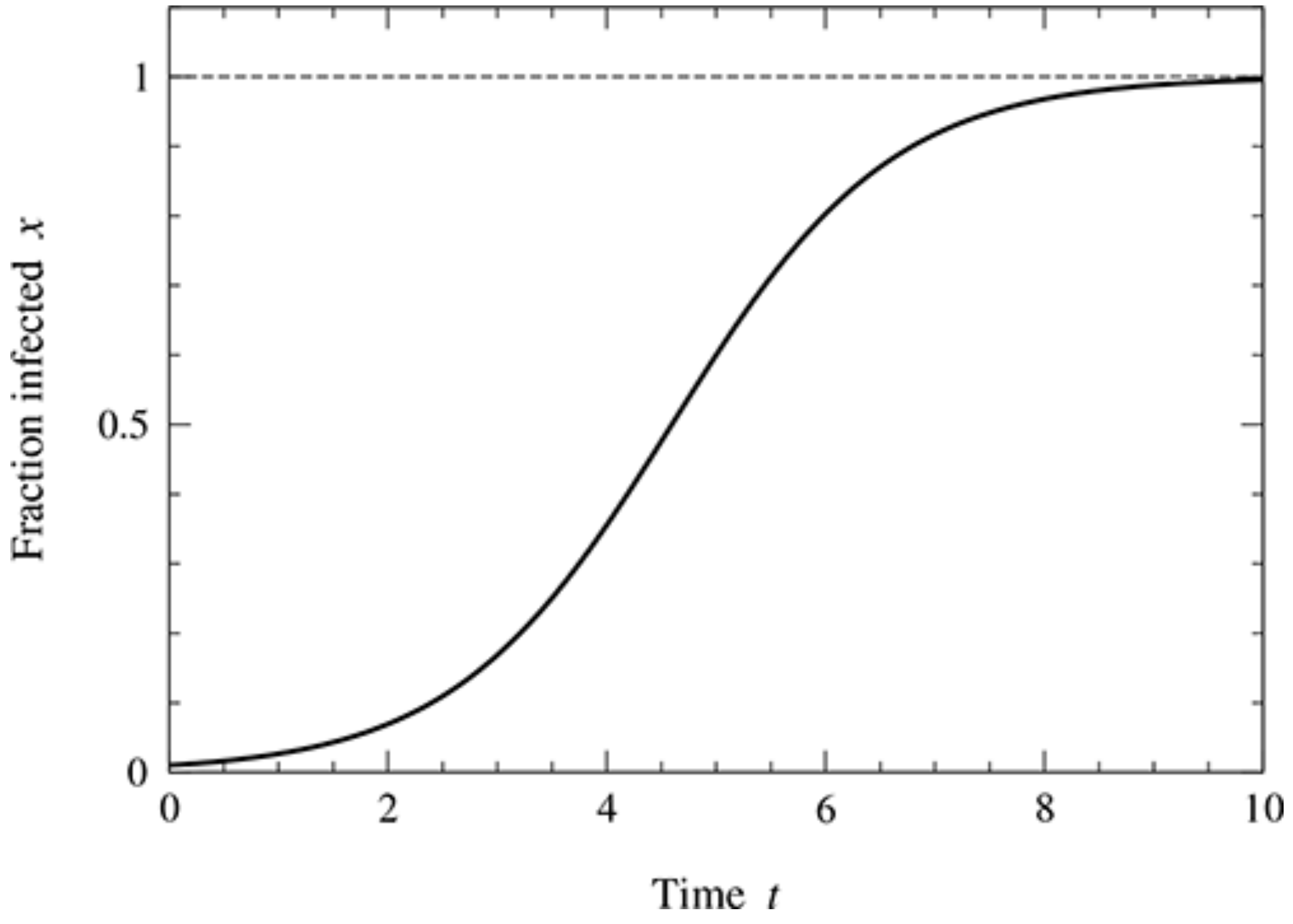
- AKA "spreading"
- Behaviors that cascade from node to node like an epidemic
- Examples
  - Biological (e.g. COVID-19)
  - Technological (e.g. cascading failures on a power grid)
    → how nodes fail and recover over time
  - Social (e.g. rumors, viral marketing)

Let’s start with the theory



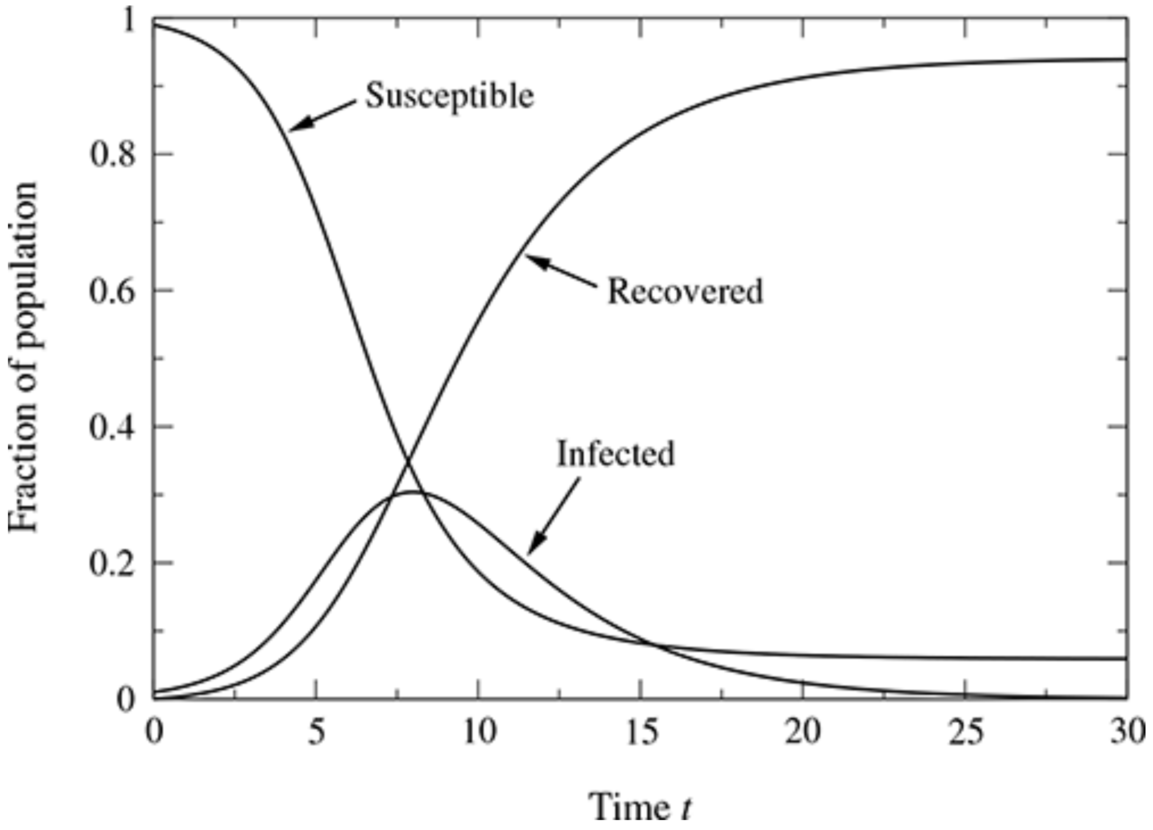
- Model 1: SI model
  - S(t) = # of nodes “susceptible” at time t
  - X(t) = # of nodes “infected” at time t
  - n = total population
  - S = susceptible
  - X = infected
  - β = # of contacts
- Nodes can only be infected when they come into contact with other nodes

SI model gives us classic logistic growth



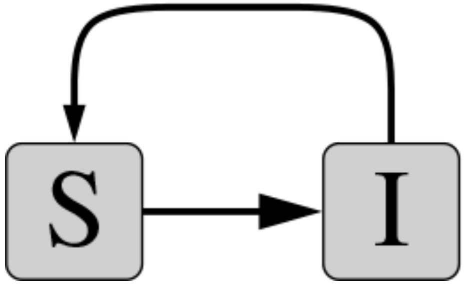
SIR model

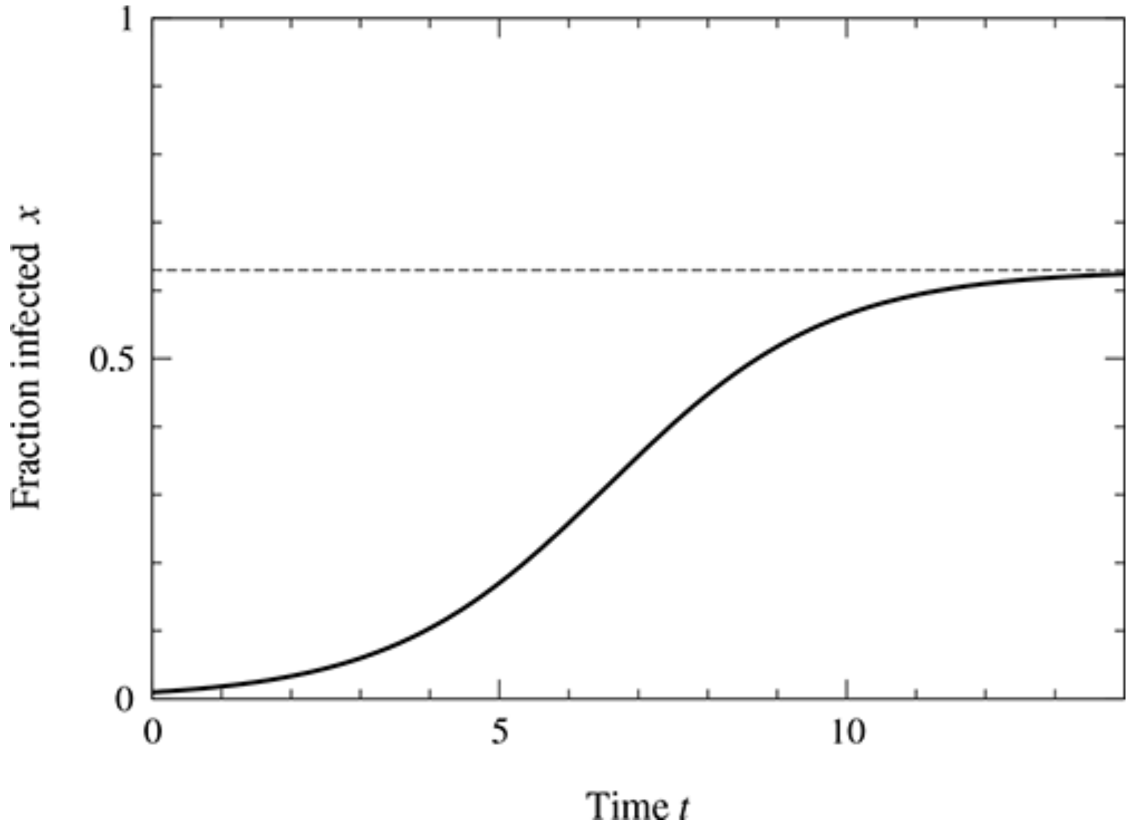
- Model 2: SIR model
  - R(t) = # of nodes that are recovered



SIS model

- Model 3: SIS model
  - Nodes that are infected and recover become susceptible again





Cascading behavior and systems thinking

- These models can easily be implemented as systems thinking models
- Your task: SIR model that explicitly considers the fatality rate
  - One could call it an SI(R/D) model where infected nodes either recover or die
  - Create a systems diagram first!
  - Then code it up
  - Parameters:
    - 10,000 members of the population
    - Initially 1 is infected and 9,999 are susceptible
    - Each infected person contacts 2 random others
    - 40% of those contacted are infected
    - 10% of those infected die
    - At each time step, 20% of those infected either recover or die (it takes time)

What does this model miss?

- Network characteristics!
- Contacts are not “random,” they usually depend on the network structure
- Example: cascading failure in a power grid
- Let’s model it!

Sensitivity analysis

- How does uncertainty in model parameters result create uncertainty in model output?
- Which parameters have the biggest influence?
- Simplest process:
  - Vary one parameter by ±X%, keeping the others constant
  - Repeat for other parameters

By the end of this course, you will be able to…

- Identify the characteristics of **complex systems** in **engineered urban infrastructure**
  - Use two tools: **systems thinking** and **network analysis**
- Model complex system dynamics using **computational tools** (in Python)
- Develop an understanding of common system behaviors including opportunities for **interventions**
- Understand network analysis **tools and metrics**
- **Apply** network analysis tools to urban systems
- Expand your decision-making toolbox for **improving sustainability and resilience** of engineered urban infrastructure

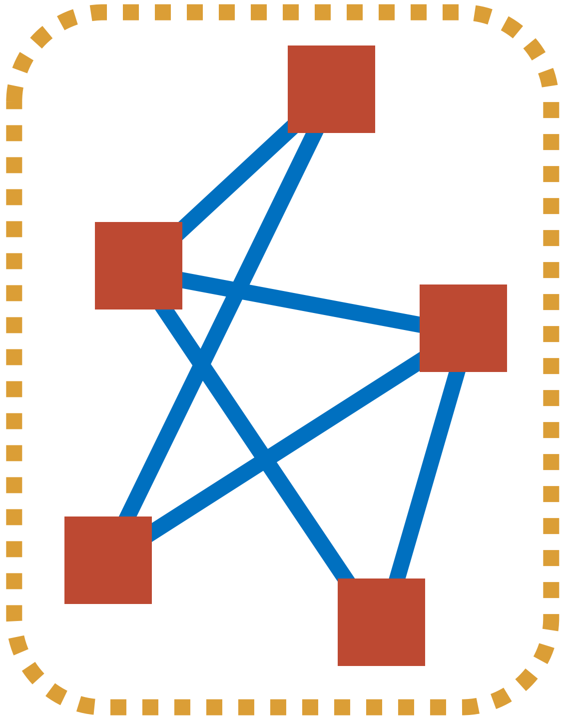
Identify the characteristics of complex systems in engineered urban infrastructure

A system is…

a set of elements

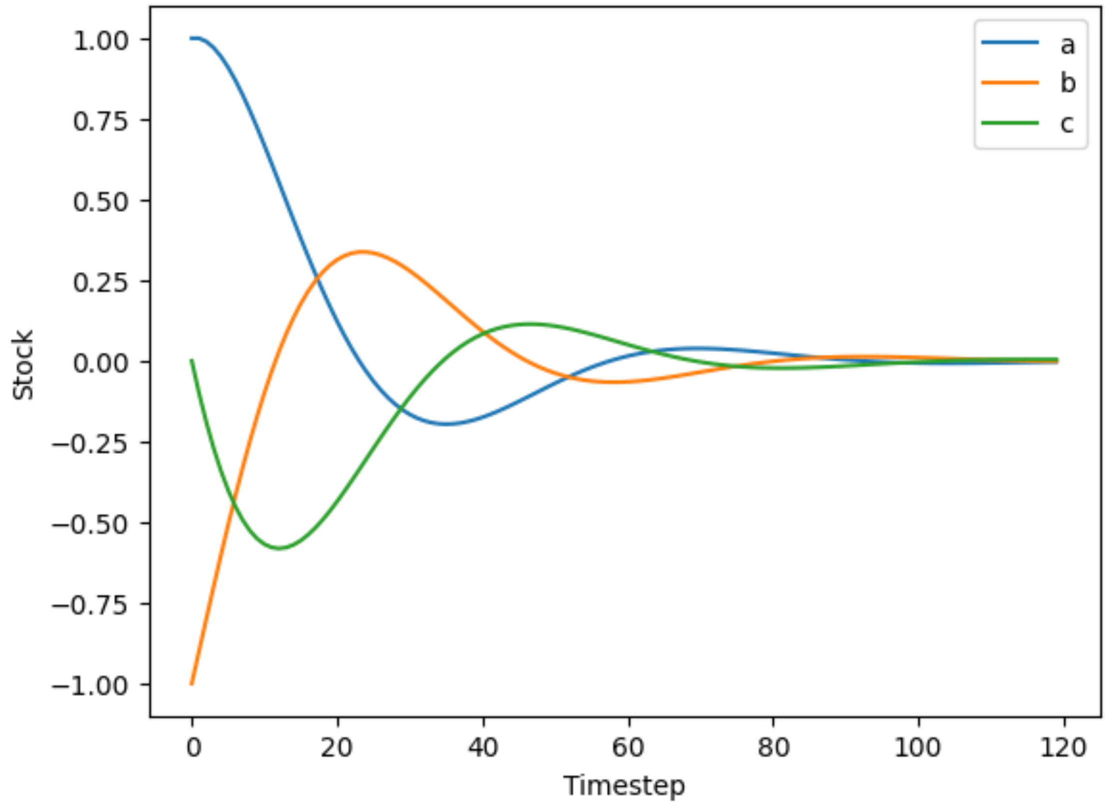
interconnected coherently organized

in a way that achieves something

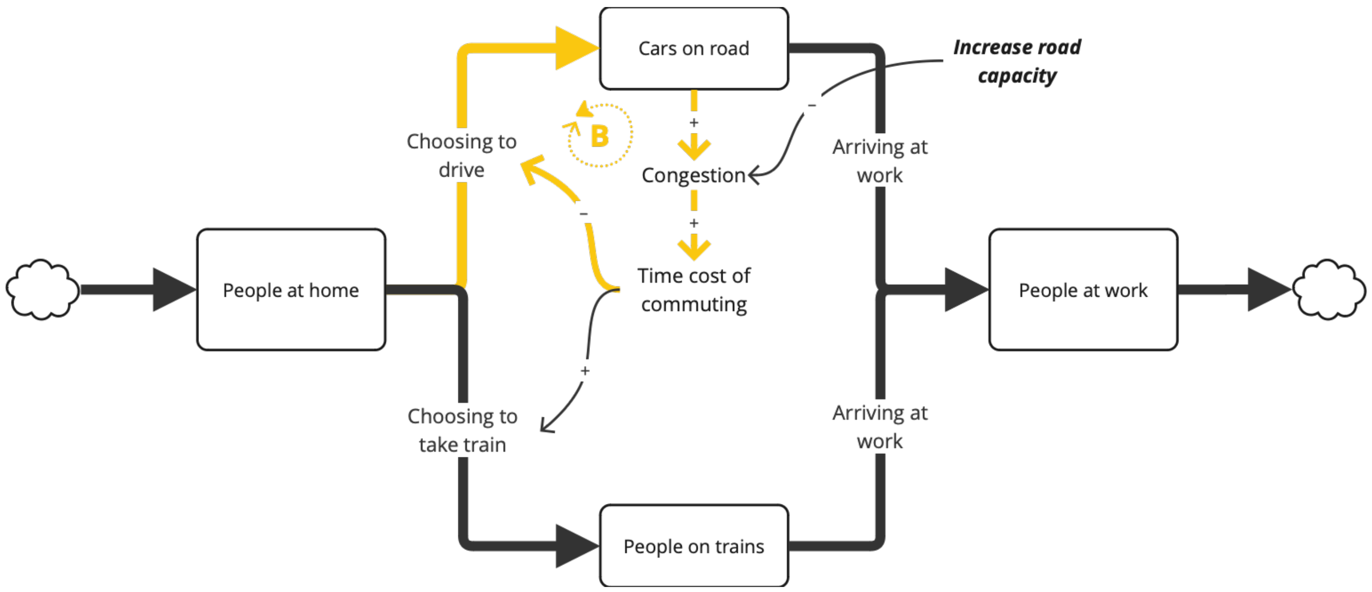


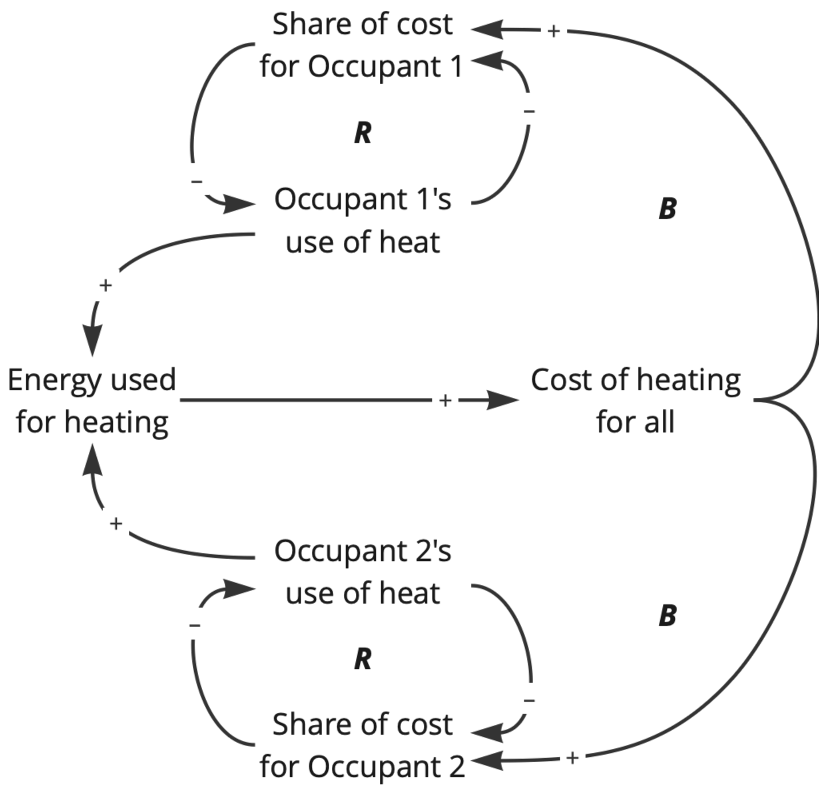
- Multiple parts without interdependencies are just collections
- The structure helps to drive the system toward its purpose

Model complex system dynamics using computational tools (in Python)

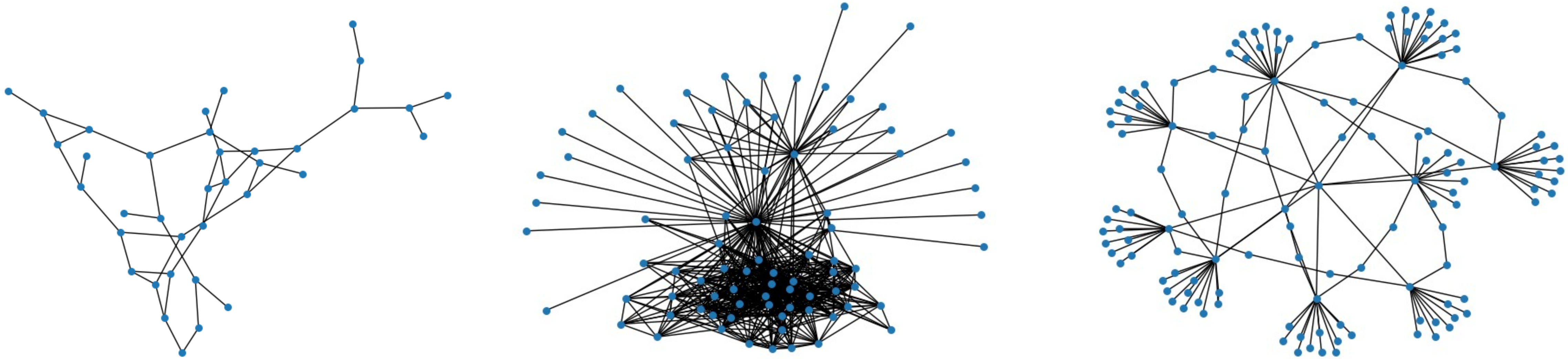


Develop an understanding of common system behaviors including opportunities for interventions

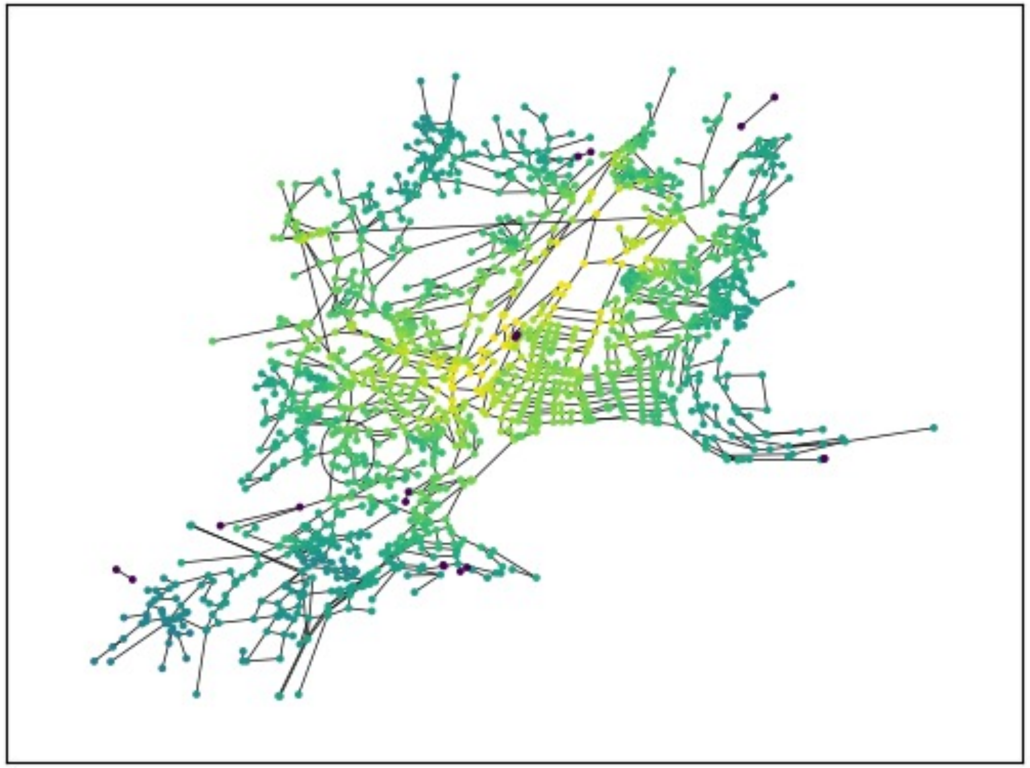


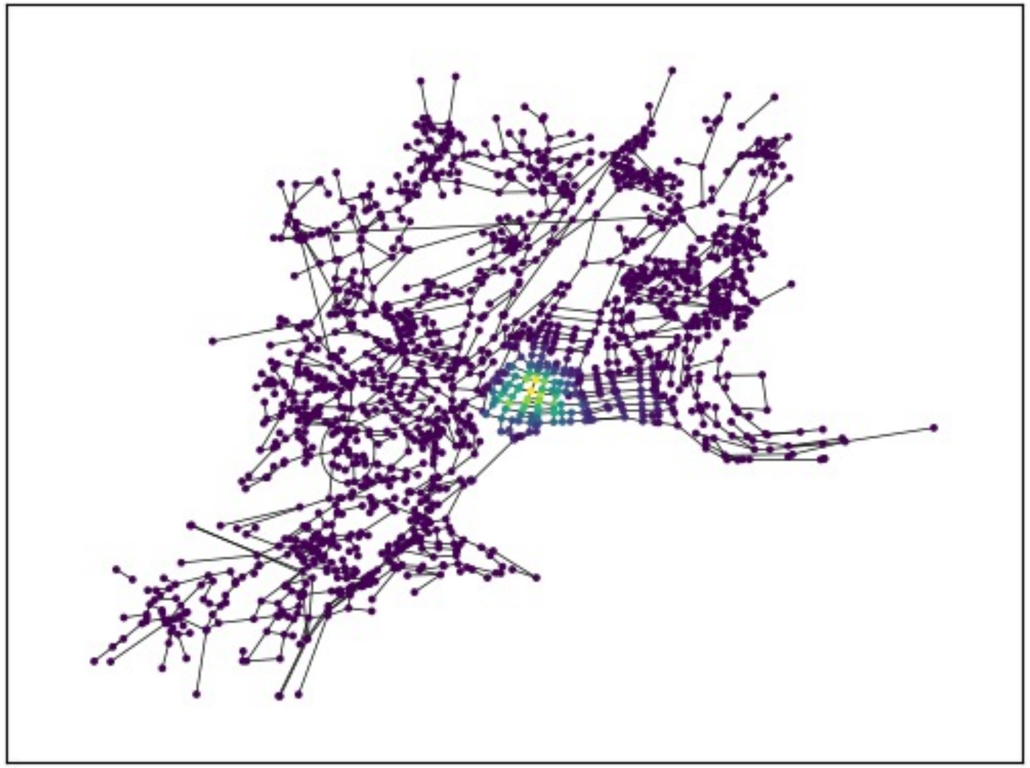


Understand network analysis tools and metrics



Apply network analysis tools to urban systems





Expand your decision-making toolbox for improving sustainability and resilience of engineered urban infrastructure