Lecture 01
Course introduction

Andrew Sonta

CIVIL 534: Computational systems thinking for sustainable engineering

19 February 2025

Today’s objectives

- Introduce myself and the lab
- Introduce the course
- Introduce yourselves
- Discuss the course structure and syllabus
    - Course information, schedule, assignments, project, expectations
- Introduce the course topics

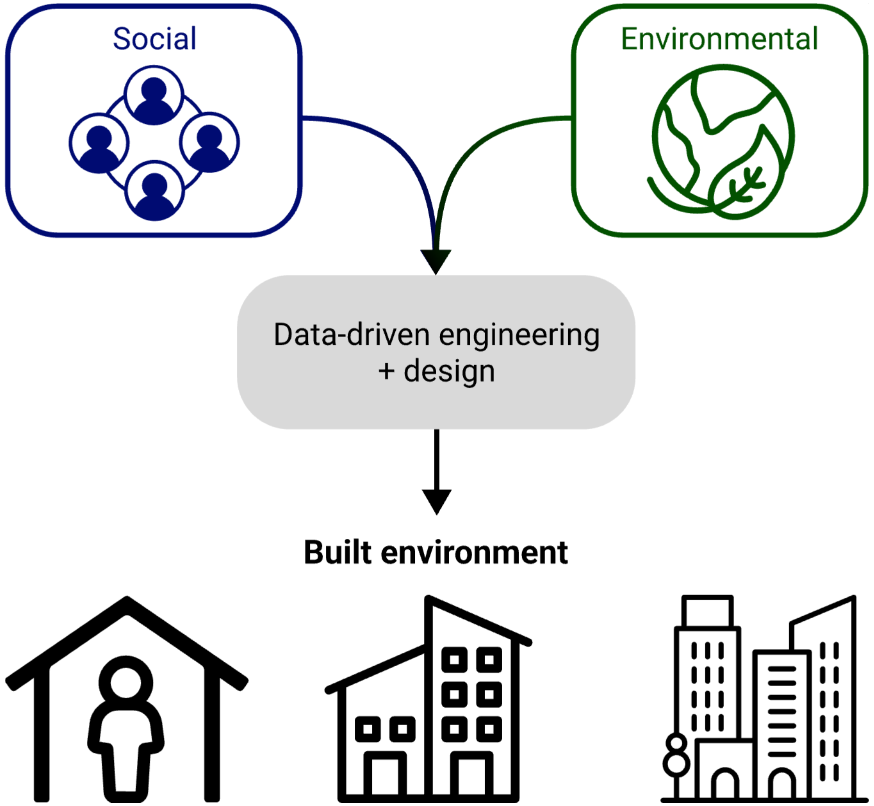
Andrew Sonta

Tenure-Track Assistant Professor
September 2022 – present

Previously:
- Postdoc, Columbia University, Data Science Institute
- PhD, Stanford University, Civil and Environmental Engineering

ETHOS Lab

Engineering and Technology for Human Oriented Sustainability



Research vision

Using **data**, **engineering**, and **design** to create interventions in the built environment that integrate our **social** and **environmental** goals.

Teaching team

Kanaha Shoji, PhD Student, ETHOS Lab

kanaha.shoji@epfl.ch

Will primarily support lecture content and assignments

Vasantha Ramani, Postdoc, ETHOS Lab

vasantha.ramani@epfl.ch

Will primarily support the course project

ETHOS research areas

Occupants in buildings

Inferring, analyzing, and optimizing human-building interactions.

See more

Social analysis of urban form

Studying the relationships between walkable urban form and social characteristics in cities and neighbourhoods.

See more

Urban-scale energy systems

Extending the concepts of social and environmental integration to urban-scale systems

See more

ETHOS: located on Fribourg campus

New building coming soon…

At a high level, what is this course about?

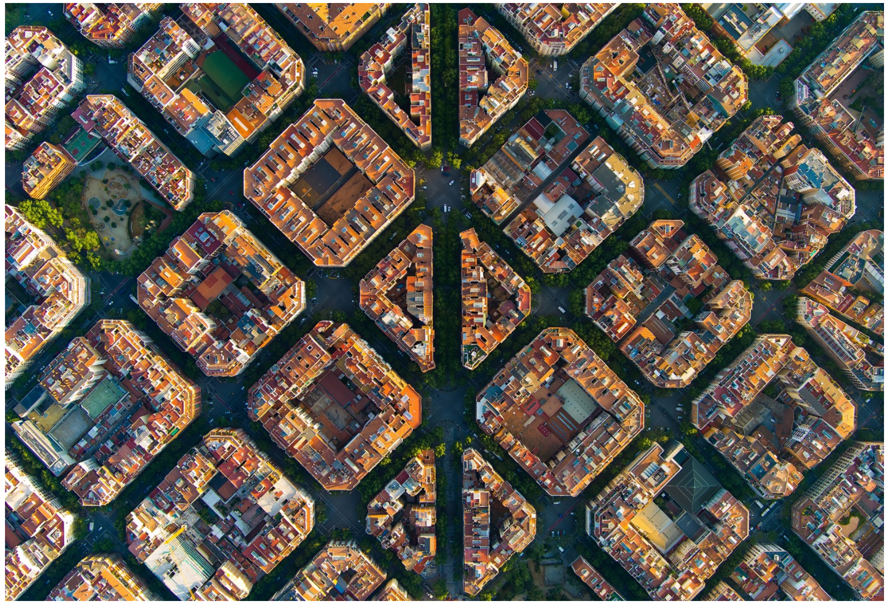
- It is about systems, relationships, and complexity in the engineering of the built environment
- What is a system?
- What is a relationship?
- What is complexity?

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

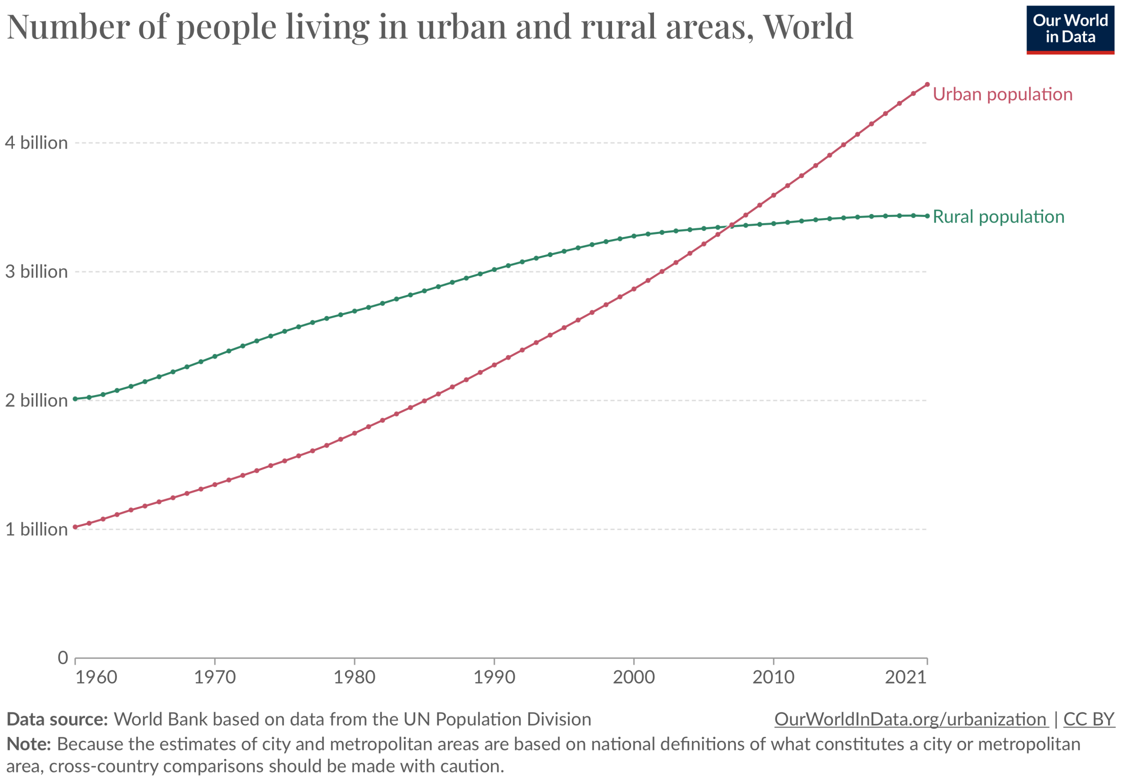
- Identify the characteristics of **complex systems** in **engineered urban infrastructure**
  - Use two tools: **systems thinking** and **network analysis**
- Model complex system dynamics using **computational tools** (in Python)
- Develop an understanding of common system behaviors including opportunities 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

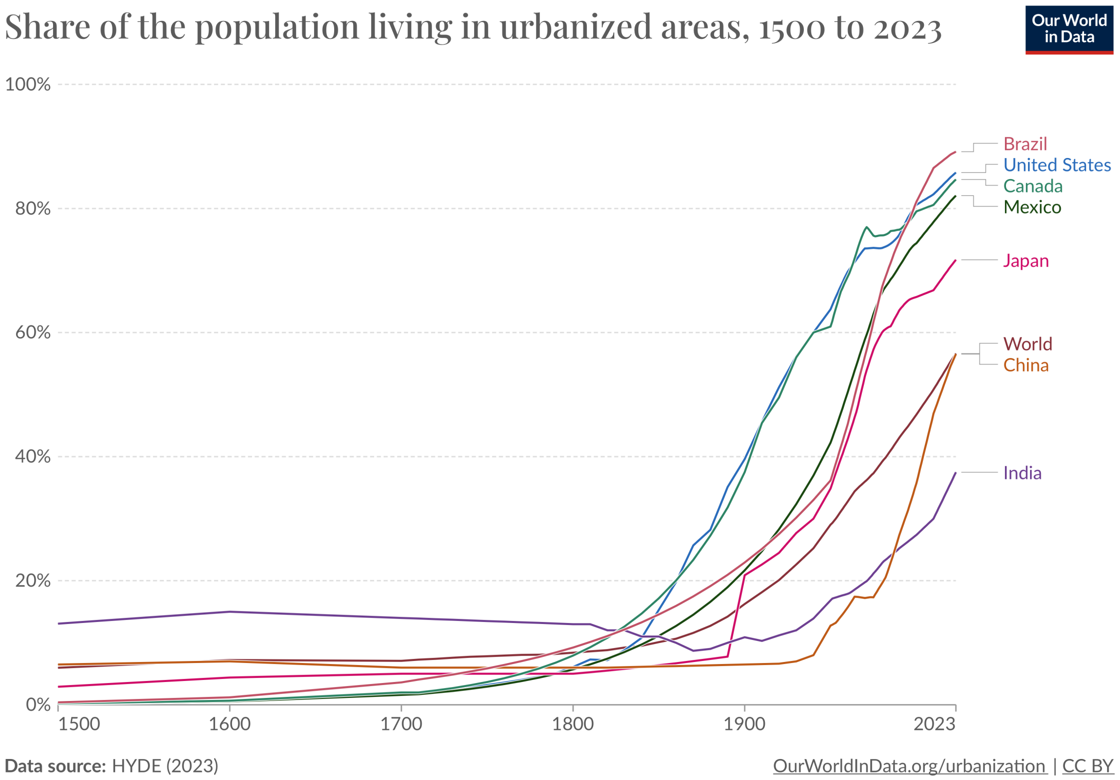
Our context for the course:

Cities

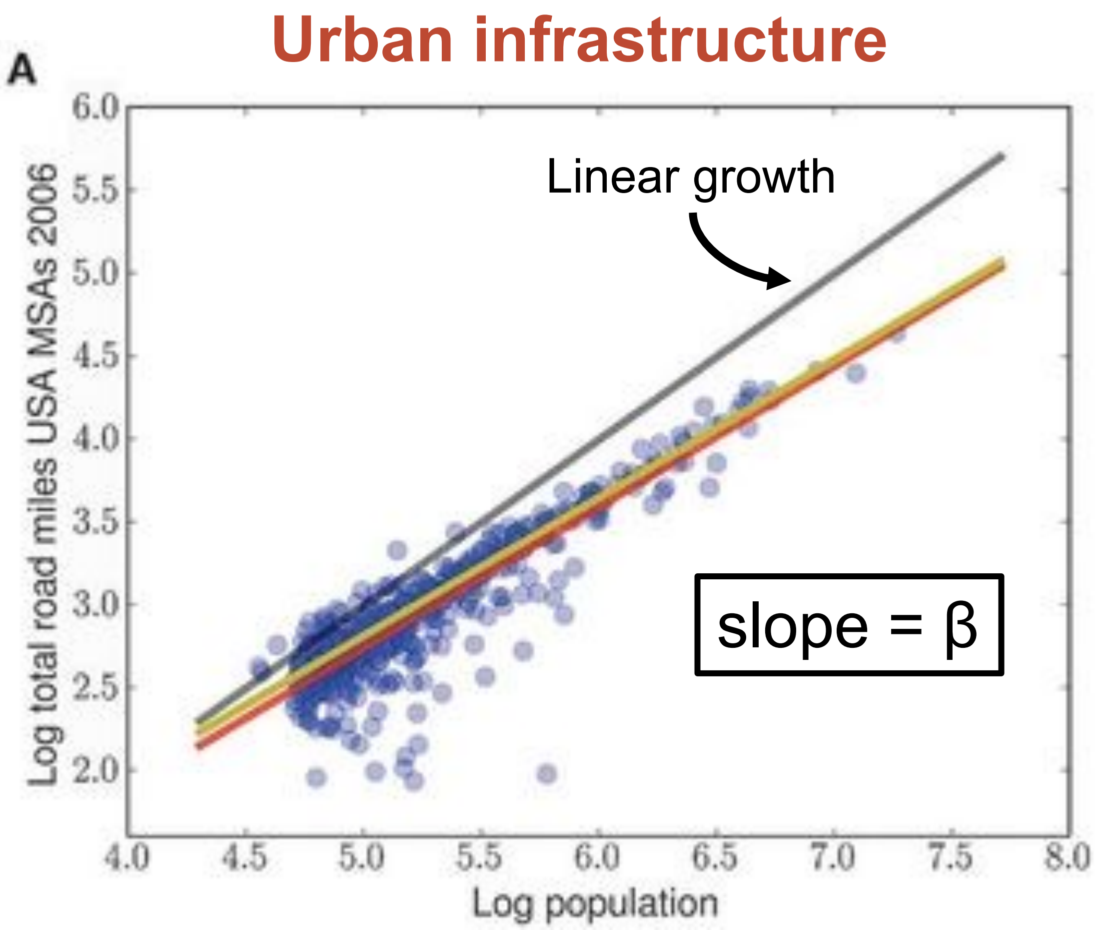



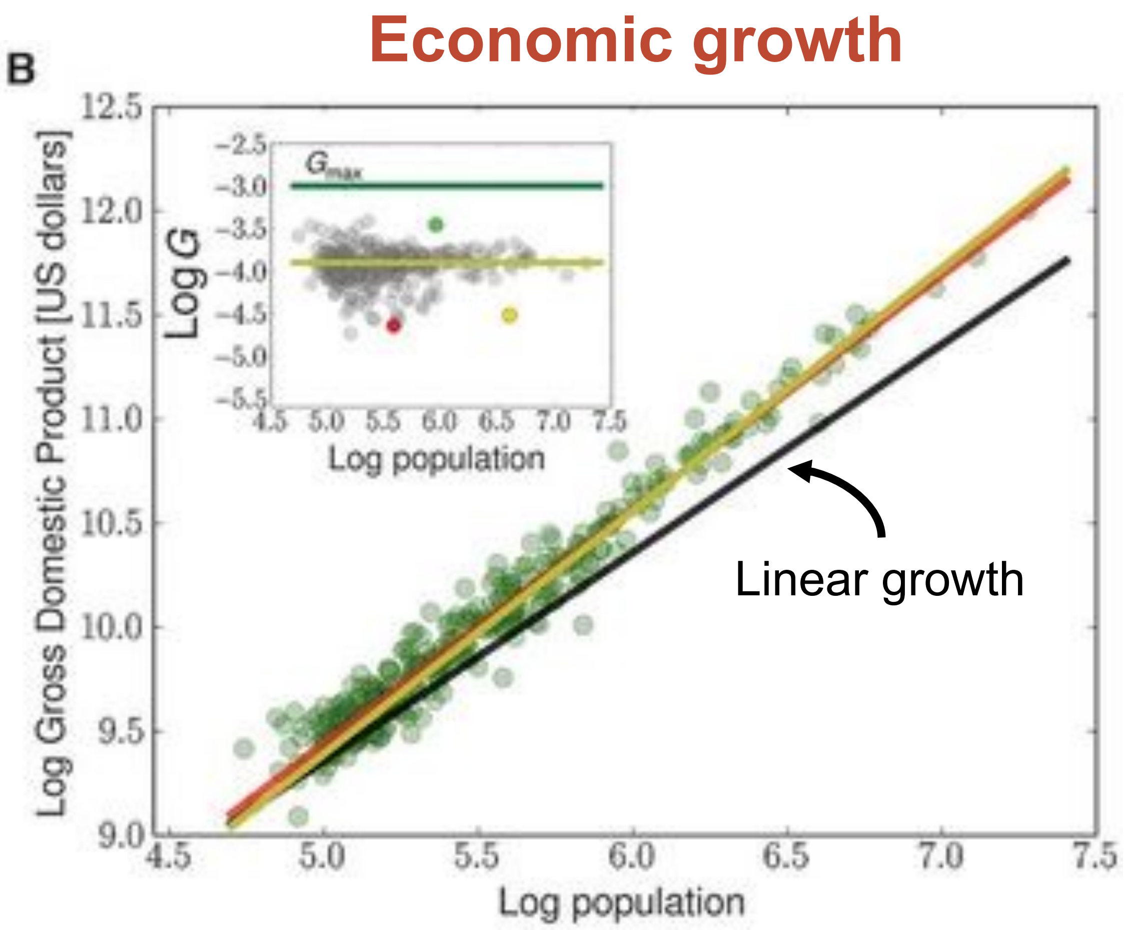
Urbanization and urban growth





Why do cities grow?





Luís M. A. Bettencourt. The Origins of Scaling in Cities. *Science* **340**,1438-1441(2013). DOI:[10.1126/science.1235823](https://doi.org/10.1126/science.1235823)

Why do cities grow?

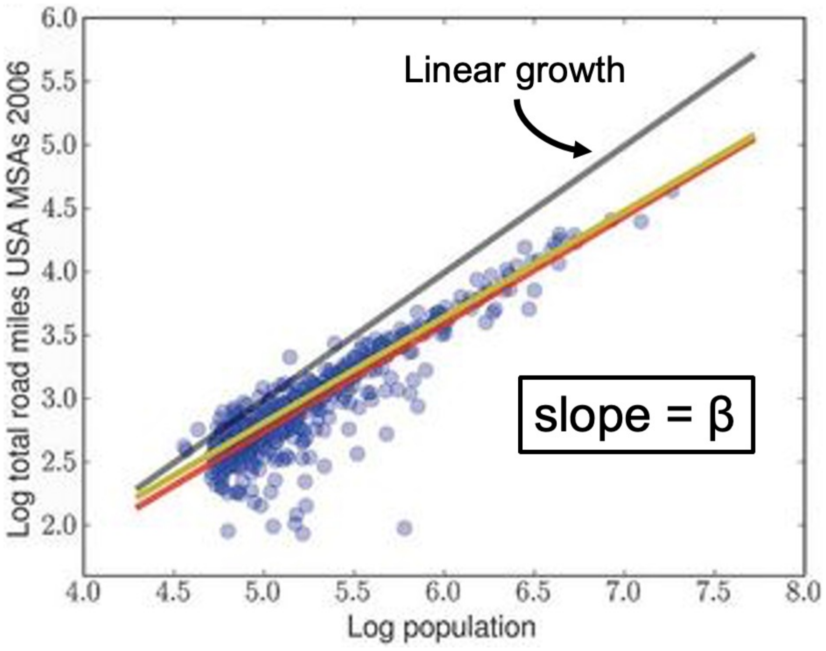


Table 2. Classification of scaling exponents for urban properties and their implications for growth

Scaling exponent	Driving force	Organization	Growth
$\beta < 1$	Optimization, efficiency	Biological	Sigmoidal: long-term population limit
$\beta > 1$	Creation of information, wealth and resources	Sociological	Boom/collapse: finite-time singularity/unbounded growth; accelerating growth rates/discontinuities
$\beta = 1$	Individual maintenance	Individual	Exponential

Bettencourt et al. 2007. https://doi.org/10.1073/pnas.0610172104

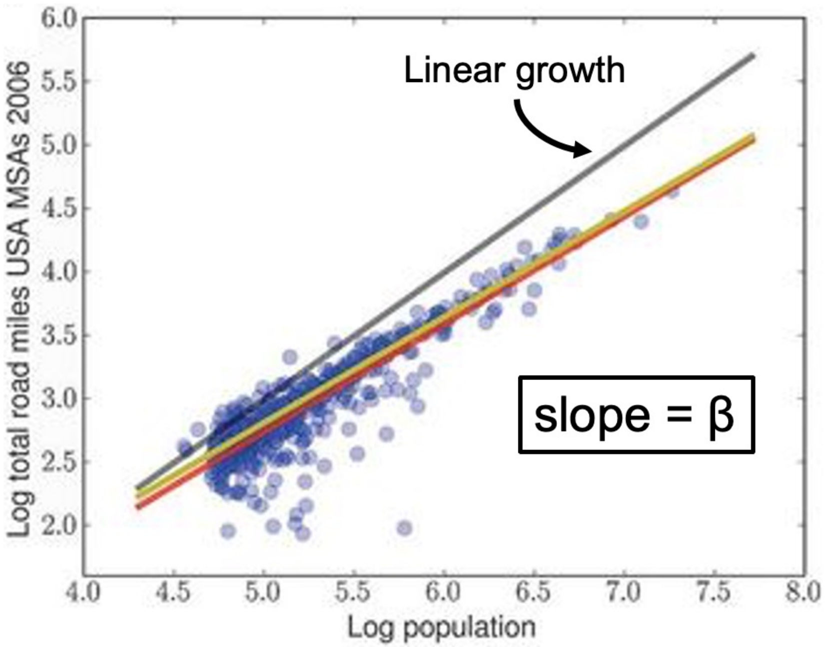
Why do cities grow?

Table 1. Scaling exponents for urban indicators vs. city size

Y	β	95% CI	Adj-R^2	Observations	Country–year
New patents	1.27	[1.25,1.29]	0.72	331	U.S. 2001
Inventors	1.25	[1.22,1.27]	0.76	331	U.S. 2001
Private R&D employment	1.34	[1.29,1.39]	0.92	266	U.S. 2002
"Supercreative" employment	1.15	[1.11,1.18]	0.89	287	U.S. 2003
R&D establishments	1.19	[1.14,1.22]	0.77	287	U.S. 1997
R&D employment	1.26	[1.18,1.43]	0.93	295	China 2002
Total wages	1.12	[1.09,1.13]	0.96	361	U.S. 2002
Total bank deposits	1.08	[1.03,1.11]	0.91	267	U.S. 1996
GDP	1.15	[1.06,1.23]	0.96	295	China 2002
GDP	1.26	[1.09,1.46]	0.64	196	EU 1999–2003
GDP	1.13	[1.03,1.23]	0.94	37	Germany 2003
Total electrical consumption	1.07	[1.03,1.11]	0.88	392	Germany 2002
New AIDS cases	1.23	[1.18,1.29]	0.76	93	U.S. 2002–2003
Serious crimes	1.16	[1.11, 1.18]	0.89	287	U.S. 2003
Total housing	1.00	[0.99,1.01]	0.99	316	U.S. 1990
Total employment	1.01	[0.99,1.02]	0.98	331	U.S. 2001
Household electrical consumption	1.00	[0.94,1.06]	0.88	377	Germany 2002
Household electrical consumption	1.05	[0.89,1.22]	0.91	295	China 2002
Household water consumption	1.01	[0.89,1.11]	0.96	295	China 2002
Gasoline stations	0.77	[0.74,0.81]	0.93	318	U.S. 2001
Gasoline sales	0.79	[0.73,0.80]	0.94	318	U.S. 2001
Length of electrical cables	0.87	[0.82,0.92]	0.75	380	Germany 2002
Road surface	0.83	[0.74,0.92]	0.87	29	Germany 2002

β > 1

β < 1



Bettencourt et al. 2007. https://doi.org/10.1073/pnas.0610172104

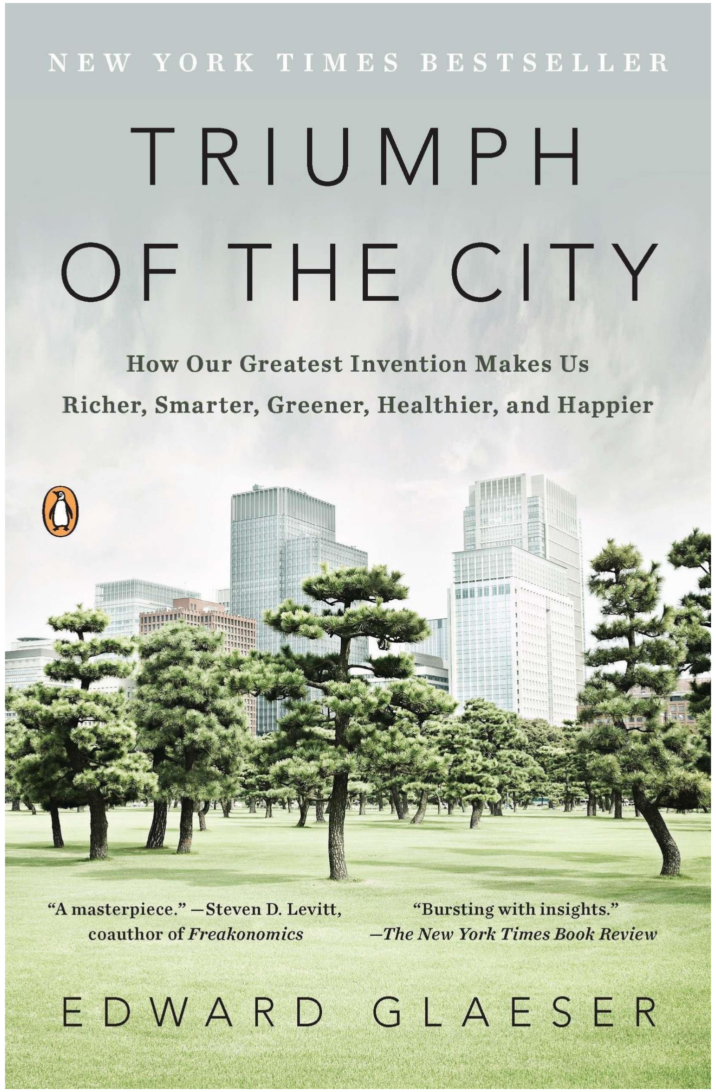
Why do cities grow?

"Cities magnify humanity's strengths"

-Edward Glaeser, Professor of Economics, Harvard

"They spur ***innovation*** *by facilitating face-to-face interaction, they attract talent and sharpen it through competition, they encourage entrepreneurship, and they allow for social and economic mobility."*

-Diana Silver, Asst. Professor of Public Health, NYU (review of Triumph of a City in NY-Times)



Why do you live where you do?

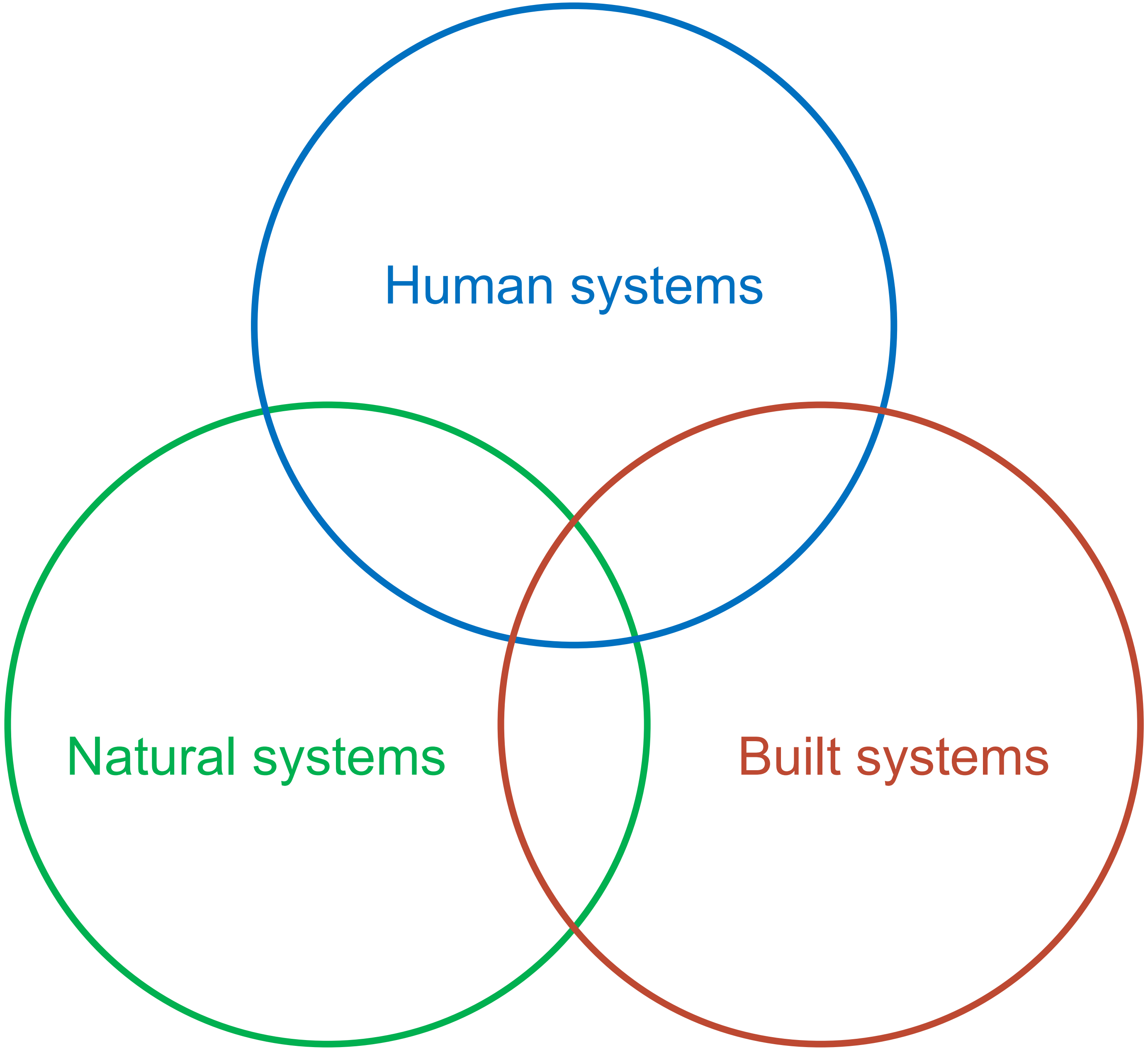
- Think about where you live now, and where you may want to live in the future…

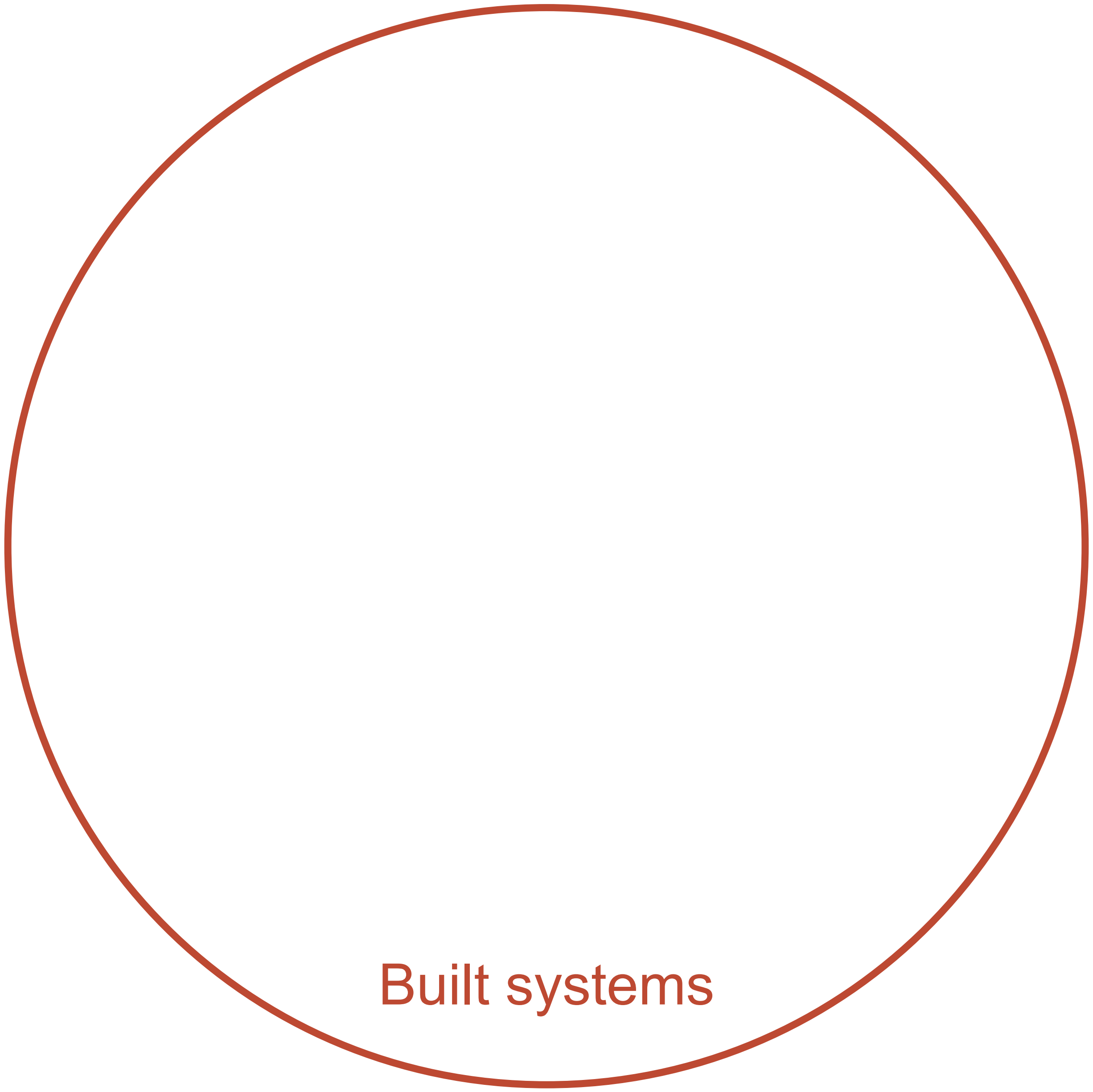
Disciplines involved

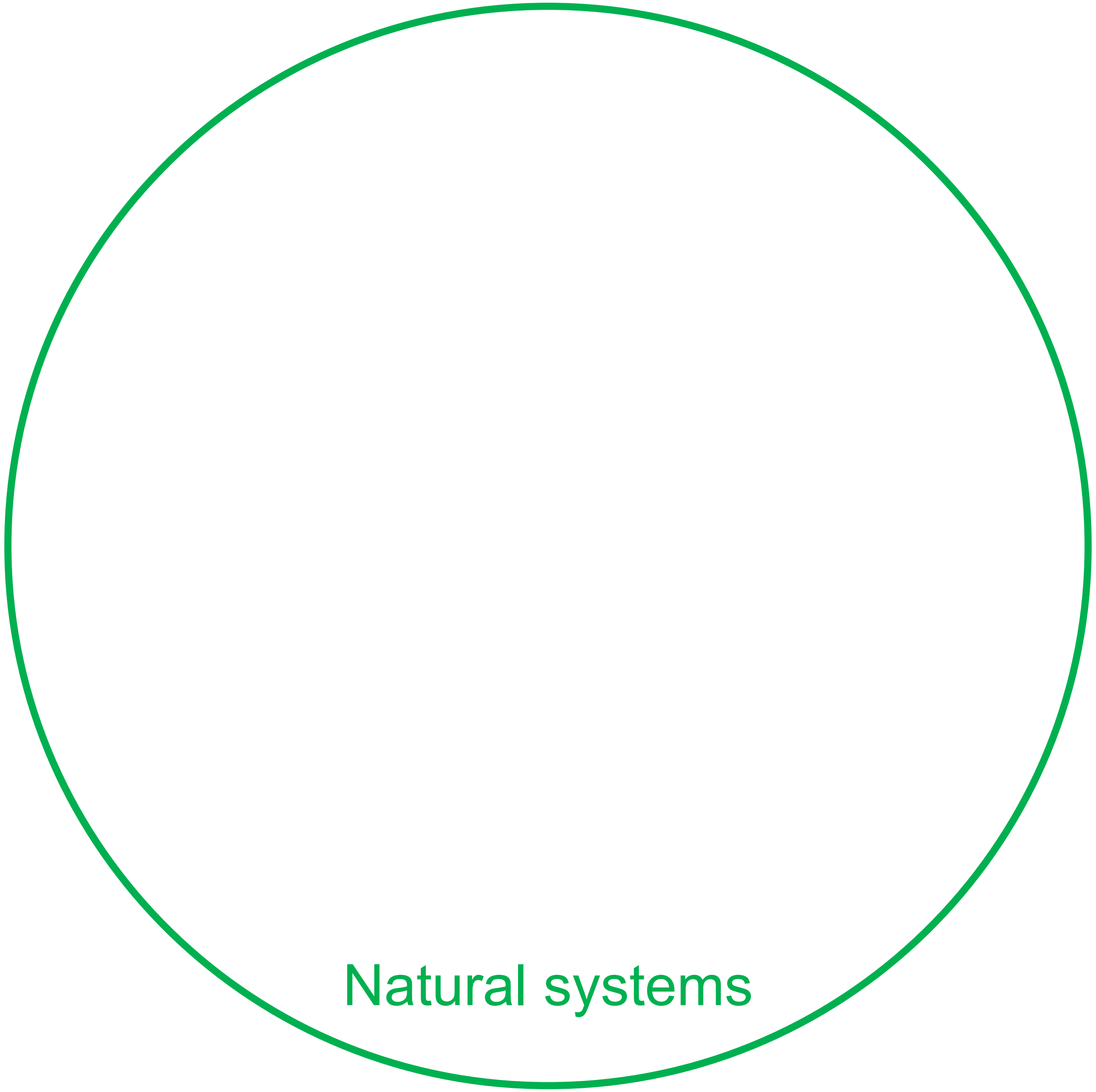
- Economics
- Sociology
- Public health
- Ecology
- Geography
- Urban planning
- …

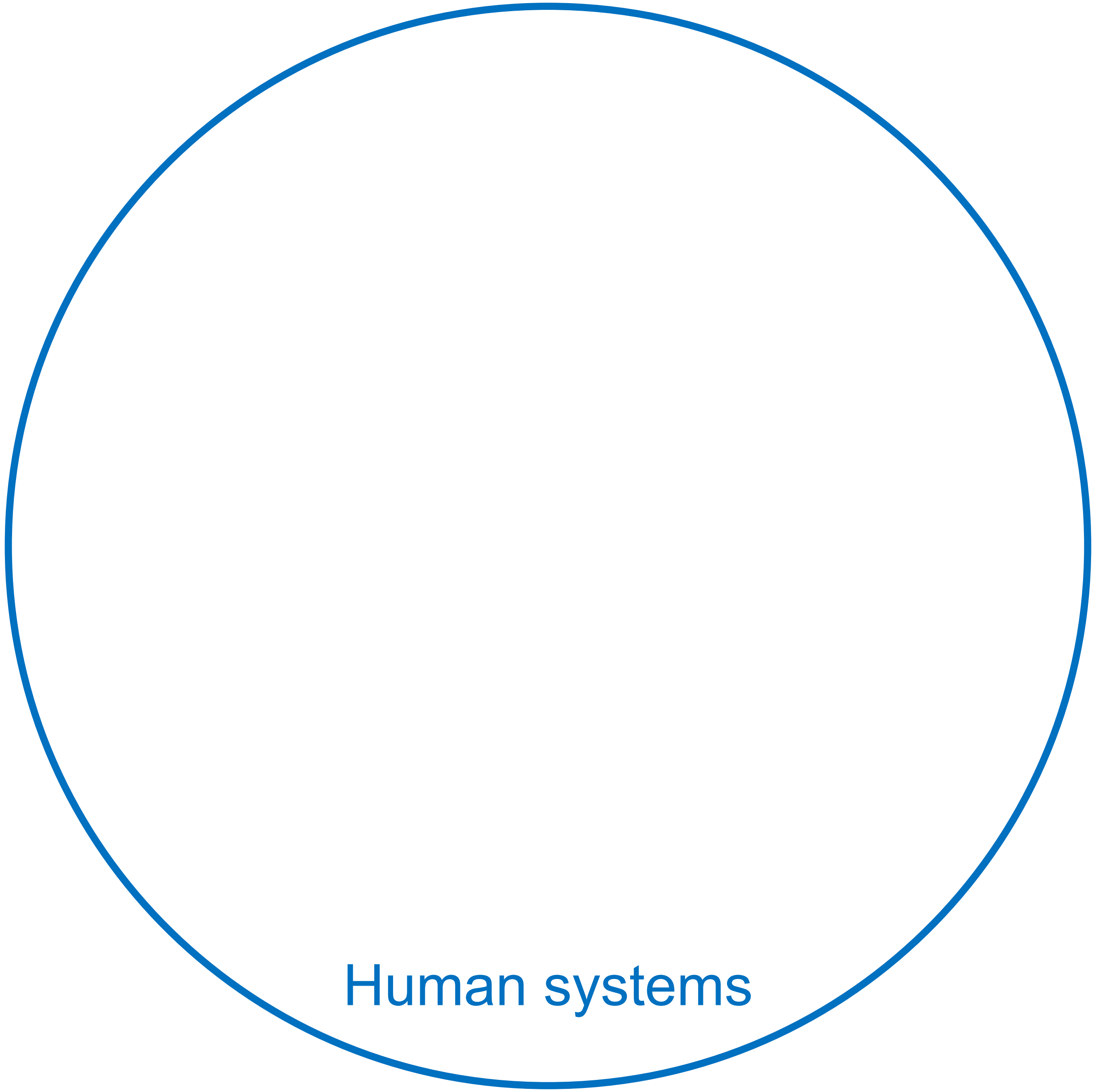
- Engineering
  - Environmental
  - Civil
    - Transportation
    - Water
    - Power/Energy
    - Buildings

What are urban systems?

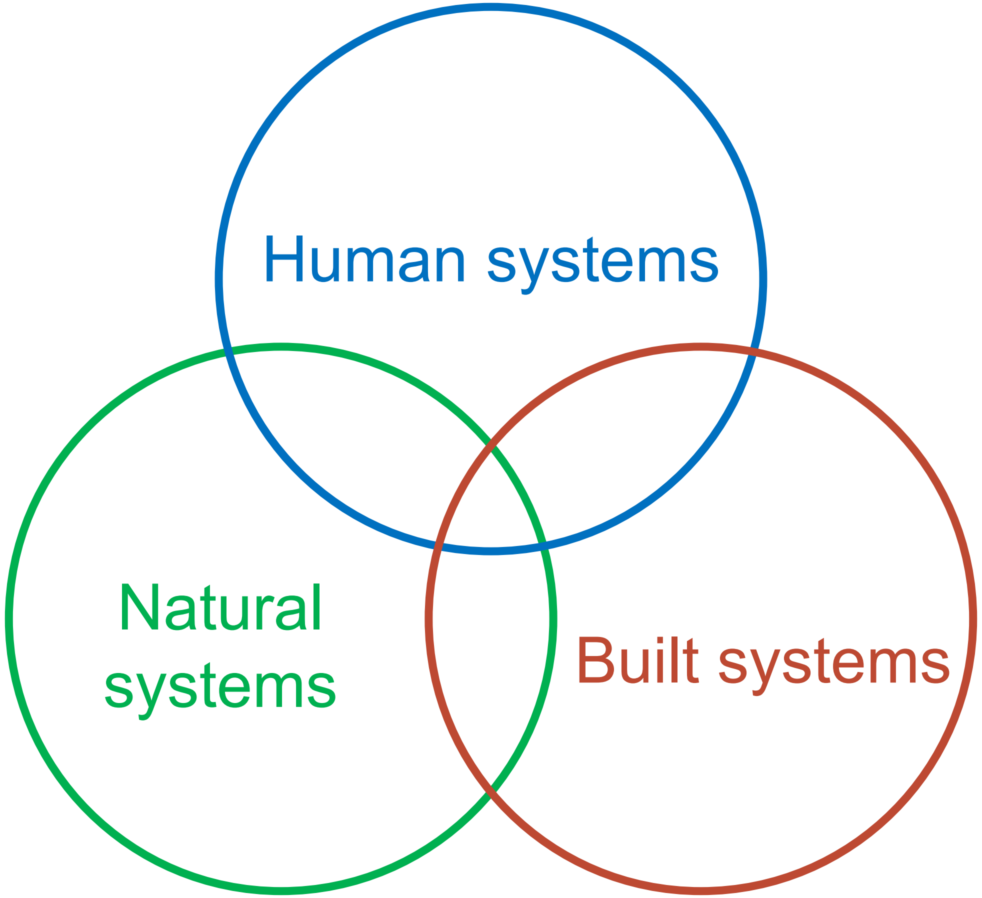



Built systems


Natural systems


Human systems

What about the intersections?



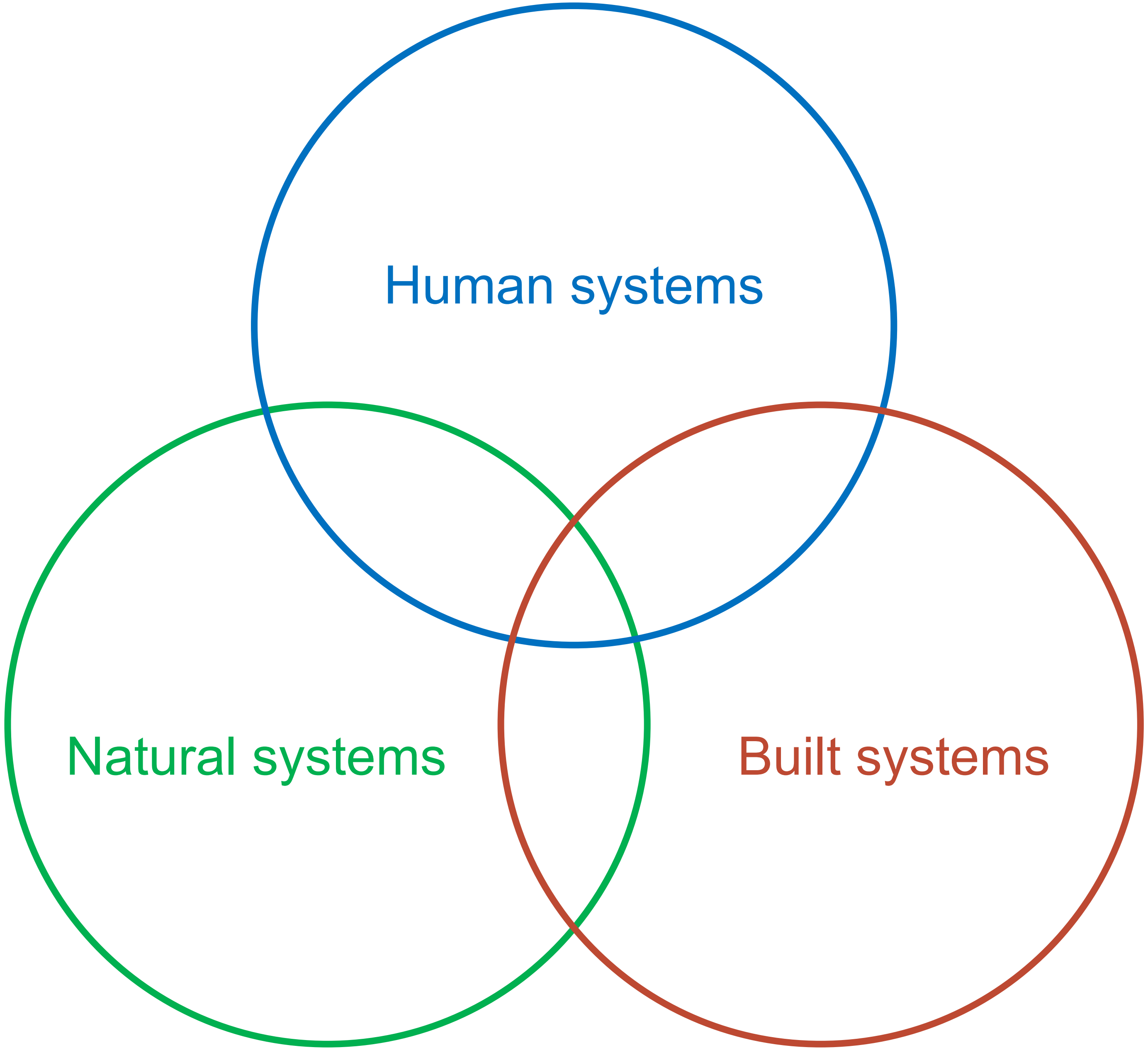
Why are cities complex?

"[Real cities, present] situations in which several dozen quantities area all varying simultaneously and in subtly connected ways."

– Jane Jacobs,
The Death and Life of Great American Cities

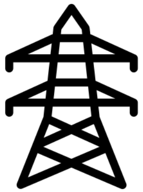
Source: Wikimedia commons

What makes an urban system sustainable?

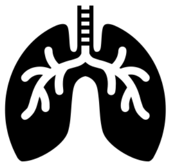
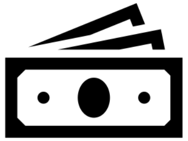


Examples of complex urban systems

- Power grid ←→ buildings ←→ people

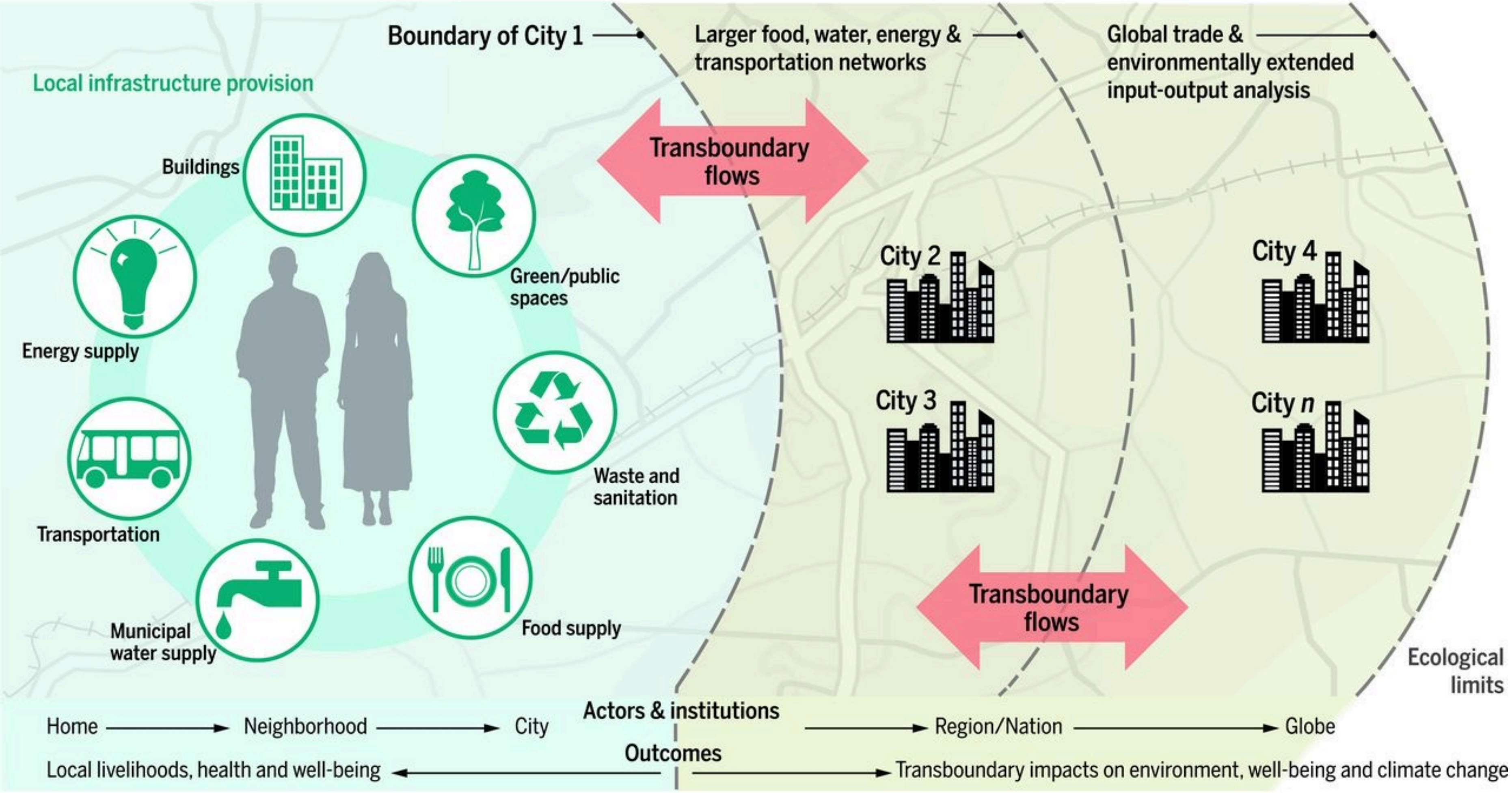


- Transportation ←→ pollution ←→ real estate/economics

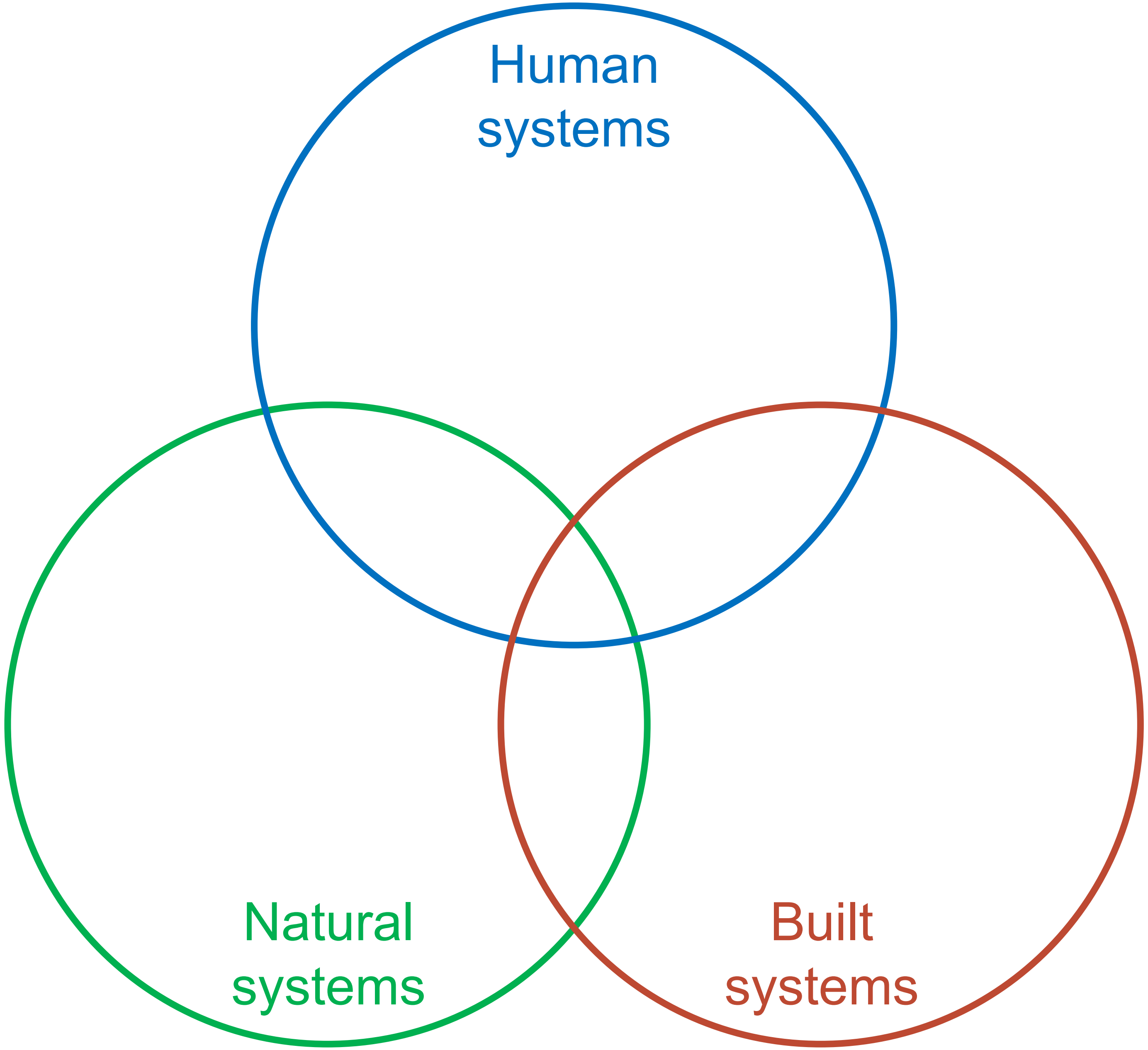
- Others?

Key sustainable urban systems challenges



Anu Ramaswami *et al*. Meta-principles for developing smart, sustainable, and healthy cities. *Science* **352**,940-943(2016). DOI:10.1126/science.aaf7160

Disciplines involved



How can we describe urban systems?

- How can we do this with an engineering mindset?
- In this course, we will use two tools to describe systems:

Computational systems thinking

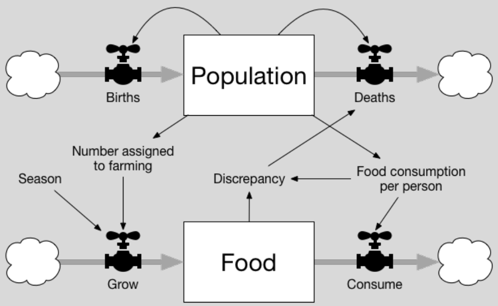
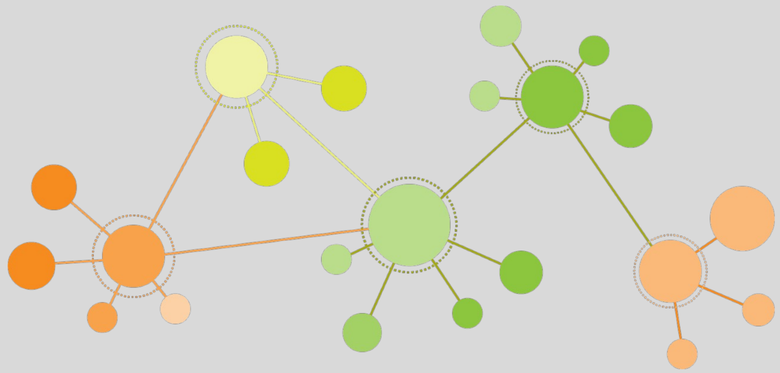


Figure 7: Population and food dynamics in *Banished*

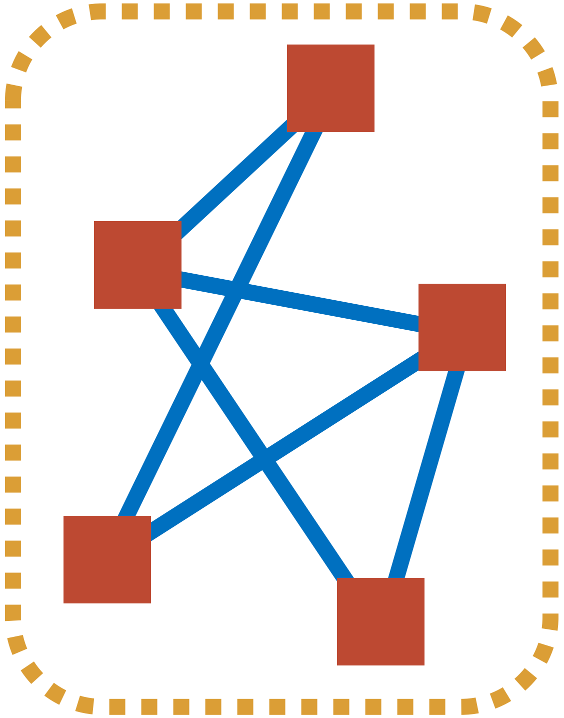
Network analysis



Our definition of a system

A system is…

a set of elements | interconnected coherently organized | in a way that achieves something

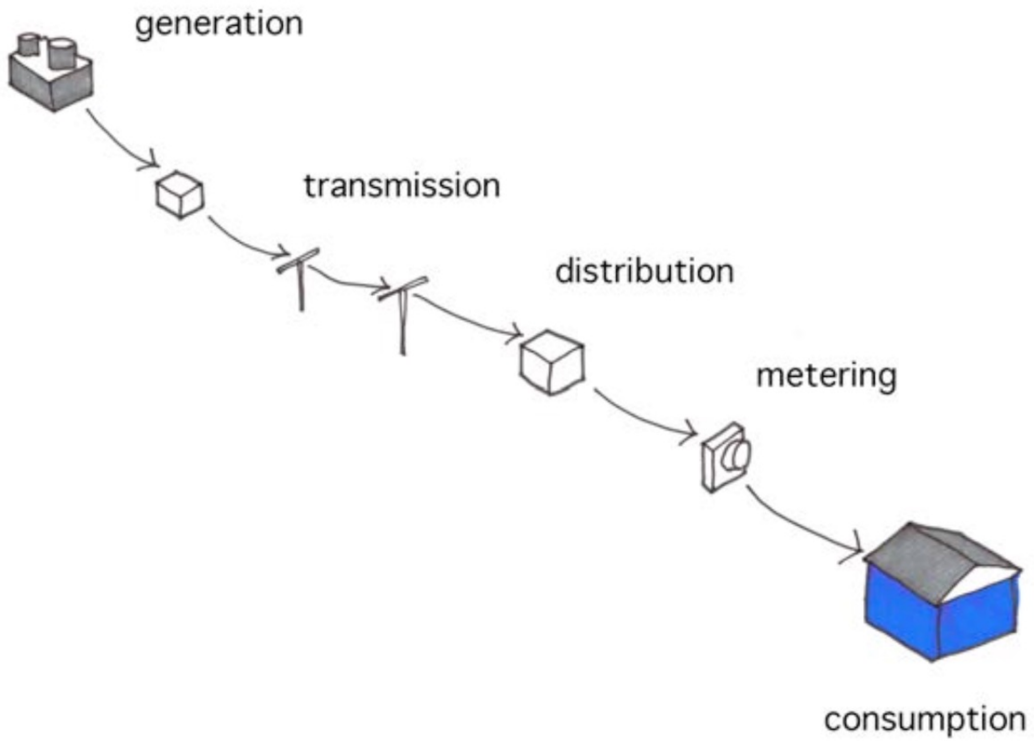


- Multiple parts without interdependencies are just collections
- The structure helps to drive the system toward its purpose

Systems definition: Meadows, 2008

Example: the energy grid

- Supply (power plants, renewables)
- Transmission
- Storage
- Demand (buildings, efficiency, human behavior)
- Taking our example, how can we describe this system?



Source: David Hsu, MIT

System dynamics

System structure

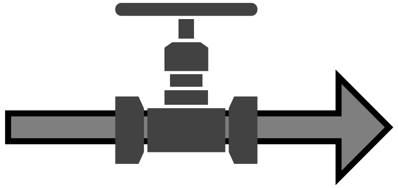
Taking our example, how can we describe this system?

- Two key tools:
  - Representation of system dynamics (systems thinking)
  - Representation of structure (network analysis)
  - These are related but not the same
- These tools are not exhaustive
  - Economic models
  - Dynamical systems (purely mathematical)
  - etc…

Systems thinking definitions

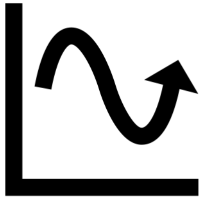
Elements that can be measured as quantities

flow



Flows cause changes in quantities of stocks

dynamics



Dynamics represent behaviors of stocks and flows over time

Network definitions

Objects: nodes, vertices **V**

Interactions: links, edges **E**

System: network, graph **G(V,E)**

Refining definitions…

Systems thinking

- Refers to the description of systems as **stocks** and **flows**
- Focused on dynamics of how certain components of the system affect others
- More on this in Part 1 of the course

Network analysis

- Refers to the definition of a system as **nodes** and **edges**
- Focused on **mathematical structure** of interconnections in the system
- More on this in Part 2 of the course

Computational systems thinking … ***for sustainable engineering***

- Urban systems are complex and interconnected
- Addressing sustainability requires a holistic perspective to manage resources, infrastructure, and human behavior
- These tools can help us identify:
  - Feedback loops
  - Critical components of urban systems (e.g. transport hubs, energy infrastructure)
  - Characteristics of resource flows
  - Opportunities to improve system resilience
- A ”systems” approach can offer new insights for decision-making

This semester

- Content:
  - Part 1: Systems thinking
  - Part 2: Network analysis
- Course project (involves 2 milestones and a final presentation)
  - Work in groups of ~3-4
- 2 Assignments
  - One on systems and one on networks
  - Work individually – can work together but each person must submit their own assignment (in their own words) and indicate with whom they worked
  - Using Python for simulation and analysis
- 2 Midterm exams

Course project:

World dynamics model

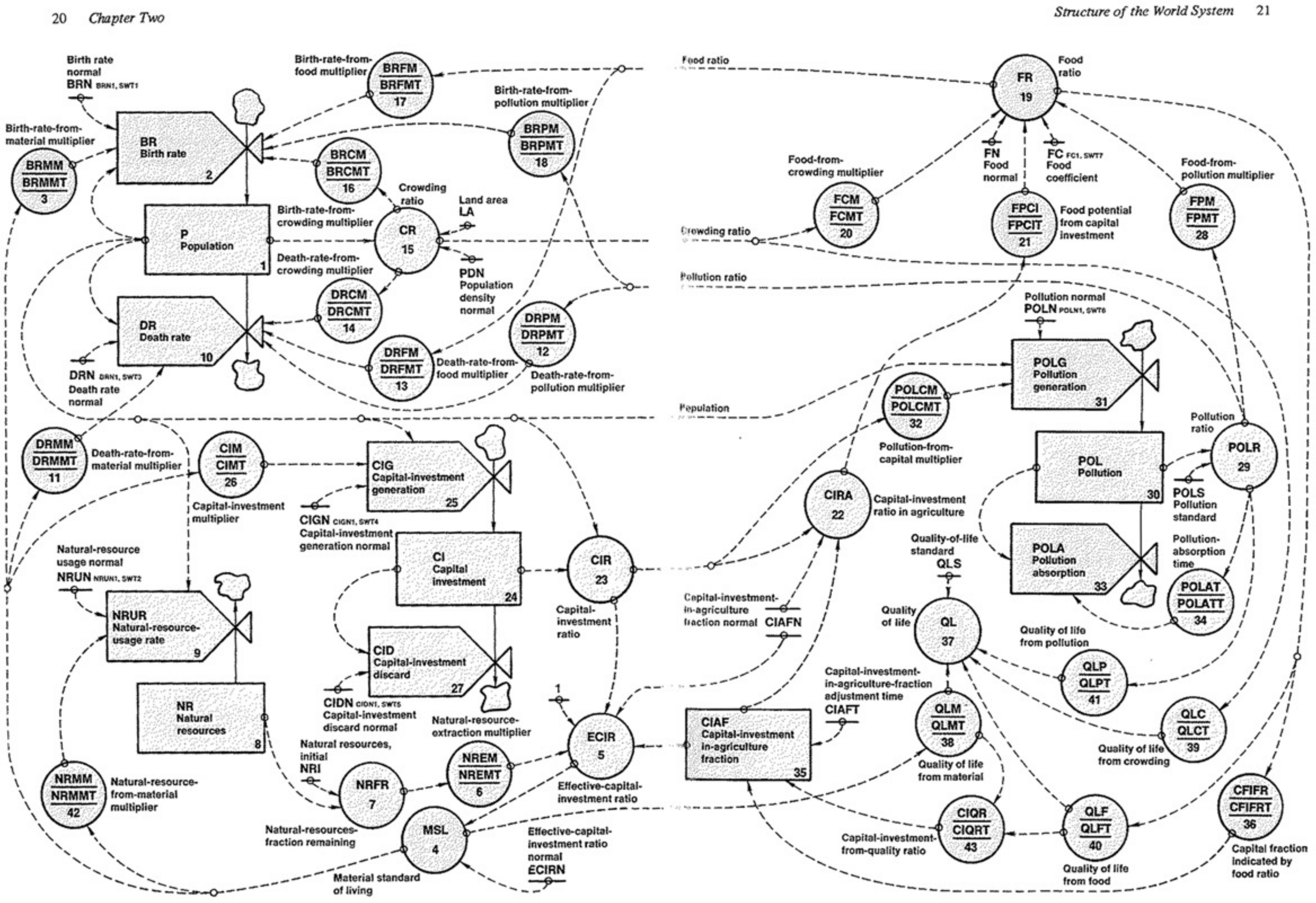


Figure 2-1 Complete diagram of the world model interrelating the five level variables — population, natural resources, capital investment, capital-investment-in-agriculture fraction, and pollution.

Course project: world dynamics model

Milestone 1:

Characterizing the model and creating optimal policies (Systems analysis)

Milestone 2:

Network analysis of the structure of the system

Final presentation: final learnings and recommendations

Course project: additional details

- Two milestones:
  - Milestone 1: due April 4
  - Milestone 2: due May 9 (get started early)
- Final presentations: May 28 (last day of class)
  - You should consider feedback provided in first two milestones
- Group formation
  - Groups of 3-4
  - You may choose who you want to work with
  - Let me and Vasantha know by Friday, March 7
- More details in the coming weeks

Other course logistics

- Lectures: 9:15-11:00, Wednesday, CO 121
- Exercises: 11:15-12:00, Wednesday, same location is reserved for you to work on your graded assignments and project milestones
  - Teaching assistant, Kanaha Shoji, will be present at this times
- An additional hour is scheduled 8:15-9:00 on Wednesday
  - Use this time for your own self-study, assignment work, and group project work
- My office hours: 14:00-15:00, Wednesday, GC G1 484

Course "ground rules"

- Slides will be posted on Moodle
  - I will sometimes annotate them during class, and sometimes slides are hidden for discussion purposes
- Ask questions! And feel free to share your comments/experiences related to the class
- Participate in the class discussions
- Feel free to use the discussion page on the class Moodle
- I will communicate with the class using the Moodle announcements (sends you an email)

I have written Python code before

A. True
B. False

I have used the EPFL noto interface before

A. True
B. False

responseware.eu
Session ID: ethos

I am confident in my Python skills

A. True
B. False

responseware.eu
Session ID: ethos

I am comfortable with object-oriented programming in Python

A. True
B. False

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Session ID: ethos

Next time

- Readings:
  - “Top of the food chain” (on Moodle)
  - Meadows Chapter 1
- Start Part 1 of the course: Systems thinking