Lecture 04
Systems Thinking 3

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CIVIL 534: Computational systems thinking for sustainable engineering

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Outline

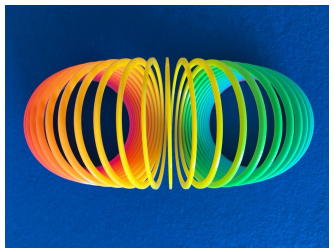
- Questions on course project?
- Characteristics of (urban) systems
  - **Resilience**
  - **Self-organization**
  - **Hierarchy**
- Why systems surprise us
  - **Structure vs. behavior**
  - Nonlinearity
  - Boundaries
  - Limiting factors
  - Delays
  - **Bounded rationality**
- Intervention points

Characteristics of (urban) systems

Why systems work so well

Resilience

"ability to bounce or spring back into shape, position, etc. after being pressed or stretched"



Measure of a system's ability to survive and persist within a variable environment

Urban systems resilience

Resilience

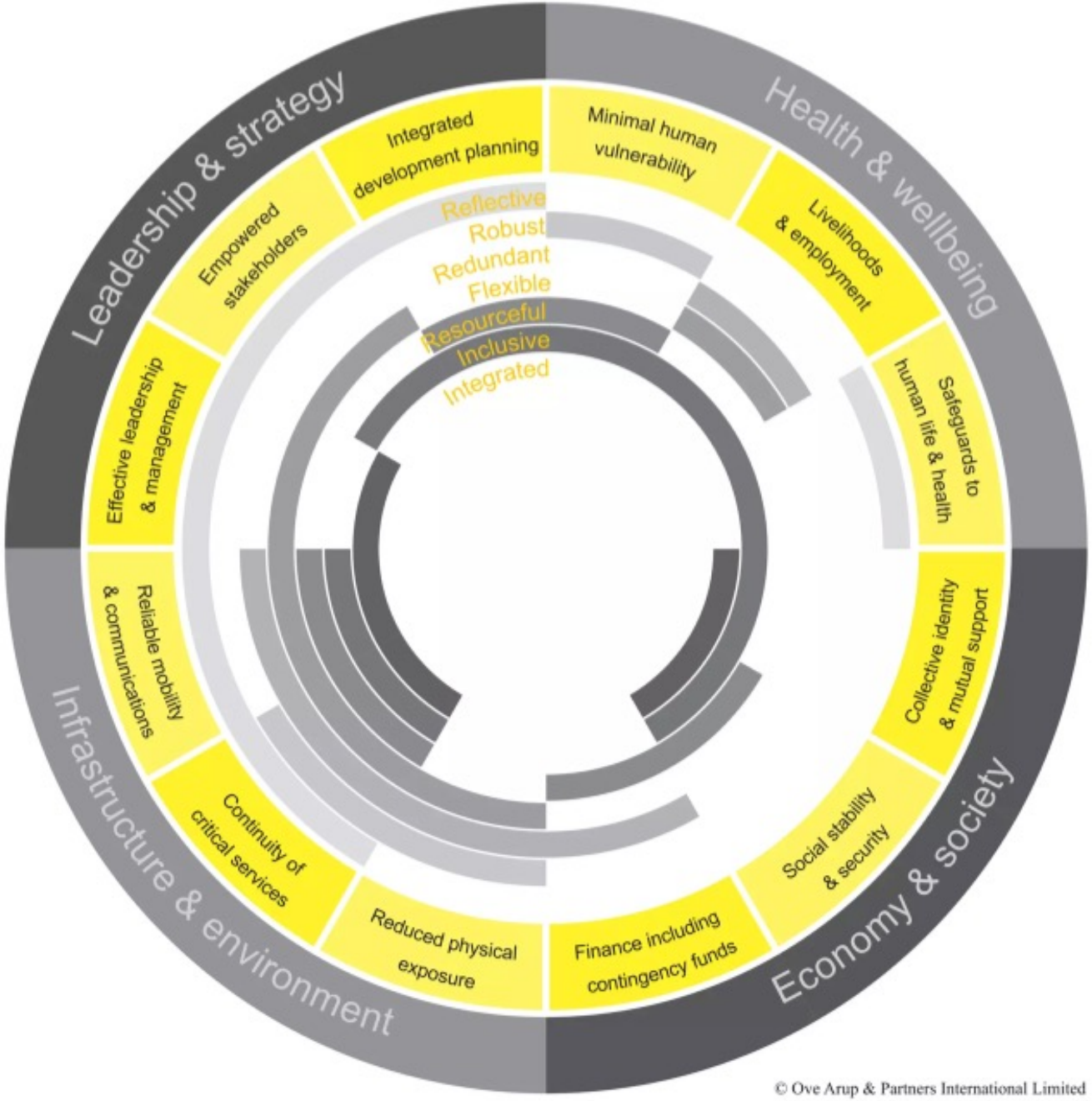
- Resilience is difficult to measure
- Our key performance indicators (KPIs) often measure aspects of "performance" (e.g. stability, productivity) which are easier to measure
- A sense of resilience requires a **systems-level perspective**

TABLE 1. URBAN ISSUES, THEIR TEMPORAL AND SPATIAL SCALES, AND THE CHARACTER OF THEIR ASSOCIATED METRICS

Problem	*Timescale*	*Spatial scale*	*Outcome metric*
Transportation (buses, subway)	Minutes	Meters	Simple
Fire	Minutes	Meters	Simple
Epidemics (HIV, influenza)	Years, days	Citywide	Simple
Chronic diseases	Decades	Citywide	Simple
Sanitation	Years	Citywide	Simple
Crime	Minutes	Meters	Simple
Infrastructure (roads, pipes, cables)	Days	Meters	Simple
Traffic	Minutes	Meters to km	Simple
Trash collection	Days	Meters	Simple
Education	Decades	Citywide	Complex
Economic development	Decades	Citywide	Complex
Employment	Years	Citywide	Complex
Poverty	Decades	Neighborhood	Complex
Energy and sustainability	Years	Citywide	Complex
Public housing	Years to decades	Neighborhood	Complex

Resilience in urban systems

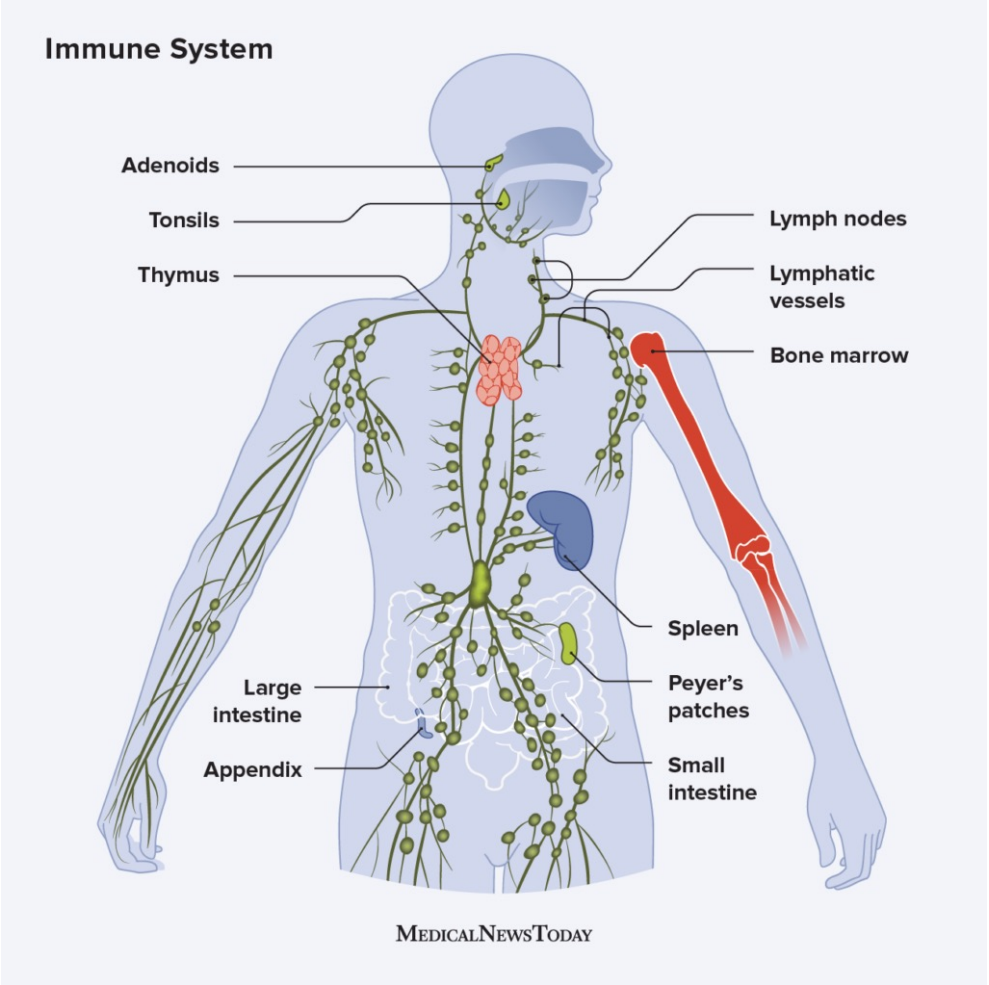
- "Urban resilience is the capacity of a city's systems, businesses, institutions, communities, and individuals to survive, adapt, and thrive, no matter what ***chronic stresses*** and ***acute shocks*** they experience."
  - Resilient cities network:



https://resilientcitiesnetwork.org/what-is-urban-resilience/

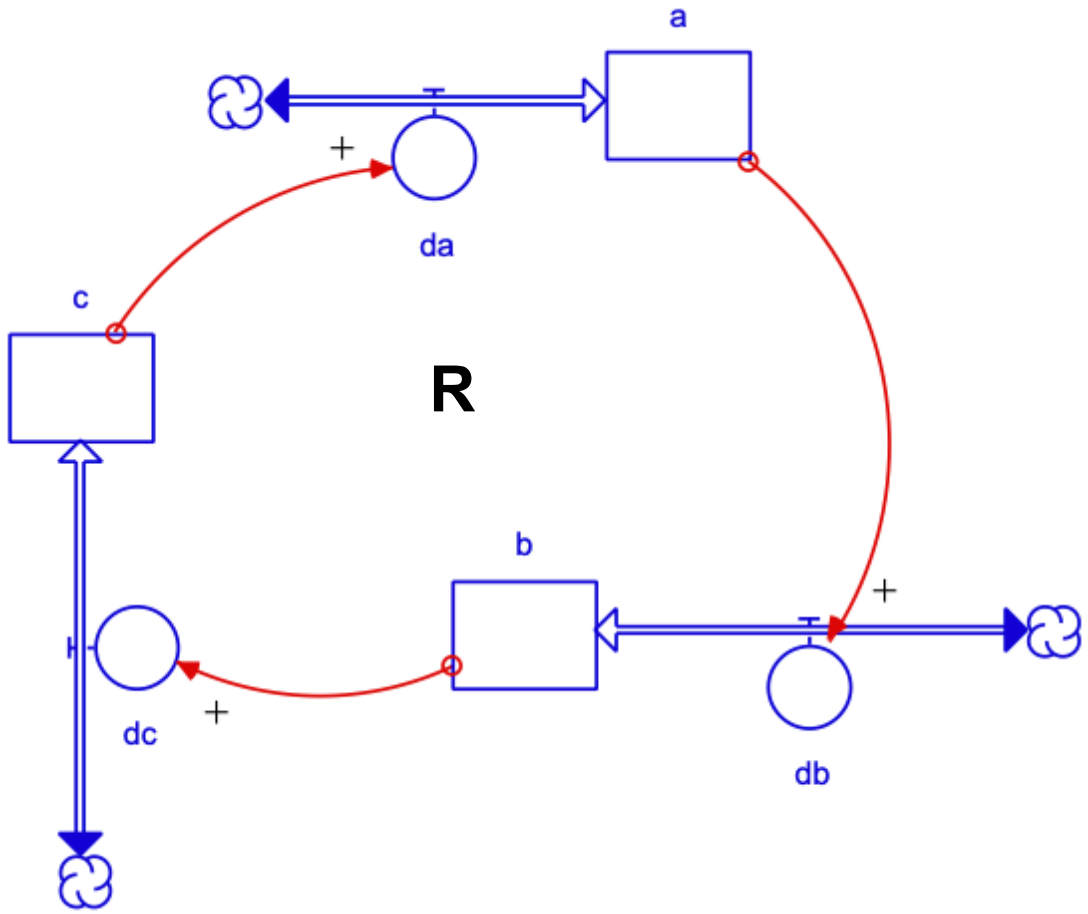
The importance of feedback loops in resilience

What happens when you get sick?



https://www.medicalnewstoday.com/articles/320101

Resilience and feedback loops



Balancing feedback loops are critical to system resilience

https://ocw.mit.edu/courses/15-988-system-dynamics-self-study-fall-1998-spring-1999/ef98818b73e2f033cf3f557e876b8db3_unexpected.pdf

Resilience example: 2010 Chile Earthquake

- **Context:** Magnitude 8.8 earthquake off the coast of Chile
- **Effects in the city of Concepción:**
  - Limited physical building damage due to strong Earthquake codes
  - Disrupted networks:
    - Electricity
    - Water
    - Transportation
    - Communication
  - Lack of communication from authorities led to spreading of rumors, and ultimately widespread looting and anxiety. Eventually, neighbors came together to form neighborhood watches and quell the violence.

The San Diego Tribune

Resilience and feedback

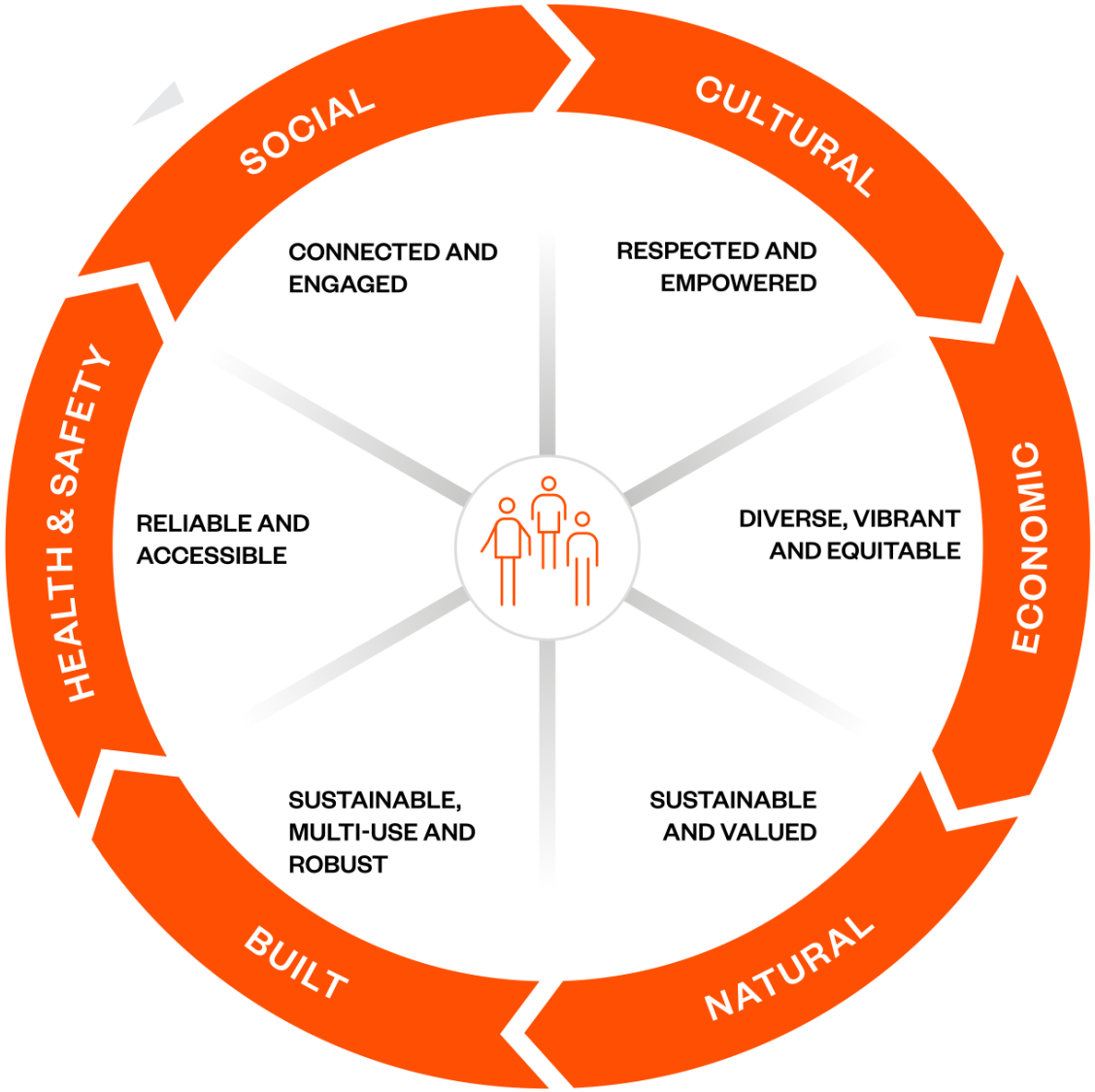
> *"In Concepción we had two earthquakes: the 8.8 one and the social earthquake—looting, arson… I think the last one affected our soul most violently*
>
> -Mayor of Concepción

- Balancing feedback loops are critical
- When systems can restore or rebuild feedback loops, this creates additional resilience
- Systems that can design new feedback loops are more resilient still

https://www.rockefellerfoundation.org/report/city-resilience-framework/

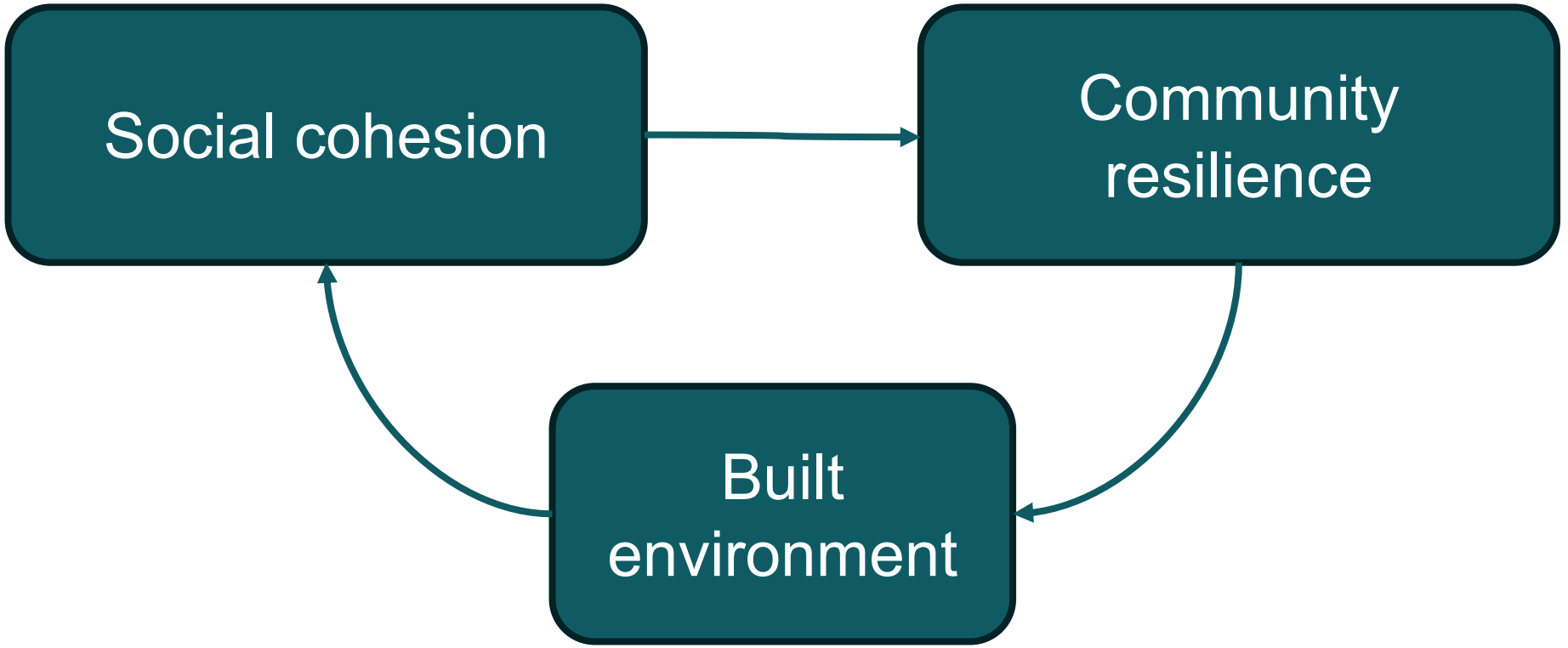
Resilient communities

"Strong social systems within a community – those that promote high levels of **social cohesion**, integration and trust – are among the most important determinants of how well a community will perform in the face of disasters."



Resilient Communities Framework, Resilient Cities Catalyst and Minderoo Foundation

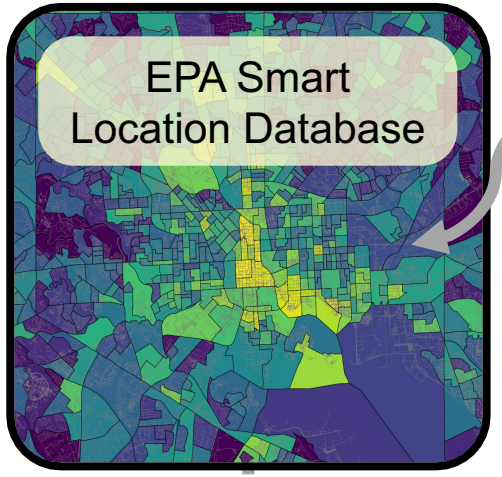
Resilience example: social cohesion



Research example

Does walkable design impact social cohesion?

Finding: more **diversity in land use** associated with **higher social cohesion**



Census Block Group
500-3,000 residents

Baltimore Ecosystem Study

6 cities
n=9670

Demographics

Statistical Analysis

Walkable Urban Design Characteristics

- Diversity
- Physical Density
- Social Density
- Connectedness

Social Cohesion

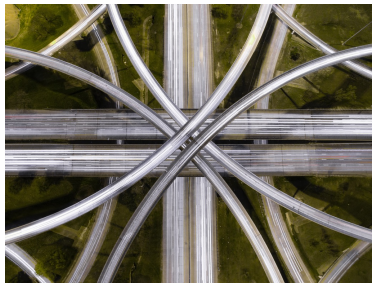
- Close knit
- Trust
- Willingness to help
- # of neighbors known

Self-organization

"capacity of a system to make its own structure more complex"

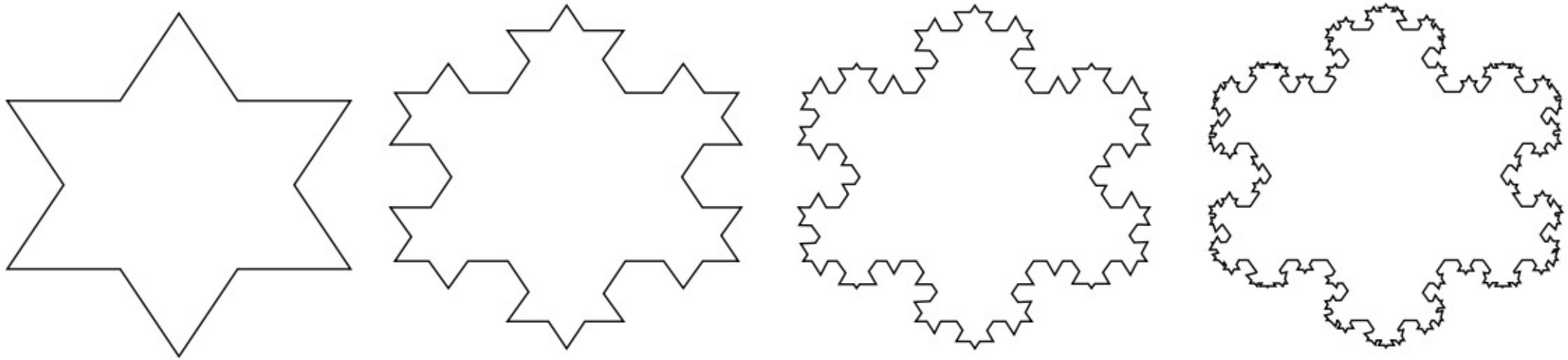
arises from feedback loops that can not only rebuild, but also learn, adapt, and redesign themselves

How do cities self organize?



Self-organization

- Rules that govern growth / how things develop and organize (e.g. snowflake example from Meadows)
- Do such rules/laws exist in cities?

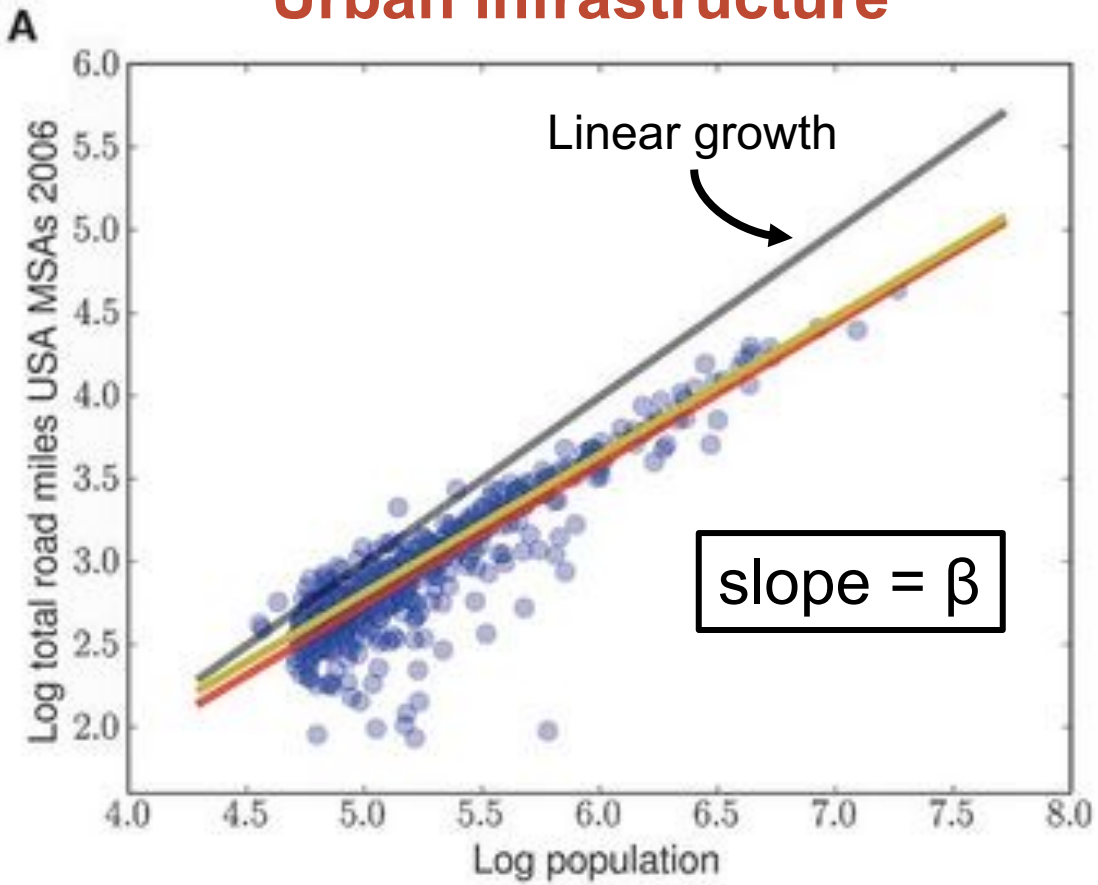


Luís M. A. Bettencourt. The Origins of Scaling in Cities. *Science* **340**,1438-1441(2013). DOI:10.1126/science.1235823

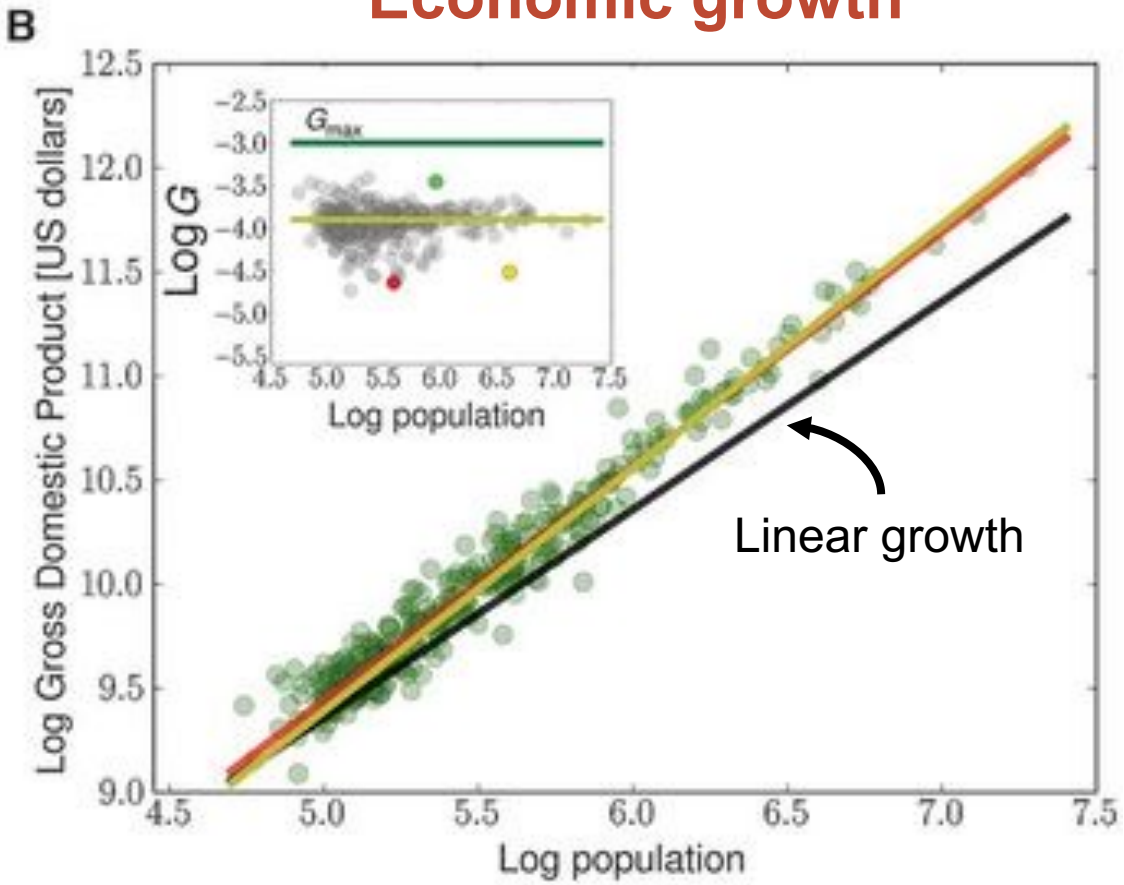
Self-organization and “fractal cities”

- Cities themselves are the result of self-organization

Urban infrastructure



Economic growth

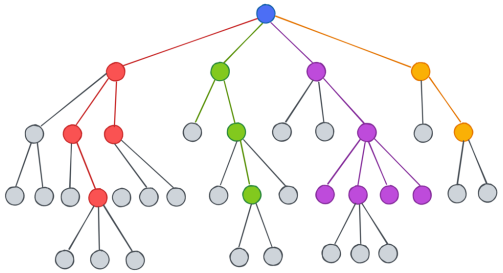


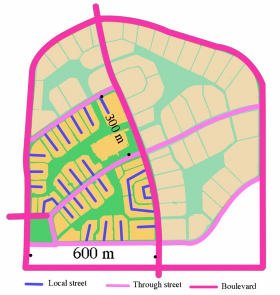
Hierarchy

"systems of systems"

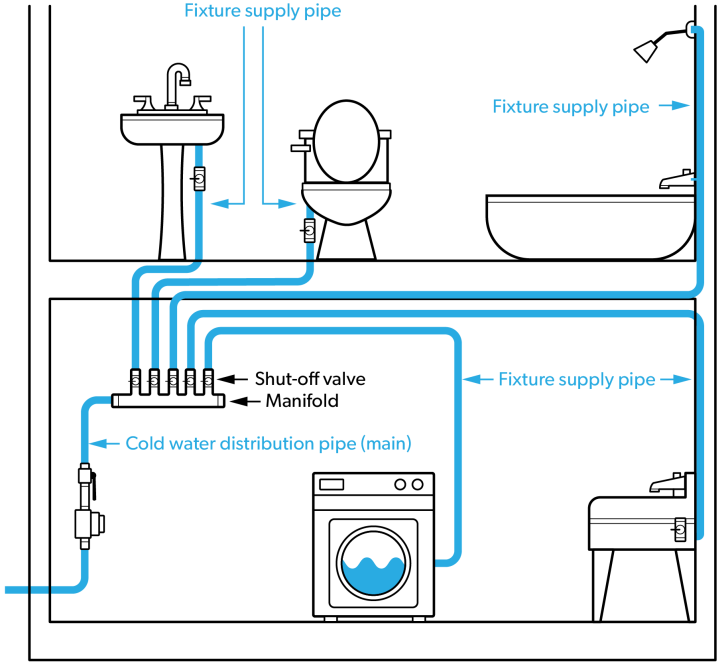
Many subsystems in the context of a larger system

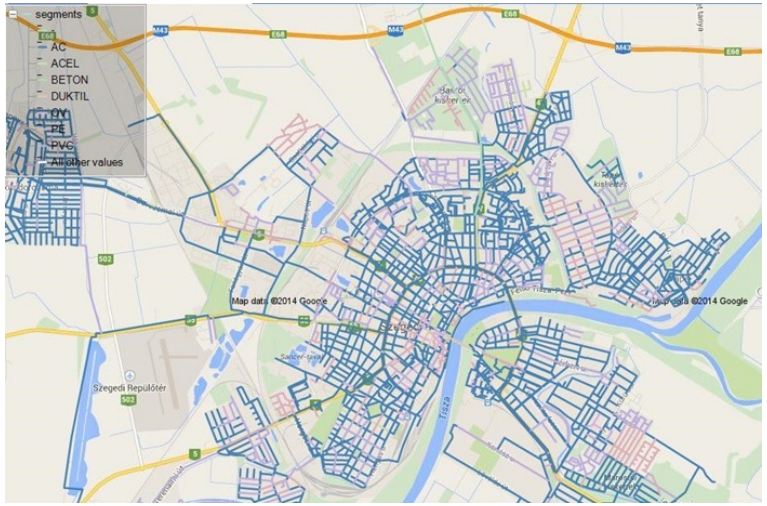
Cities are inherently systems of systems

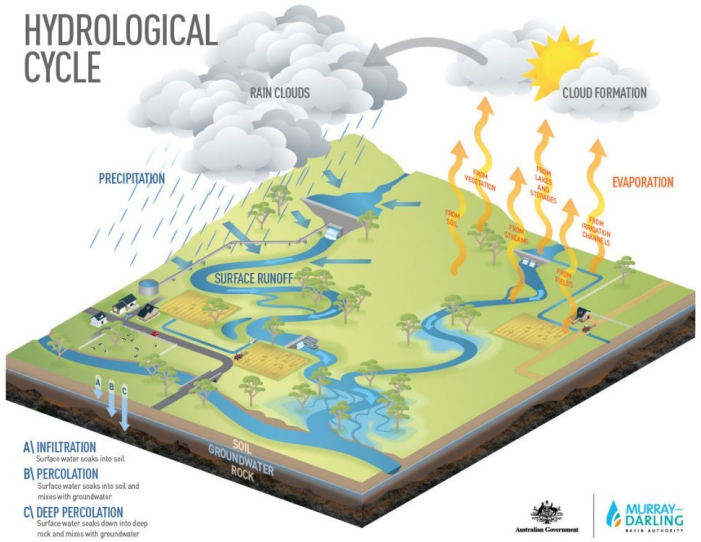




Hierarchy in cities – water systems



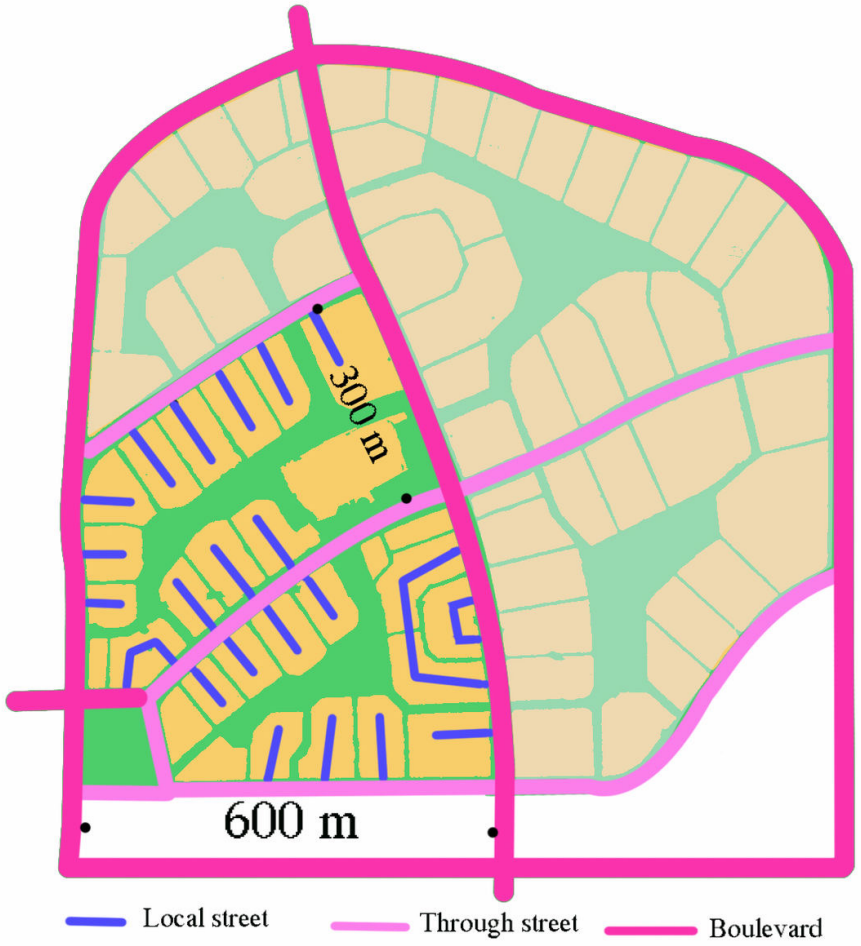




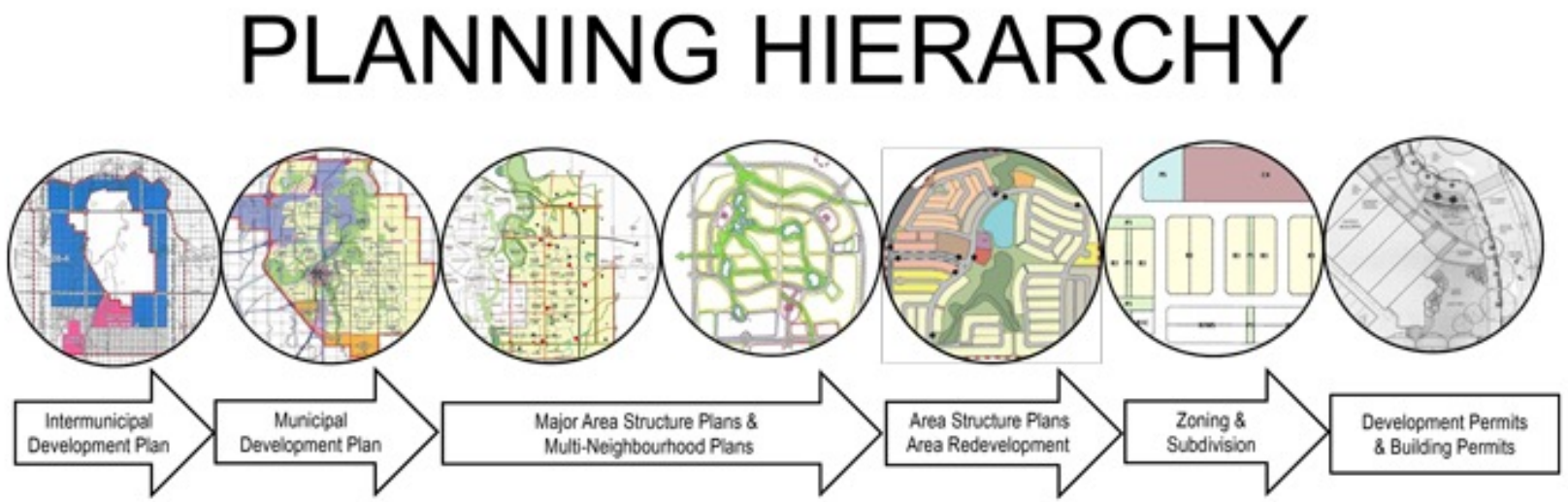
Building distribution ⟷ Urban supply network ⟷ Regional water cycle

Hierarchy in cities – road networks

- Many systems in cities are designed with hierarchy in mind



Hierarchy in cities – information



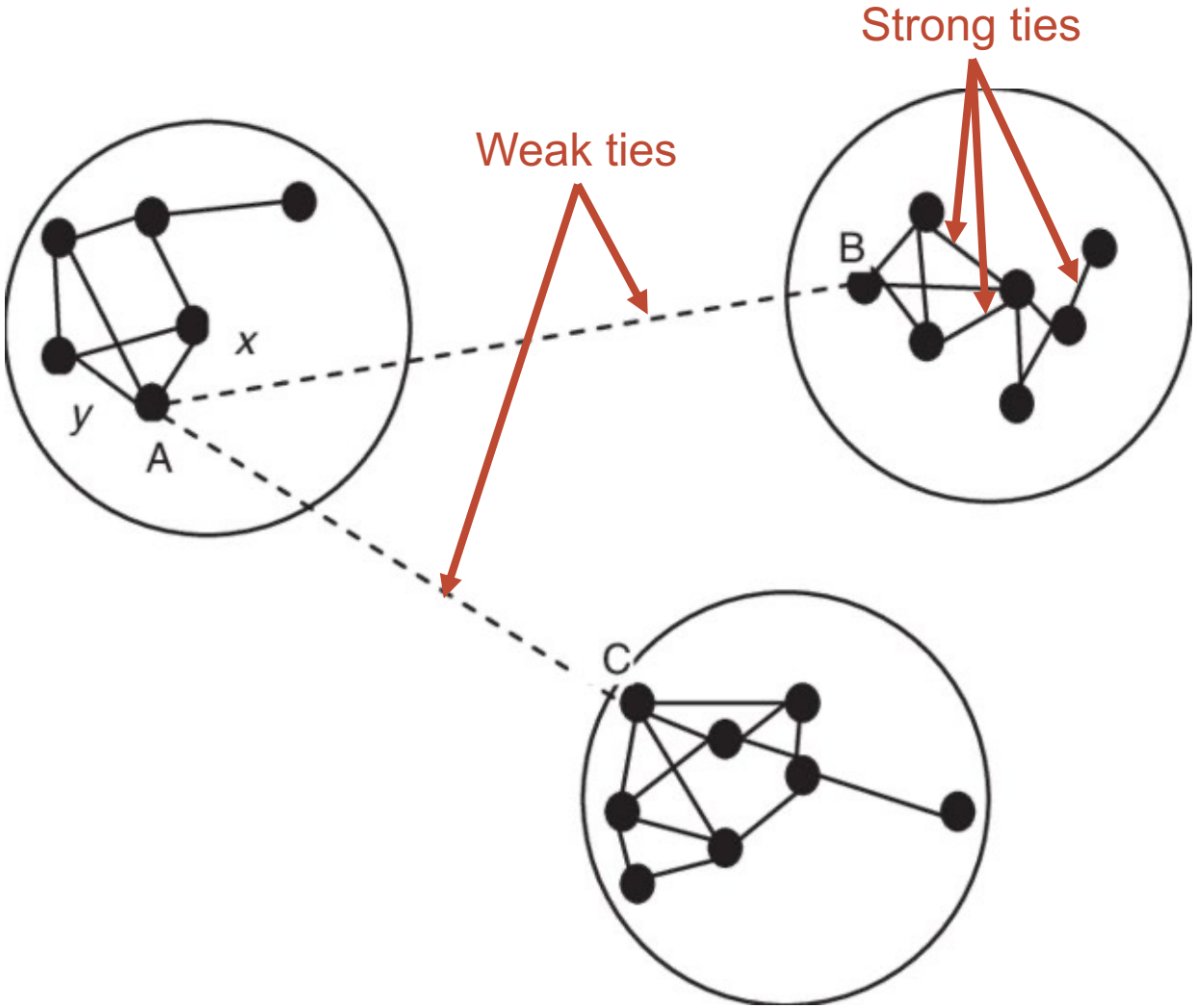
- Information required within a subsystem is less than the overall information in the system

Properties of hierarchies

- Can be caused by self-organization
- Can affect resiliency (increase or decrease)
- Reduce the amount of information that one part of the system needs to keep track of
- Relationships within subsystems are stronger that between subsystems
- Increases efficiency

Examples of hierarchies in social systems: “Strength of weak ties”

“weak ties are more likely to land you new employment, compared to your ties with people you know better.”

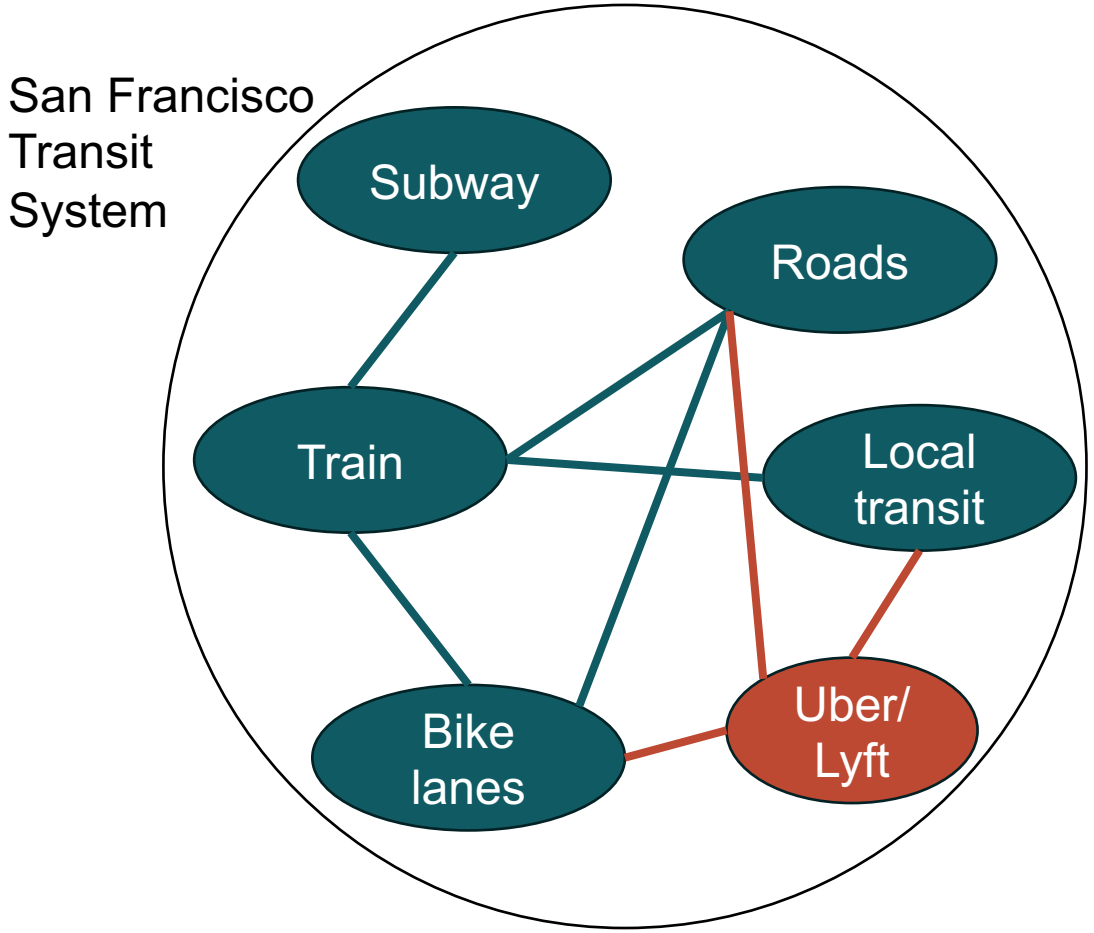


https://news.mit.edu/2022/weak-ties-linkedin-employment-0915
http://dx.doi.org/10.1017/S0143814X13000263

Suboptimization

- Suboptimization occurs when a sub-system's goals dominate over the total system's goals
- "Splintering urbanism" in cities
  - As cities grow and self organize (spatially, socially), infrastructure and social sub-systems can divide a city and increase inequality
- Balance between higher level control and local control

Example from my previous home: Uber/Lyft and “splintering urbanism”



What happens when Uber/Lyft’s goals dominate?

Example of effective use of hierarchies

- Context: Hurricane Sandy in New York City, 2012
- Damages: 53 fatalities, thousands of homes destroyed, infrastructure destroyed (subway, power systems)
- Normal functioning: NYC operates its own budget/services, within NY State, itself within the US
- After disaster: dissolve boundaries to provide assistance

Why systems surprise us

Why systems surprise us

Three truths:

1. Models are everywhere
2. Our models are pretty good
3. But we still miss a lot

> *All models are wrong but some are useful.*
>
> - George E. P. Box

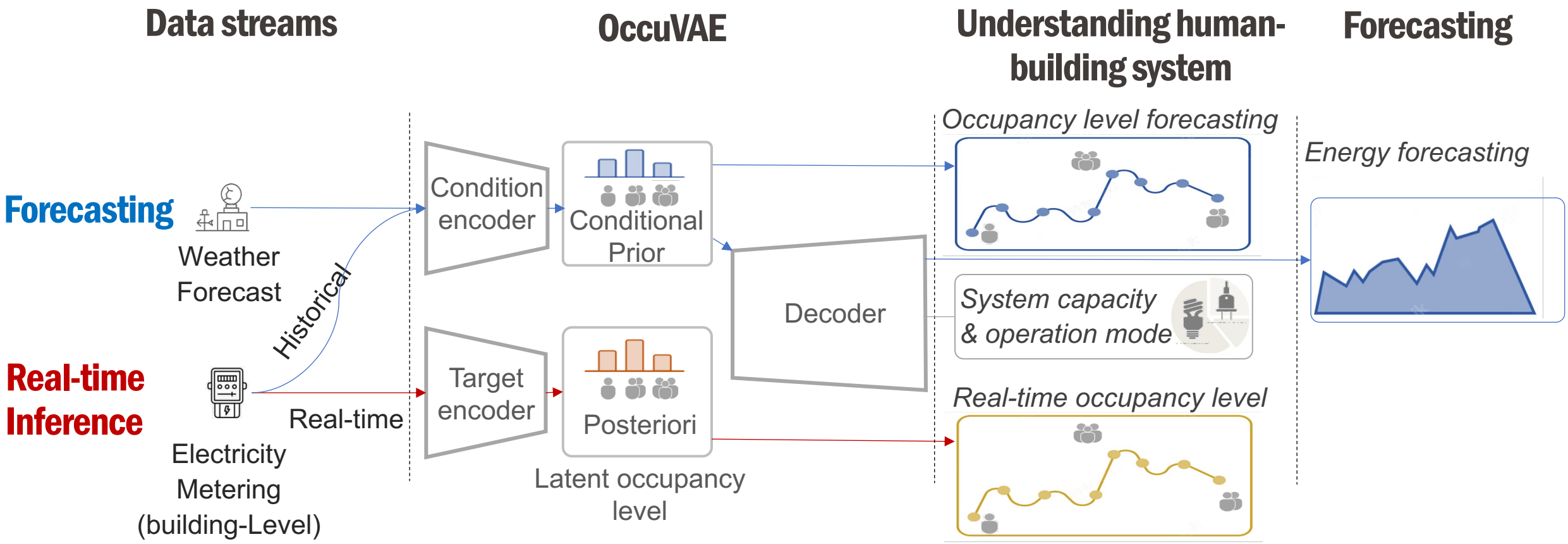
- Systems will always surprise us, but if we understand system characteristics, we may be surprised less often

Structure vs. behavior (Models vs. data)

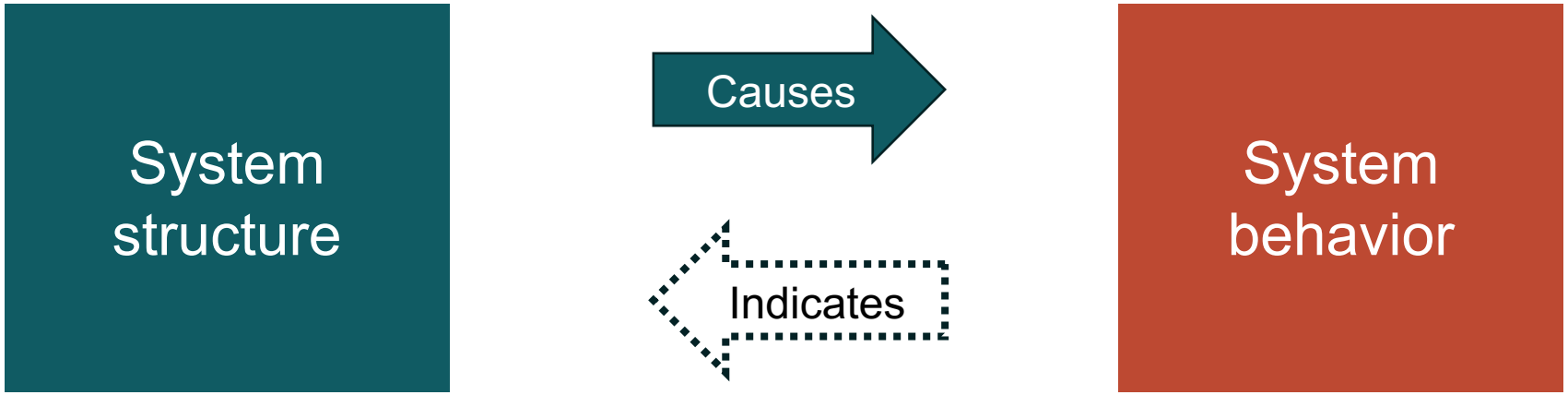
- We can look at past data on flows (e.g. heat flowing in and out of a house) and we might start to make good predictions
- But if our model is purely based on the data, and does not consider the structure of the system, we our predictions will worsen when something within the system changes

Research example: energy and occupancy

Research example: energy and occupancy

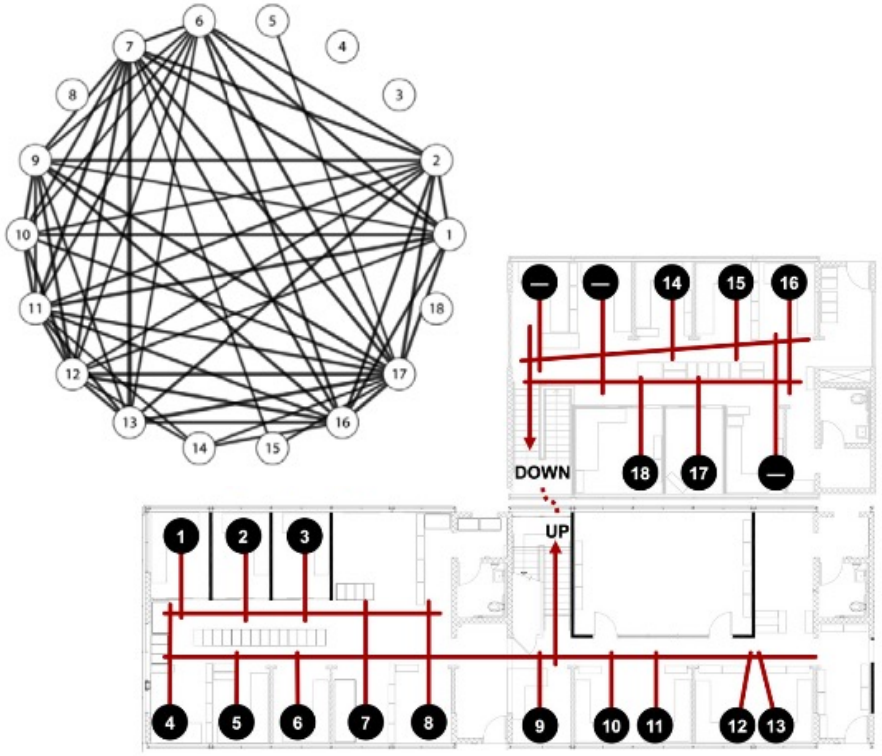


Structure vs. behavior



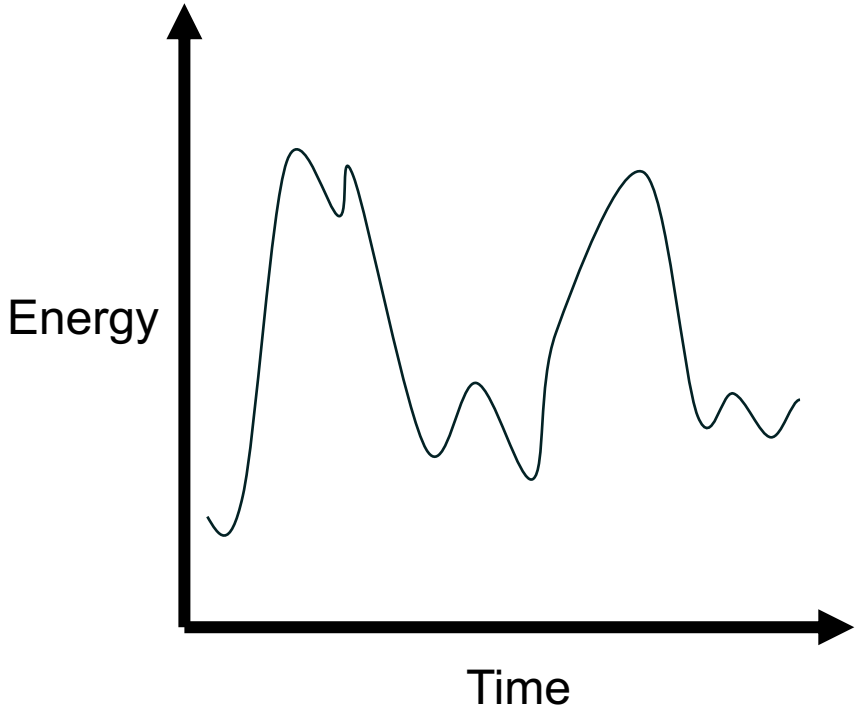
- Possible behavior is driven by the structure of the system
- Example: competing feedback loops and possible outcomes

Structure vs behavior: research example



Causes

Infer?

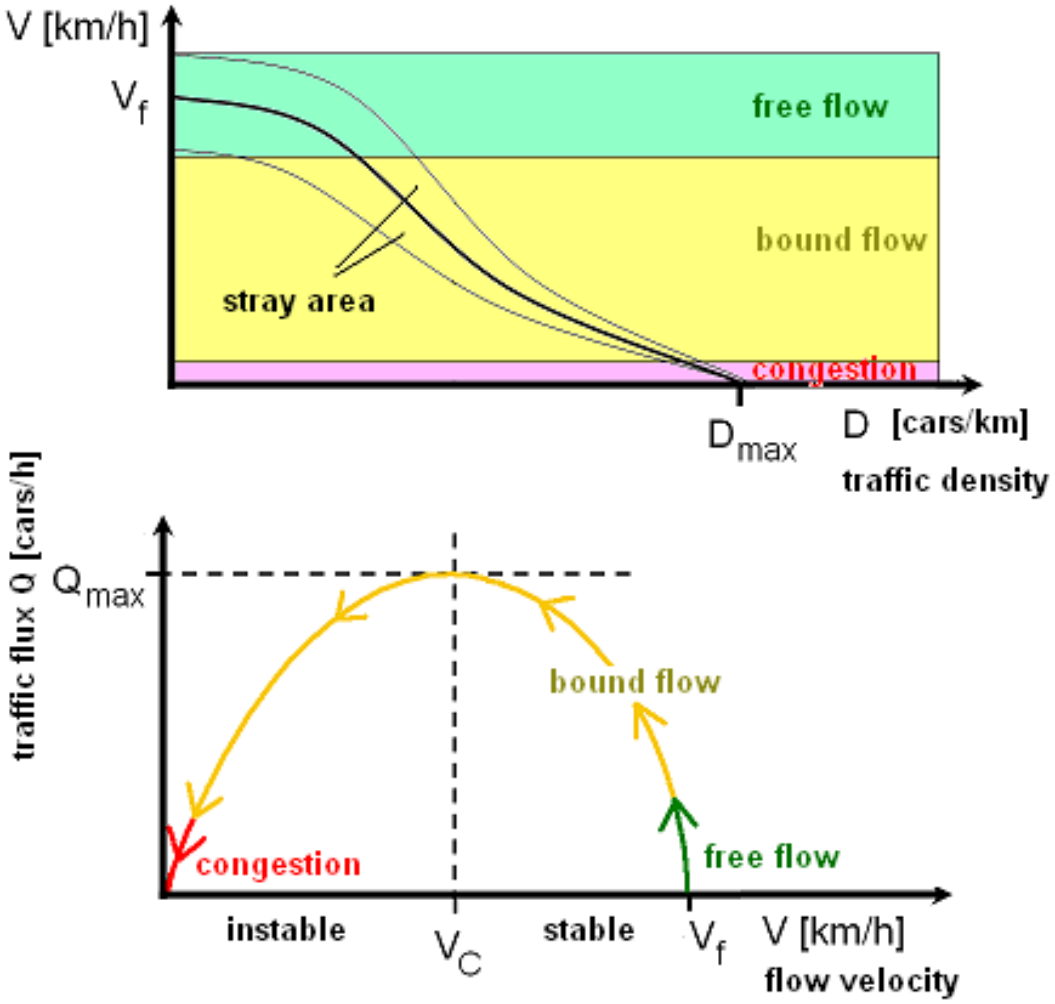


Occupant **structure**
(social, spatial, etc.)

Energy use **behavior**
(behavior over time)

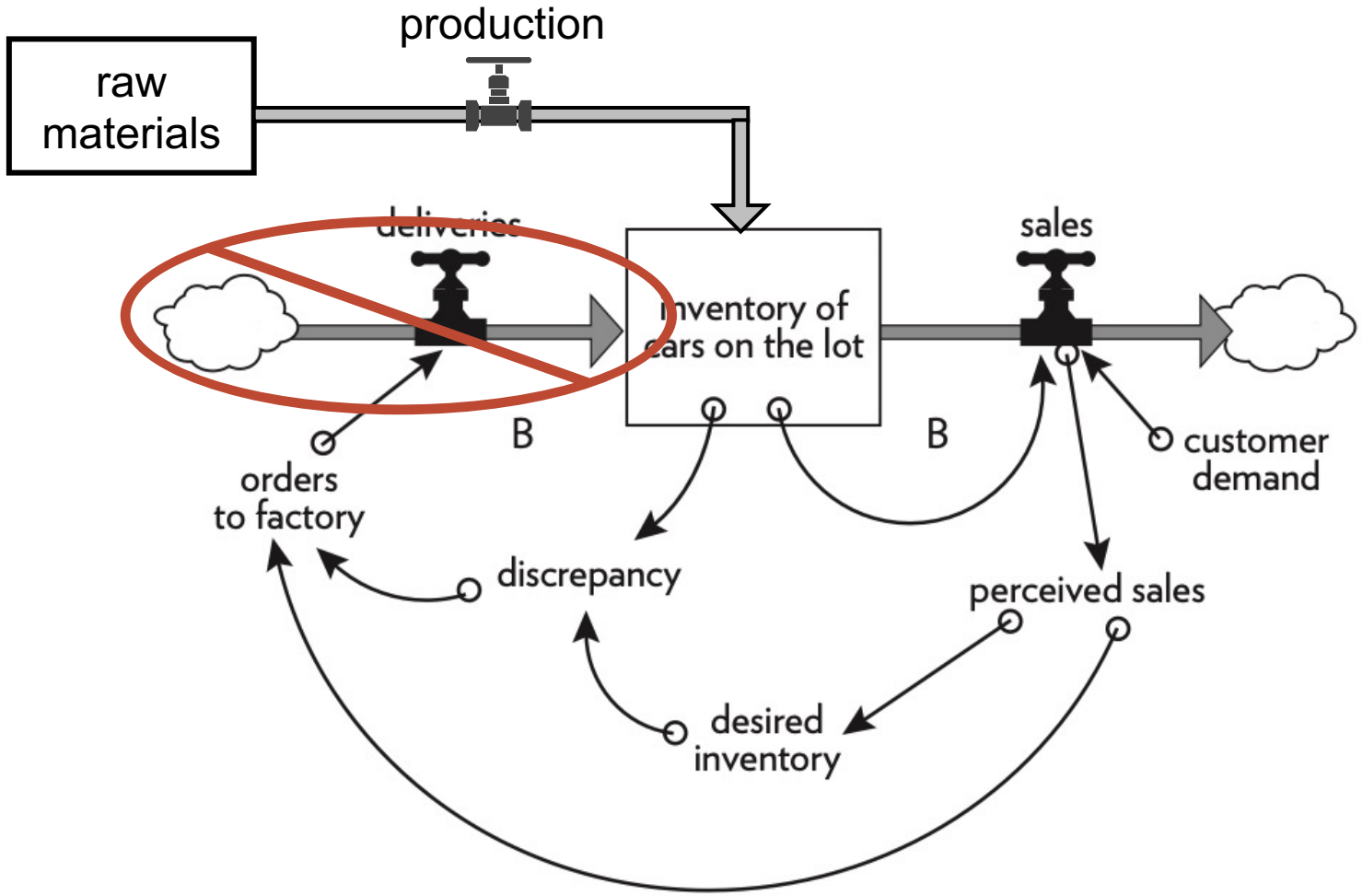
Nonlinearity

- As engineers, we are comfortable with this one ☺



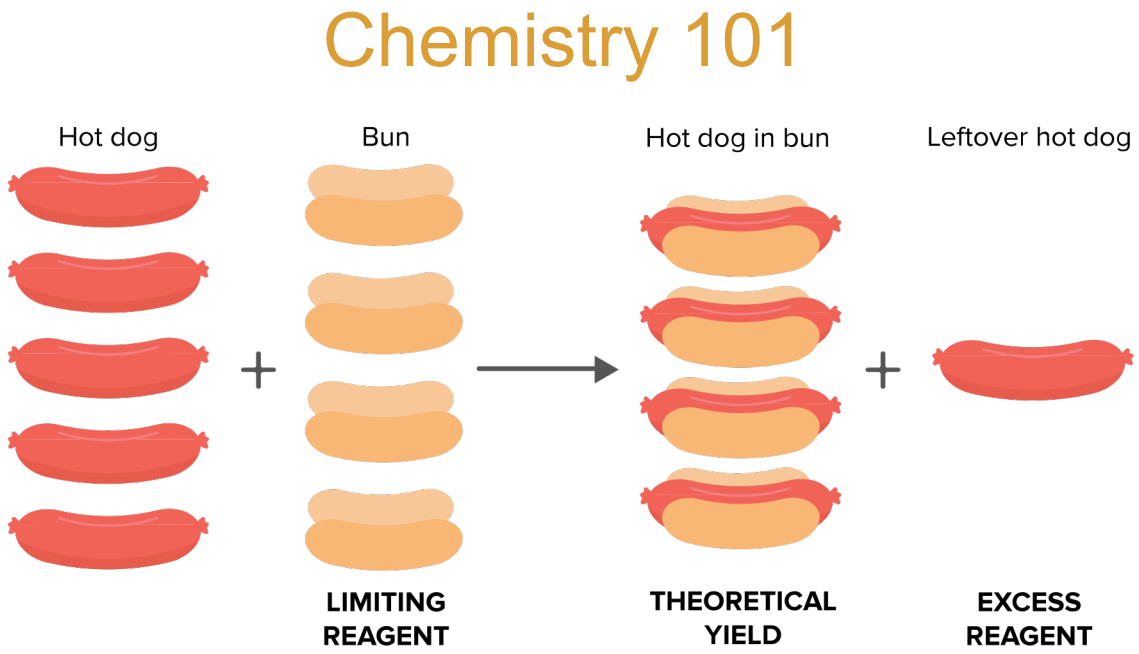
Boundaries

- Drawing boundaries is an essential part of the modeling process
- Boundaries need not be static
- Bigger isn't always better



Limiting factors

- The input that is the most important to the system is the one that is most limiting
  - With multiple inputs and outputs in a complex system, this identification is non-trivial
  - Limiting factors can change over time



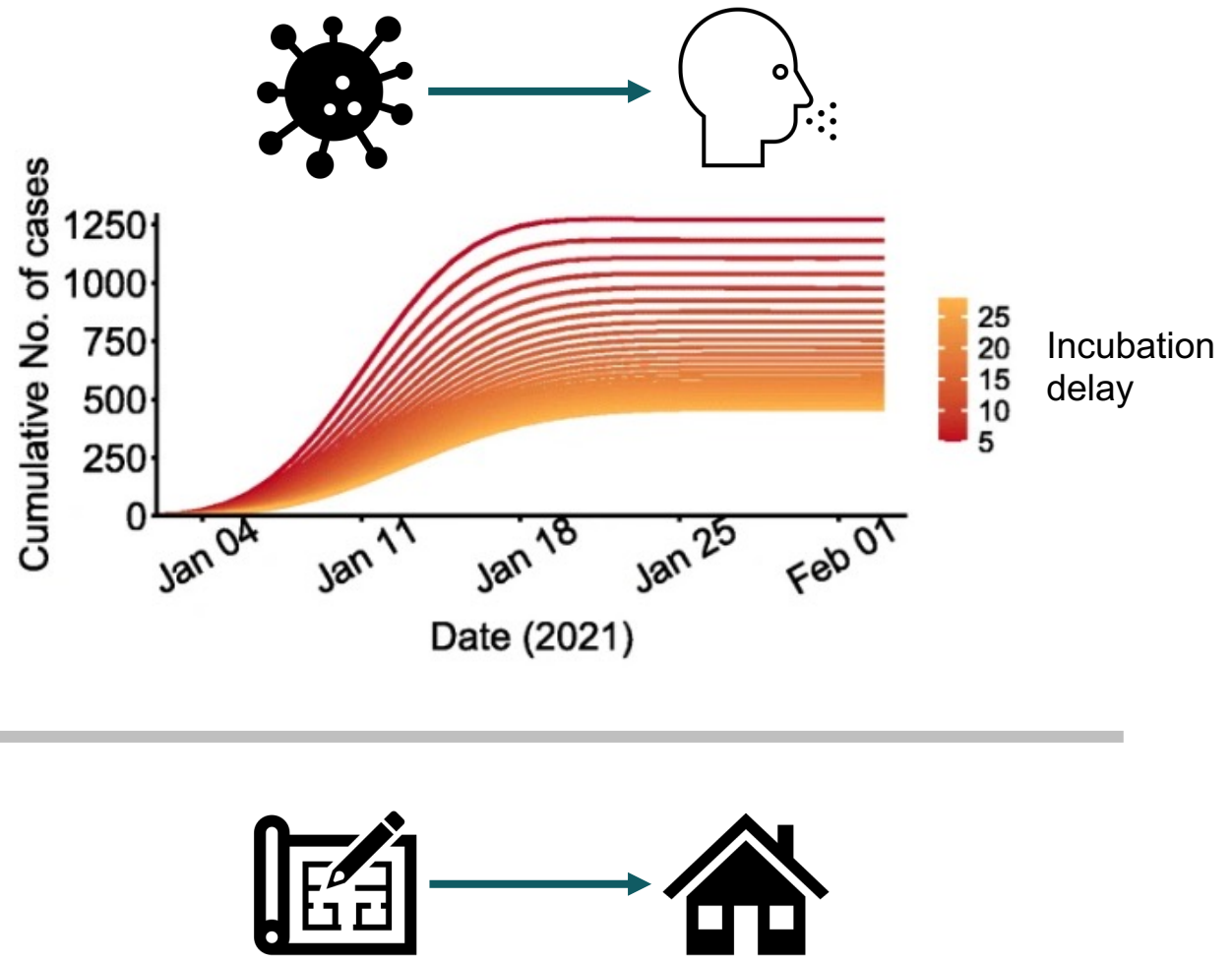
https://www.khanacademy.org/science/ap-chemistry-beta/x2eef969c74e0d802:chemical-reactions/x2eef969c74e0d802:stoichiometry/a/limiting-reagents-and-percent-yield

Limiting factors: startups

- Stocks
  - Money in bank (flows: investment/sales, expenses)
  - Inventory of product (flows: production of product, sales of product)
  - Workforce (flows: hiring of people, loss of people)
- Limiting factors can change over time as interventions are made

Ubiquitous delays

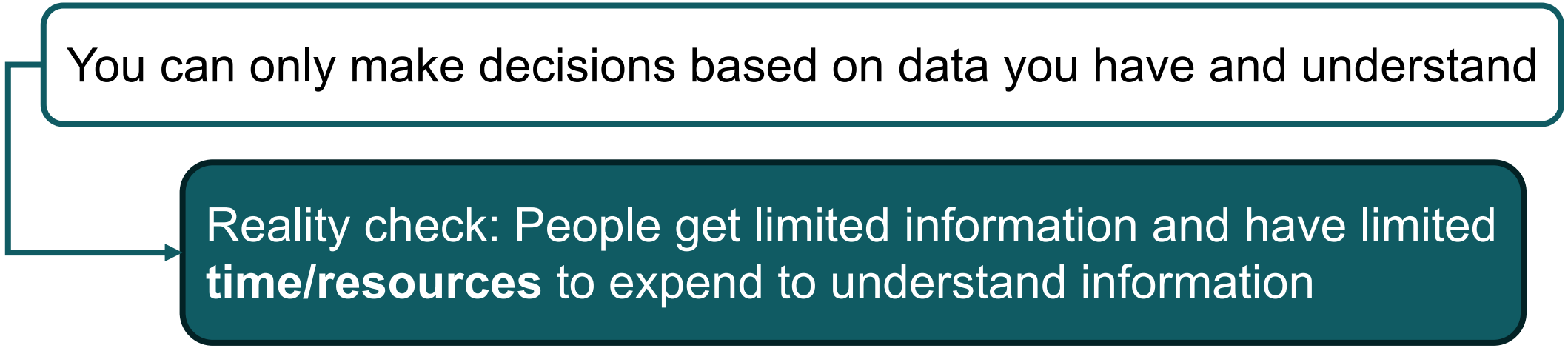
- Delays are everywhere
- Delays can have drastic impacts on system dynamics
- Delays are places to intervene (more on this later)
- Some delays can be shortened or lengthened



Zhu, W., Zhang, M., Pan, J. et al. Effects of prolonged incubation period and centralized quarantine on the COVID-19 outbreak in Shijiazhuang, China: a modeling study. BMC Med 19, 308 (2021).

Bounded rationality

- People make reasonable decisions based on the information they have
- People don’t always have access to perfect information, particularly about distant parts of the system or outside the system boundary



Bounded rationality example: eco-feedback

- Example from Meadows: identical houses used different amounts of energy based on the access to information
- Further line of questioning: How best to represent that information?

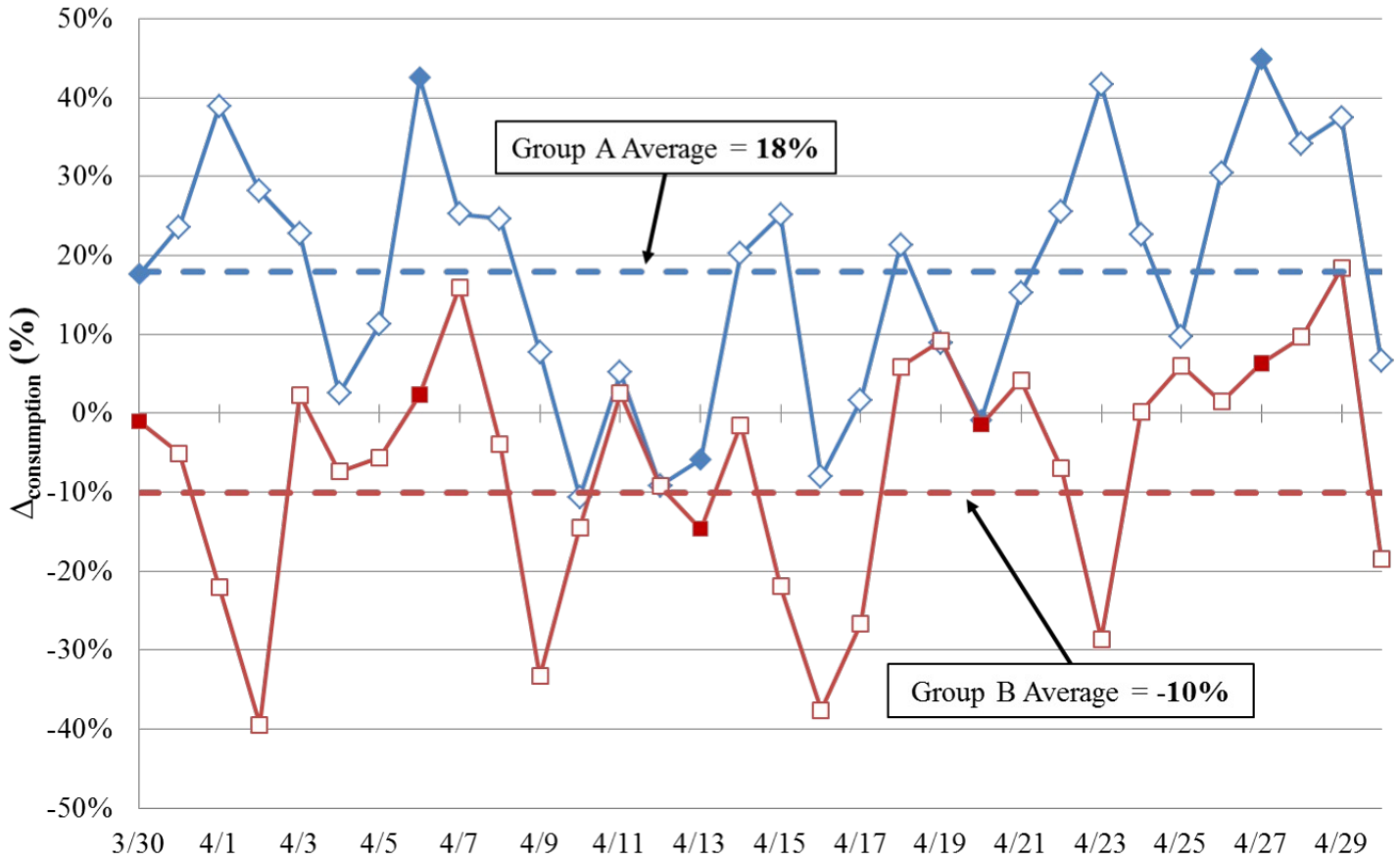
Study design

Group A:
Kilowatt-hours

Group B:
Equivalent trees required to offset CO_2 emissions

Jain, R., Taylor, J., and Culligan, P. (2013). “Investigating the Impact Eco-Feedback Information Representation has on Building Occupant Energy Consumption Behavior and Savings,” Energy and Buildings, 64: 408-414.

Bounded rationality example: eco-feedback



Group B used 28% less energy on average than Group A

What was the occupants' bounded rationality?

System intervention points

- Technical leverage points
    12. Constants, parameters, and numbers
    11. Sizes of stocks relative to their flows (buffers)
    10. The structure of system stocks and flows
    09. The length of delays relative to the rate of system change
- Feedback leverage points
    08. The strength of balancing feedback loops
    07. The strength of reinforcing feedback loops
- Social leverage points
    06. The structure of information flows (access to information)
    05. The rules of the system (incentives, punishments, constraints)
    04. The **power** to change system structure
    03. The goals of the system
- Transcendental leverage points
    02. The mindset or paradigm out of which the system arises
    01. The power to transcend paradigms