Lecture 05
Systems Thinking 4

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CIVIL 534: Computational systems thinking for sustainable engineering

19 March 2025

Outline

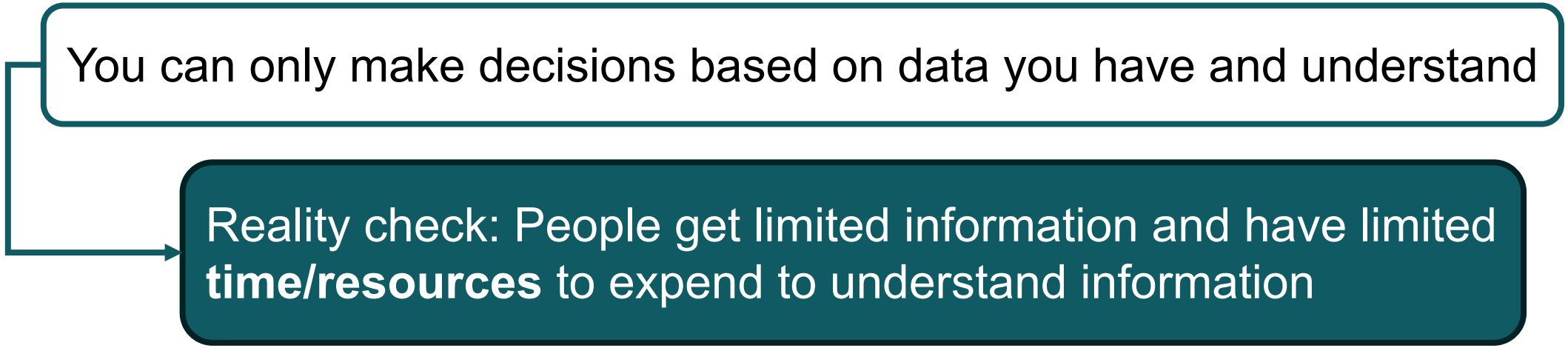
- Happy spring equinox!
- Indicative evaluation – your feedback is appreciated!
- Exam details
- Why systems surprise us
  - **Bounded rationality**
- Intervention points
- System traps and opportunities
  - Tragedy of the commons
  - Policy resistance / fixes that fail
  - Shifting the burden / addicted to interventions
  - Drift to low performance
  - Escalation
  - Success to the successful
  - Rule beating
  - Seeking the wrong goal
- Data-driven systems-of-systems approaches
- Review

Exam details

- Next class time – Wednesday 26th (9:15 to 11:00 am)
- Closed book and notes
- Content: based on materials in Lectures 1-5
- Format:
  - Multiple choice questions
  - Open-ended questions
  - Systems diagrams and systems behavior
  - No coding
- Practice questions on Moodle
- Tips:
  - Not intended to test memorization, but rather understanding of the material

Why systems surprise us: 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?

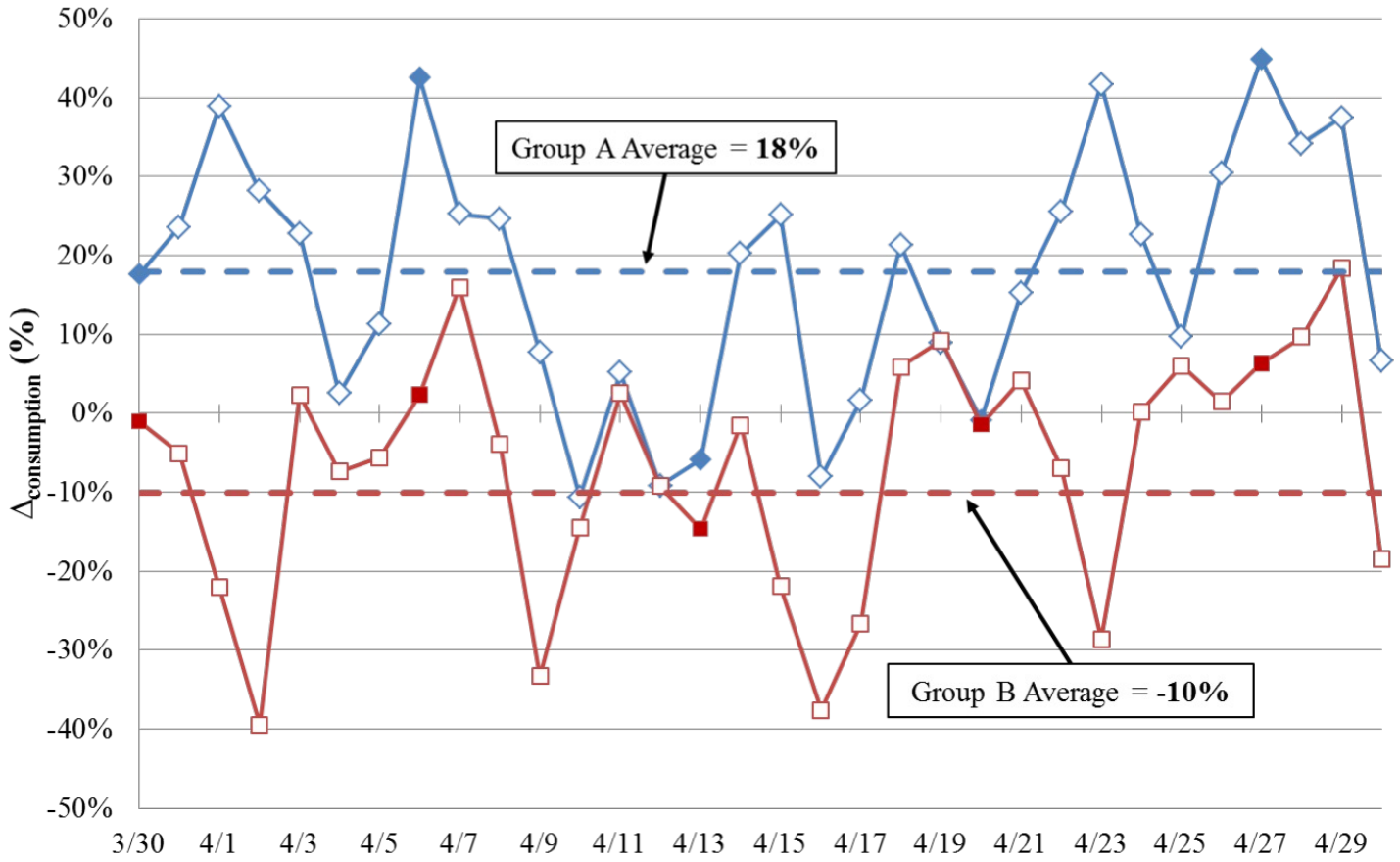
Study design

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

System traps… and opportunities

- Traps are common system behaviors in which we can get “stuck”
  - Various forms
  - Many result from system “archetypes”
- Traps create opportunities to intervene in a system

System ***surprises*** vs. system ***traps***

Why systems surprise us

- Causes of surprises are properties of all dynamic systems
  - e.g. nonlinearities, delays, etc.
- Can learn to better understand these causes and be less surprised

System traps

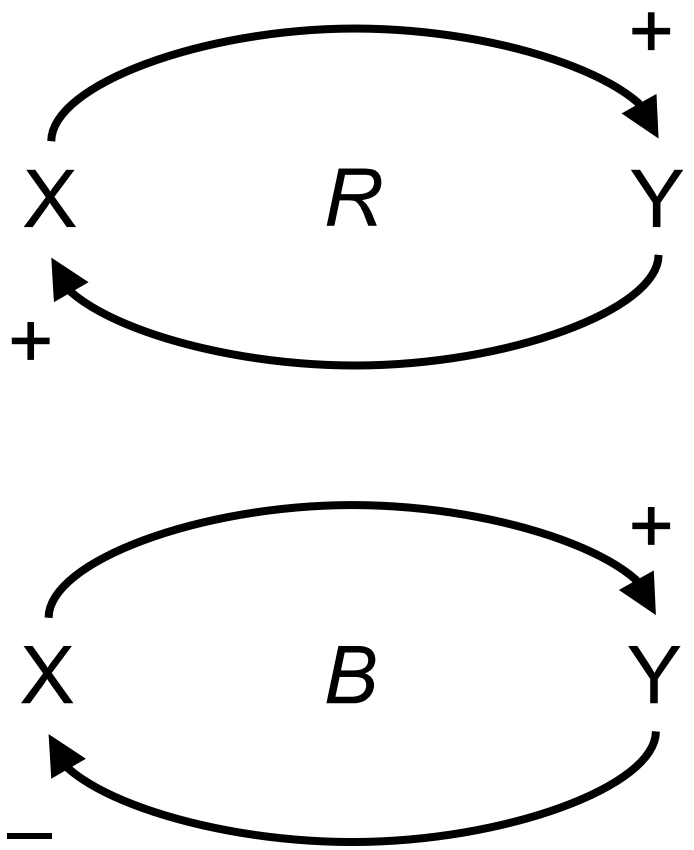
- Some systems produce problematic behavior because they follow some kind of ***archetype:***
  - System structures that produce common patterns of problematic behavior
- There are opportunities to escape these traps

Archetype #1: Tragedy of the commons

- Disconnect between user actions and consequences to a common resource (weak feedback loop)
- Some archetypes are so common they have made their way into common discourse

Interlude: causal-loop diagram (CLD)

- Visual tool for representing feedback loops in a system.
- Reduces stocks, flows, and variables to a single “variable” type
- Can be used to represent general system structure without getting into the details



Tragedy of the Commons example: Shared heating bill

- Energy cost for each occupant:

$$C_i = \frac{\sum_{j=1}^{n} E_j}{N}$$

- What is the weak feedback loop?

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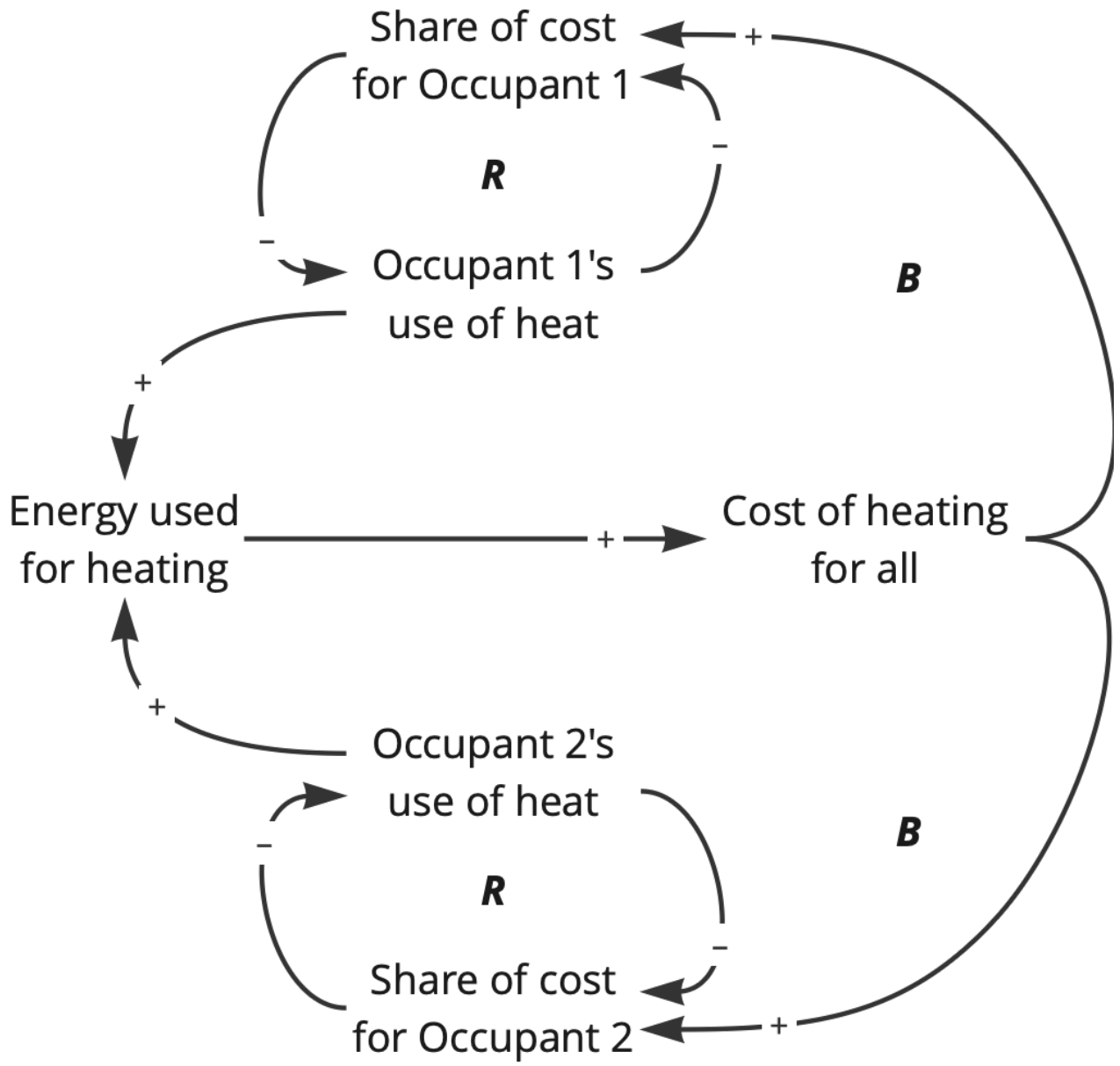
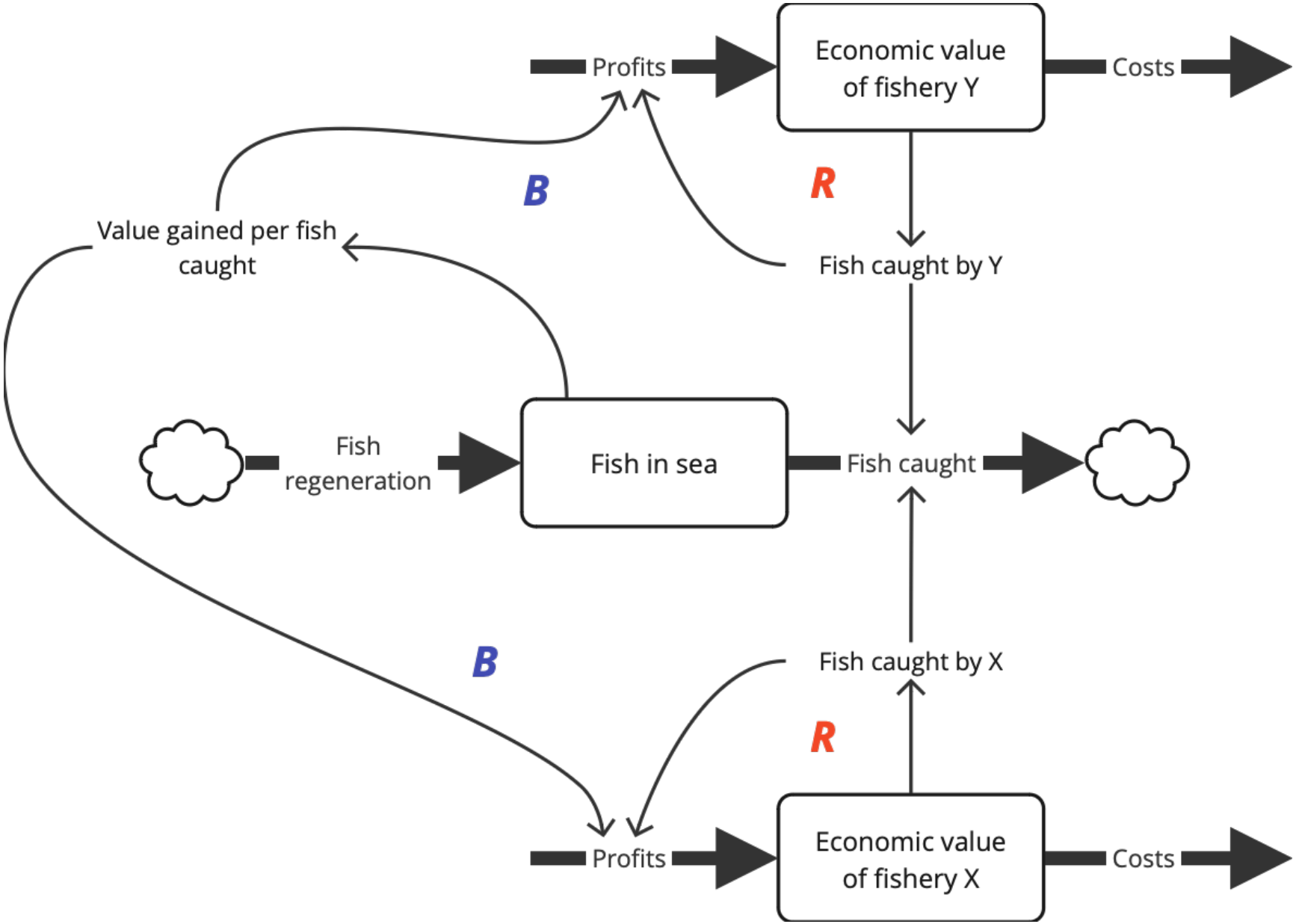


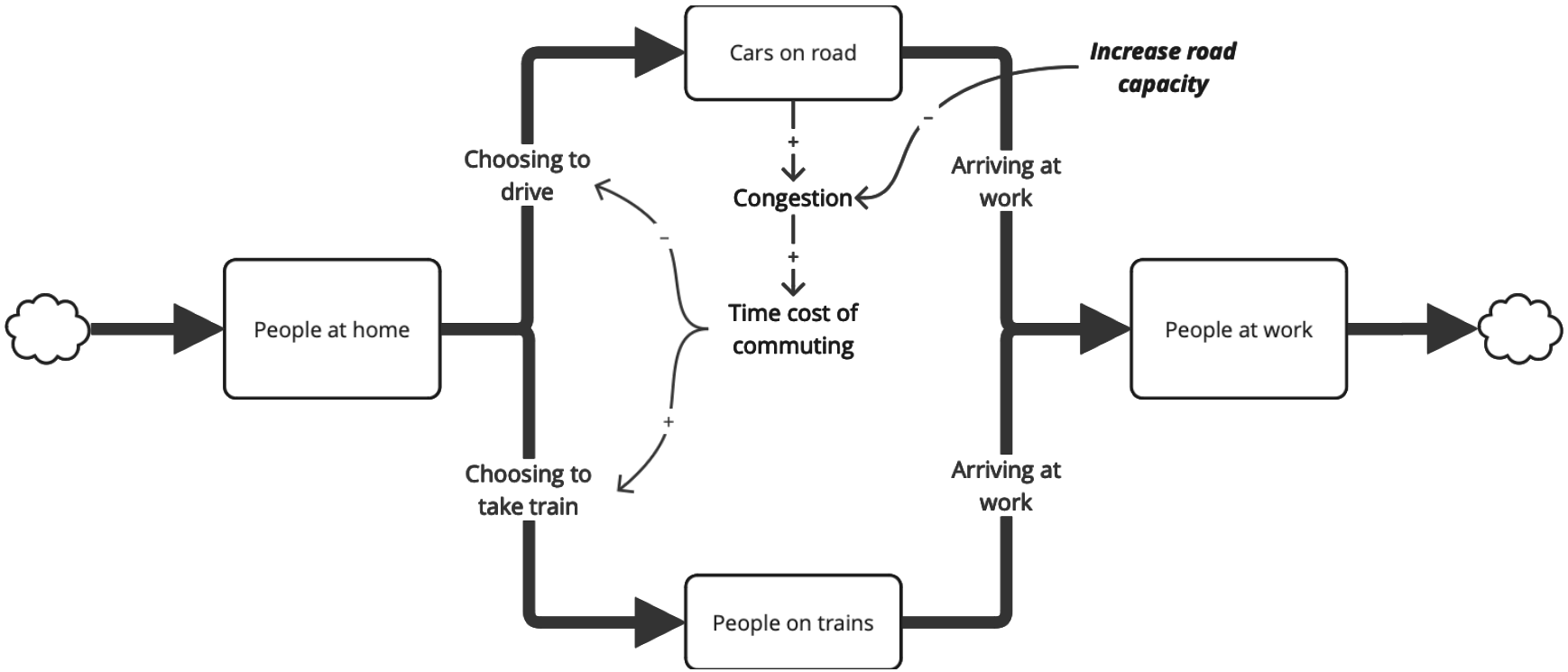

Profits
Economic value of fishery Y
Costs
B
R
Value gained per fish caught
Fish caught by Y
Fish regeneration
Fish in sea
Fish caught
B
Fish caught by X
R
Profits
Economic value of fishery X
Costs

Archetype #1: Tragedy of the commons

- Disconnect between user actions and consequences to a common resource (weak feedback loop)
- Some archetypes are so common they have made their way into common discourse
- ***Opportunities***:
  - Educate and exhort users: help people understand the consequences of their actions
  - Impose regulations
  - Strengthen weak feedback loops: how can we do this?

Archetype #2: Policy resistance / fixes that fail

- Various actors try to pull a system toward their goals
- Example: Multi-mode commuting



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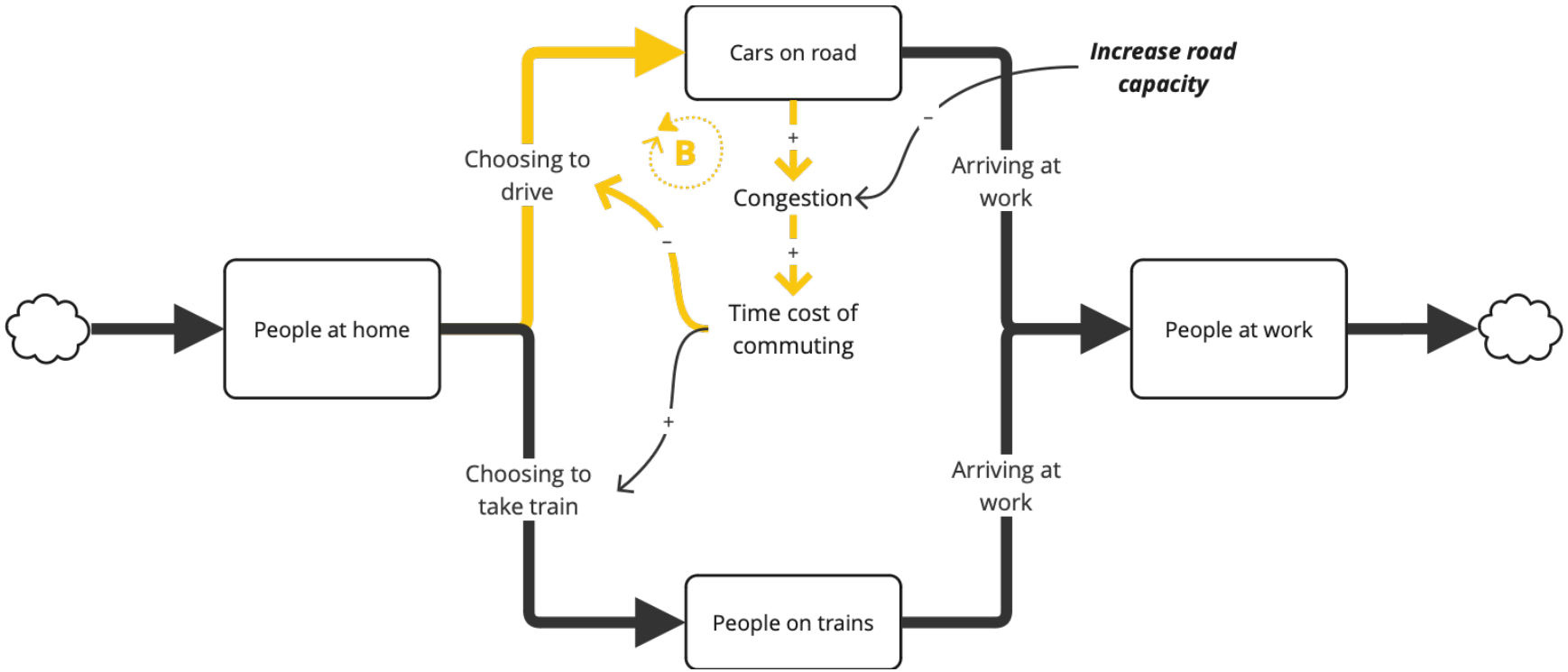


Archetype #2: Policy resistance / fixes that fail

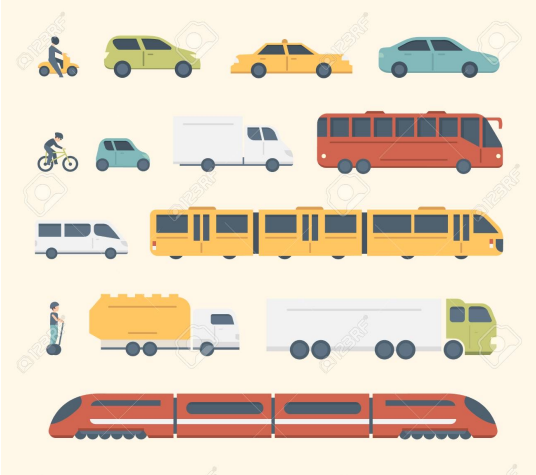
- Various actors try to pull a system toward their goals
- Example: Multi-mode commuting
- Causes:
  - Balancing feedback loops pull the system toward its ongoing state
  - Bounded rationality
- ***Opportunities***
  - Redefine larger and more important goals
  - Increase information sharing
  - Multi-mode commuting example: How can we reduce commuting times and reduce air pollution of commuting?

Archetype #3:
Shifting the burden / addicted to interventions

- Systems get addicted to interventions that mitigate issues and/or “fix” problems
- Similar to “policy resistance / fixes that fail” but involves repeated interventions
- ***Opportunities***:
  - Avoid
  - Focus on long-term relief
- Note: the need for interventions isn’t necessarily bad! We must be able to recognize when it is in fact a trap
  - Example: vaccines for smallpox, polio, etc.

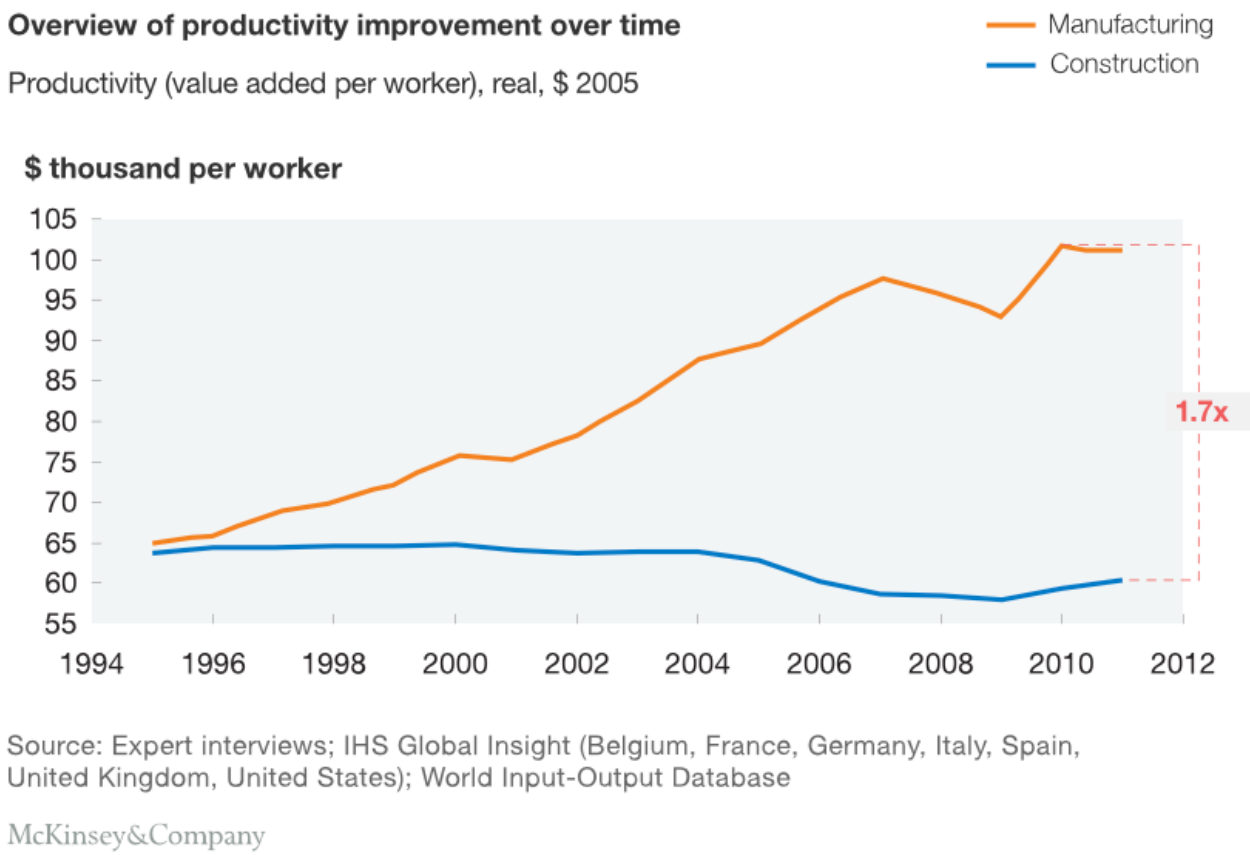
Avoiding system traps for multi-mode transit

- If we need more transit capacity, think about how all parts of the system are affected by interventions



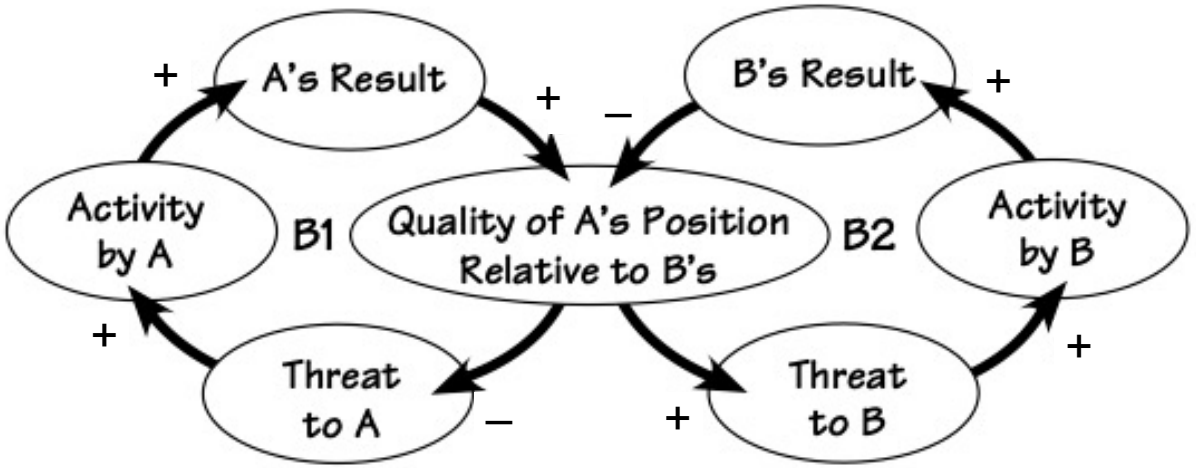
Archetype #4: Drift to low performance

- Mentality of “this is the best we can expect” leads to reinforcing loop of degrading performance over time
- Example: infrastructure project costs and delivery
- ***Opportunities:***
  - Absolute standards
  - Positive reinforcement for standards

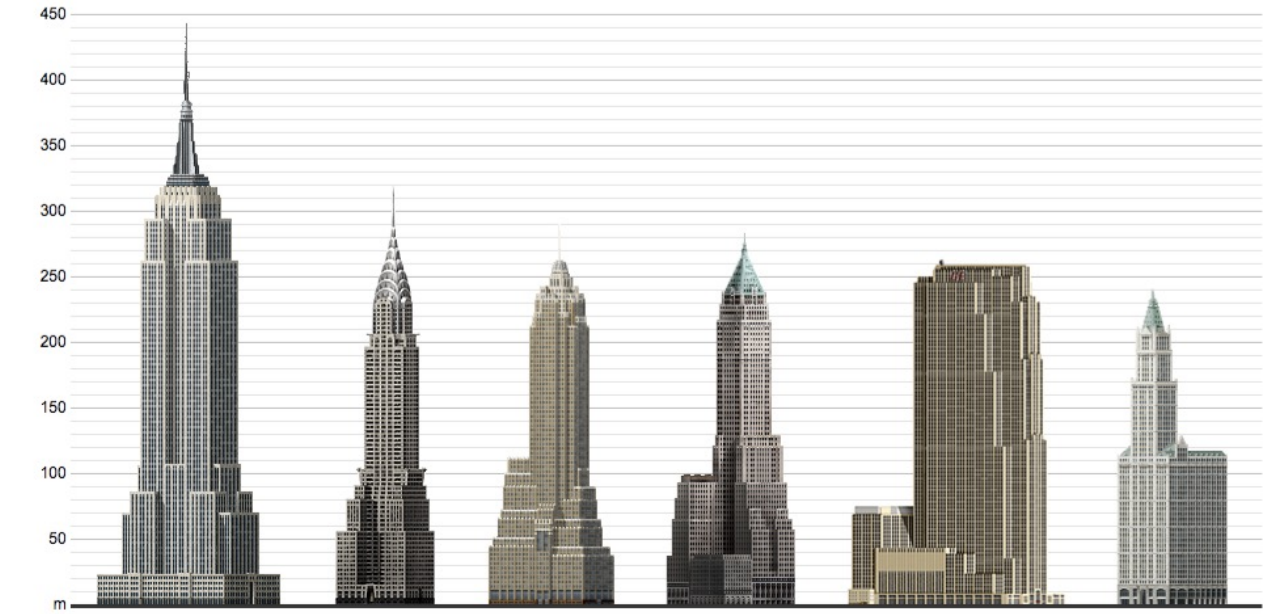


Archetype #5: Escalation AKA “arms race”

- One participant’s actions are influenced by the state of another participant
- How can 2 balancing feedback loops lead to reinforcing behavior?
- ***Opportunities***:
  - Avoid (Meadows)
  - Is escalation ever good?



Escalation: Skyscraper race led to innovation in structural engineering



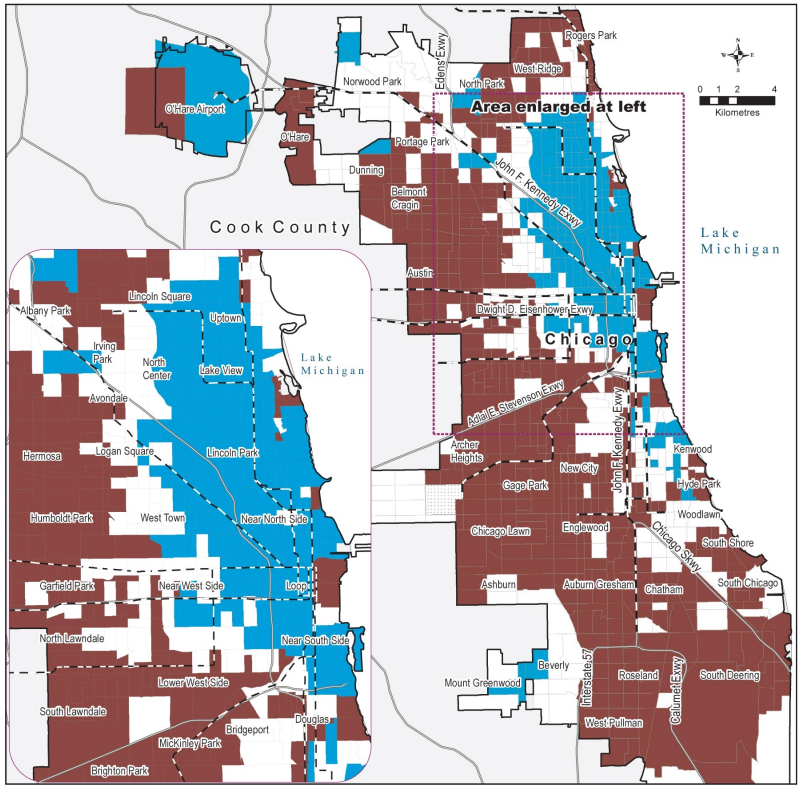
Name	Empire State Building	Chrysler Building	70 Pine Street	40 Wall Street	GE Building	Woolworth Building
City	New York City NY	New York City NY	New York City NY	New York City NY	New York City NY	New York City NY
Country	United States	United States	United States	United States	United States	United States
Illustrator	Steamboy	Someformofhuman	Steamboy	F16 freak	FrankK	Steamboy
Status	Built	Built	Built	Built	Built	Built
Built	1931	1930	1932	1930	1933	1913
Floors	102	77	67	71	70	57
Use	Office	Office	Mixed use	Office	Office	Mixed use
Antenna	443.2 m					
Spire		318.9 m	290.2 m	282.5 m		
Roof	381 m	282 m	259.1 m		259.8 m	241.4 m

Escalation for innovation in urban systems engineering?

Archetype #6: Success to the successful

- Those who have the upper hand gain an advantage to continue their success
- ”The rich get richer”
- Example: neighborhoods, tax revenue, and housing prices
- ***Opportunities***:
  - Diversify if you can
  - Policies to level the playing field – what policies would you put in place?

Neighborhood Income Change, City of Chicago 1970-2010



Change in census tract average individual income compared to the Chicago MSA average, 2010 versus 1970

- Increase 20% to 254% (167 CTs; 21% of the City)
- Increase or Decrease is Less than 20% (210 CTs; 26% of the City)
- Decrease 20% to 114% (417 CTs; 53% of the City)

Income Definition: Census tract average individual income for persons age 15 and older. Data Sources: 1970-2000 Decennial Census, 2008-2012 Five-Year American Comunty Survey.

Image produced by Cities Centre, University of Toronto.

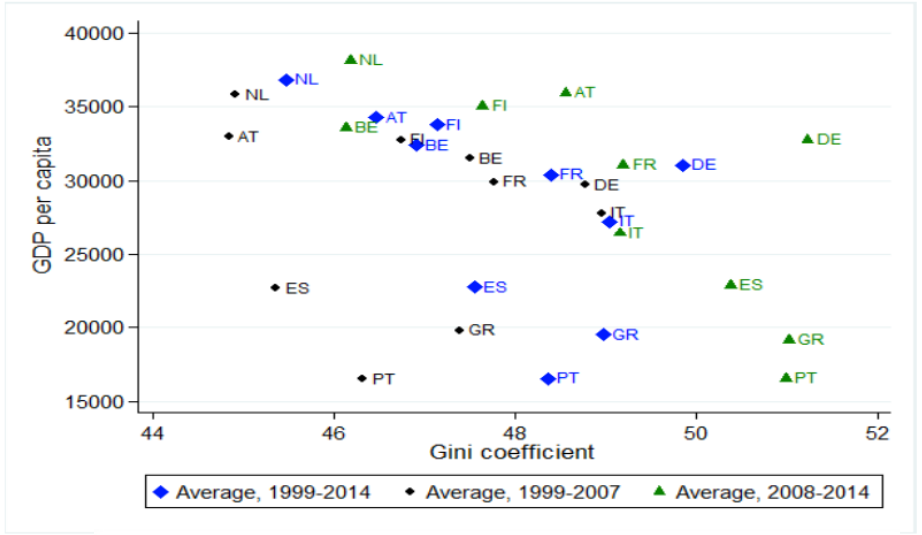
Trap: Rule beating (finding loopholes)

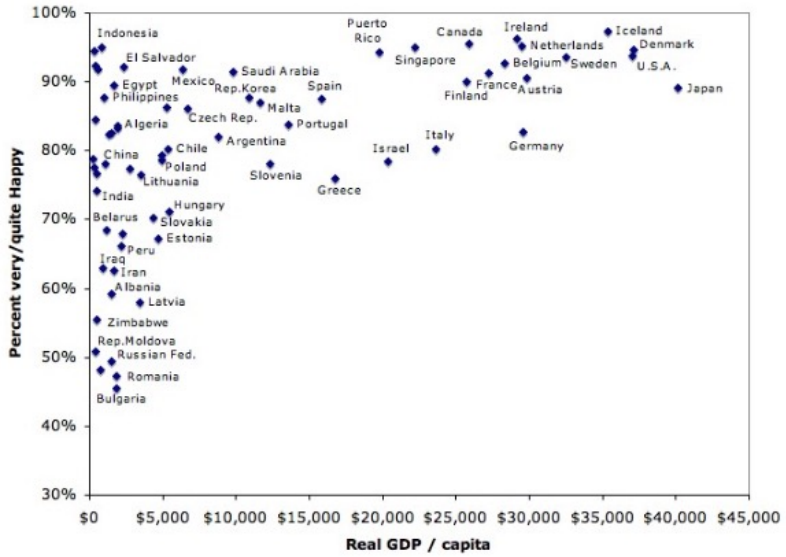
- Not necessarily tied to a specific archetype
- Following the letter of the law → working in the “gray” areas
- Opportunities:
  - Redesign rules to encourage adoption of the “spirit” of the law
  - Redesign rules to release creativity not in the direction of beating the rules, but in the direction of achieving their purpose

Trap: Seeking the wrong goal

- Optimizing the system for non-holistic and/or long-term goals
- Example: GDP vs. (in)equality vs. happiness
- ***Opportunities***:
  - Redefine metrics
  - Focus on results not effort

Figure 2: **Income inequality and GDP per capita in EA countries**





SamarIna, Anna and Nguyen, Anh D. M., Does Monetary Policy Affect Income Inequality in the Euro Area? (March 8, 2019). De Nederlandsche Bank Working Paper No. 626

More on leverage points

System intervention points

- Technical leverage points
    12. Constants, parameters, and numbers
    11. Sizes of stocks relative to their flows (buffers)
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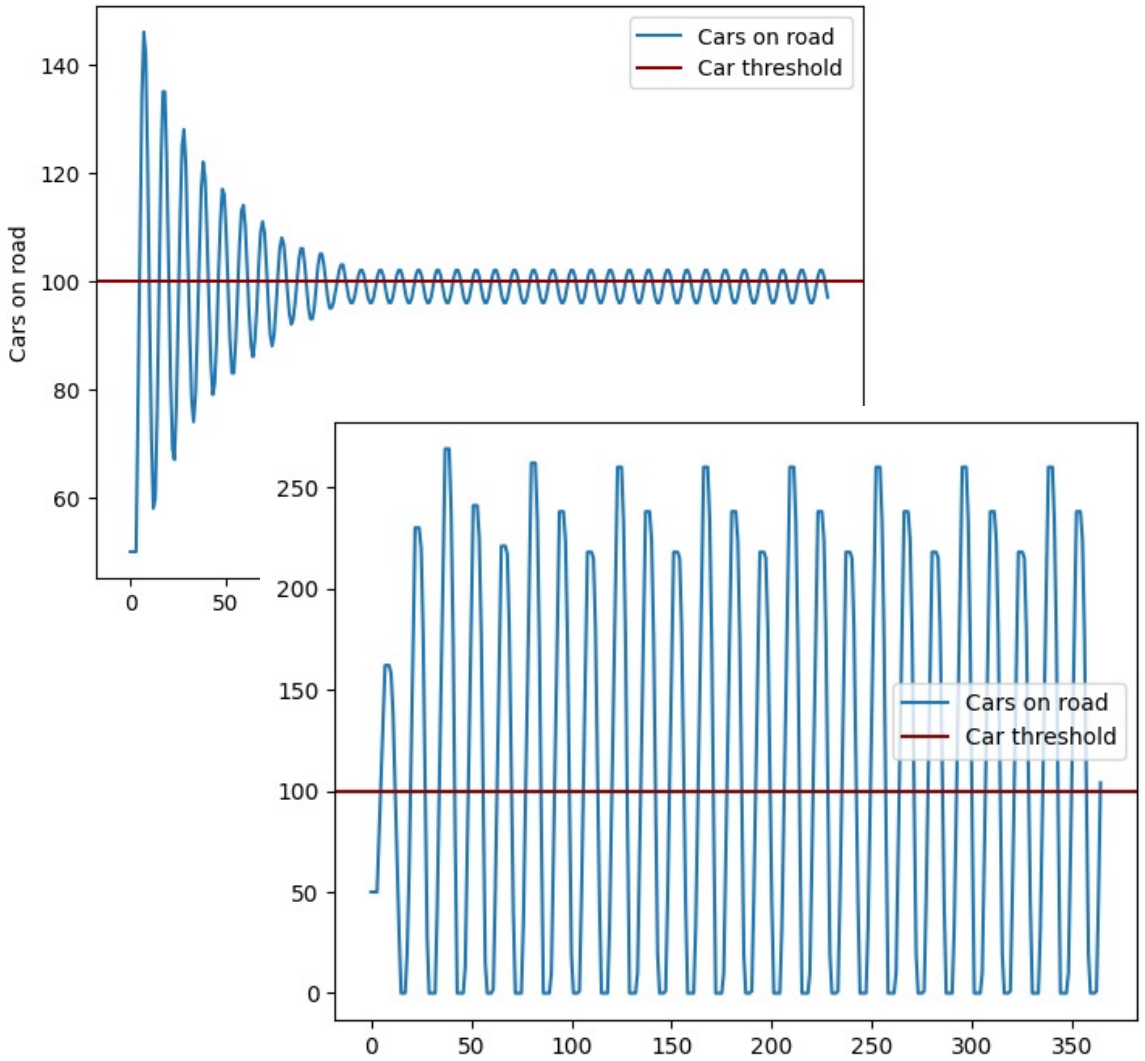
Example from “Urban Dynamics”

- In “Urban Dynamics,” Forrester found that more low-income housing led to worse outcomes
  - Controversial finding
- “High leverage wrong direction”
- Does this mean that all low-incomes housing is bad?
- Limitations to the model?
- **Key takeaway: Some system responses are counterintuitive**

Source: WBEZ Chicago

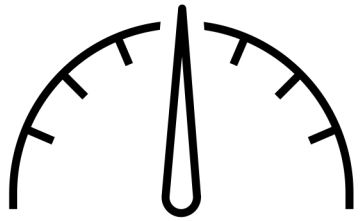
Urban system interventions: Length of delays

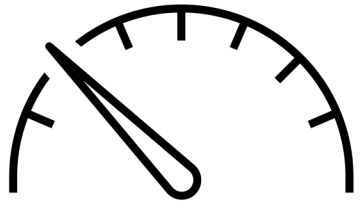
- Short delays can cause problems
  - Remember the “response delay” from the car dealership example
- Long delays can cause problems too
  - Remember the delays in the car restriction modeling from the homework
- There is value in asking “what if” questions and simulating behavior



Urban system interventions: Information flows

- Limitations due to information flows can play an important role in urban systems
  - Example: Bounded rationality and energy use behavior
- Another example:
  - Two sets of Dutch houses, completely identical except for one difference
    - In one set of houses, the electric meter was in the basement
    - In the second set, the electric meter was in the front hall
  - In the second set, occupants used 30% less electricity





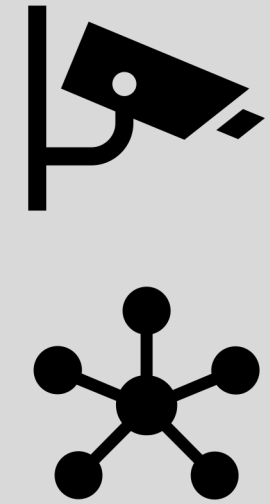
How can we improve information access?

- A **smart city** is an urban development vision to integrate multiple information and communication technology (ICT) and Internet of Things (IoT) solutions in a secure fashion to manage a city's assets – the city's assets include, but are not limited to, local departments' information systems, schools, libraries, transportation systems, hospitals, power plants, water supply networks, waste management, law enforcement, and other community services. The goal of building a smart city is to improve quality of life by using urban informatics and technology to improve the efficiency of services and meet residents' needs.

(credit – Prof. Rishee Jain)

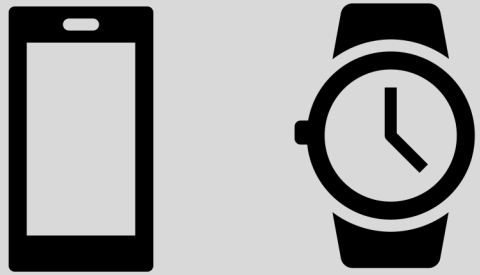
What kind of data?

Sensors



e.g. smart meters

Personal data



e.g. mobile phones

Open data

e.g. government records

Cities + data = smart?

- Data is helpful if it allows you to make decisions at the operational time and spatial scales
- You can only manage what you measure!
- Complex issues require complex decision-making
  - Data can help but is not the answer in itself

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

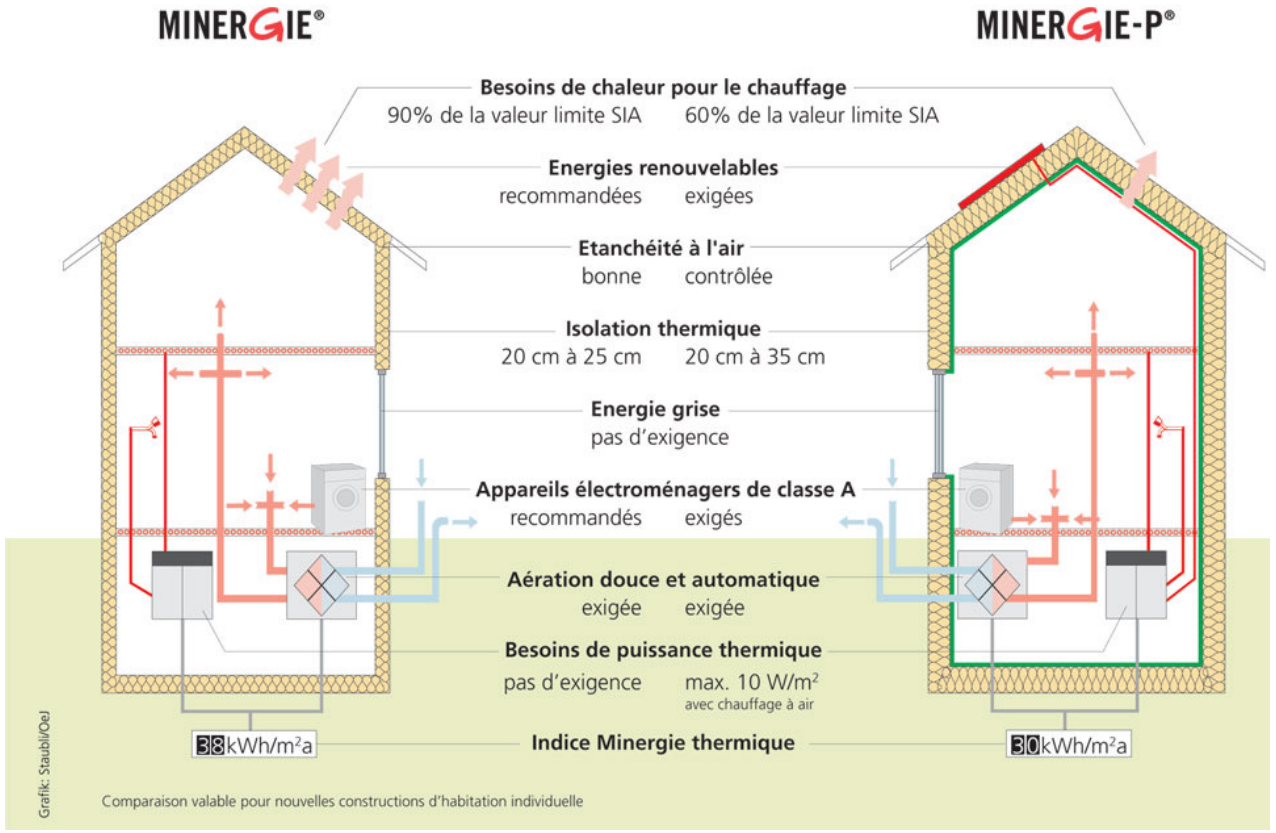
Problem	*Timescale*	*Spatial scale*	*Outcome metric*
Transportation (buses, subway)	Minutes	Meters	Simple
Fire	Minutes	Meters	Simple
Epidemics (HIV, influenza)	Years, days	Citywide	Simple
Chronic diseases	Decades	Citywide	Simple
Sanitation	Years	Citywide	Simple
Crime	Minutes	Meters	Simple
Infrastructure (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

Role of data in designing and managing urban systems

- Access to information is a common thread in addressing system traps and in designing effective interventions
- Is more data always good?
- Are there risks to data collection?

Data-driven decision-making in urban systems

- When designing, managing, or operating a systems in the built environment (e.g., building, transport system, etc.) we often use decision-making frameworks
- Example: Building rating systems (LEED, Minergie)

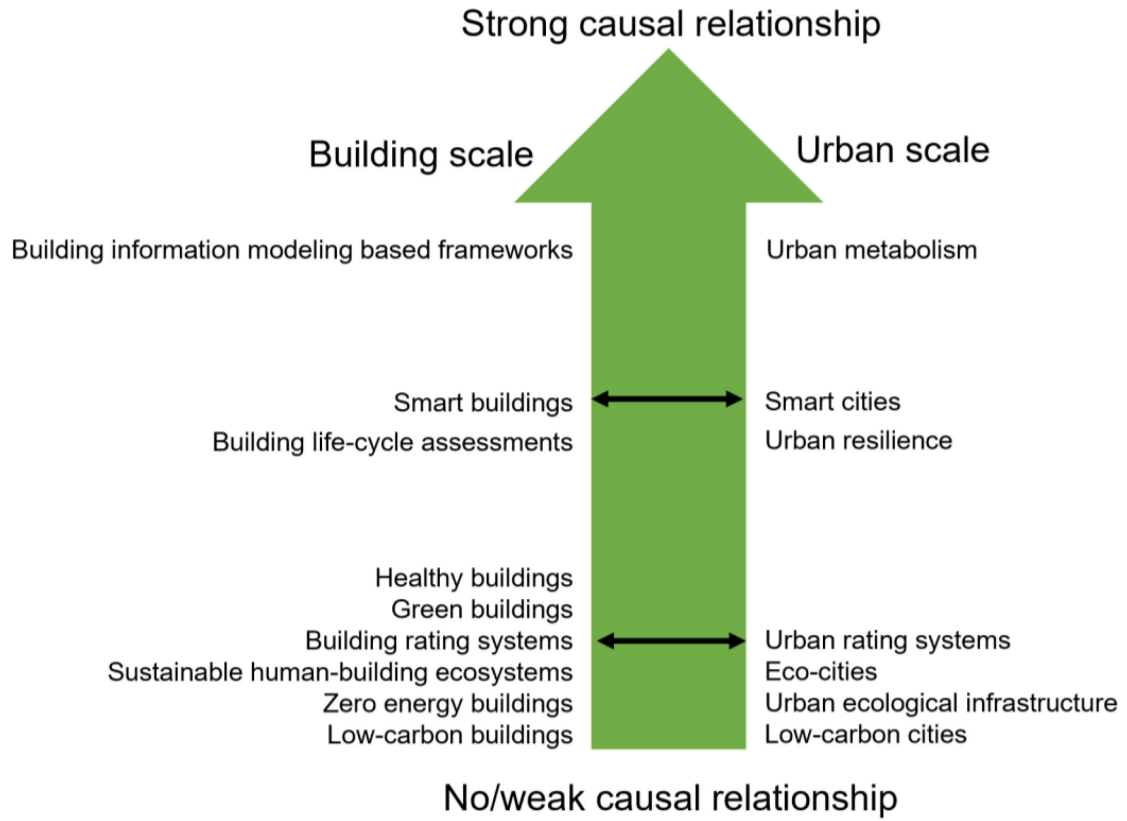


swissbois.ch

Data-driven decision-making in urban systems

- Challenge: Decision-making frameworks like LEED/Minergie are checklists
  - They do not establish **causal links** between different parts of the system
  - Example: Building air quality, building energy consumption, and HVAC system materials are inherently linked

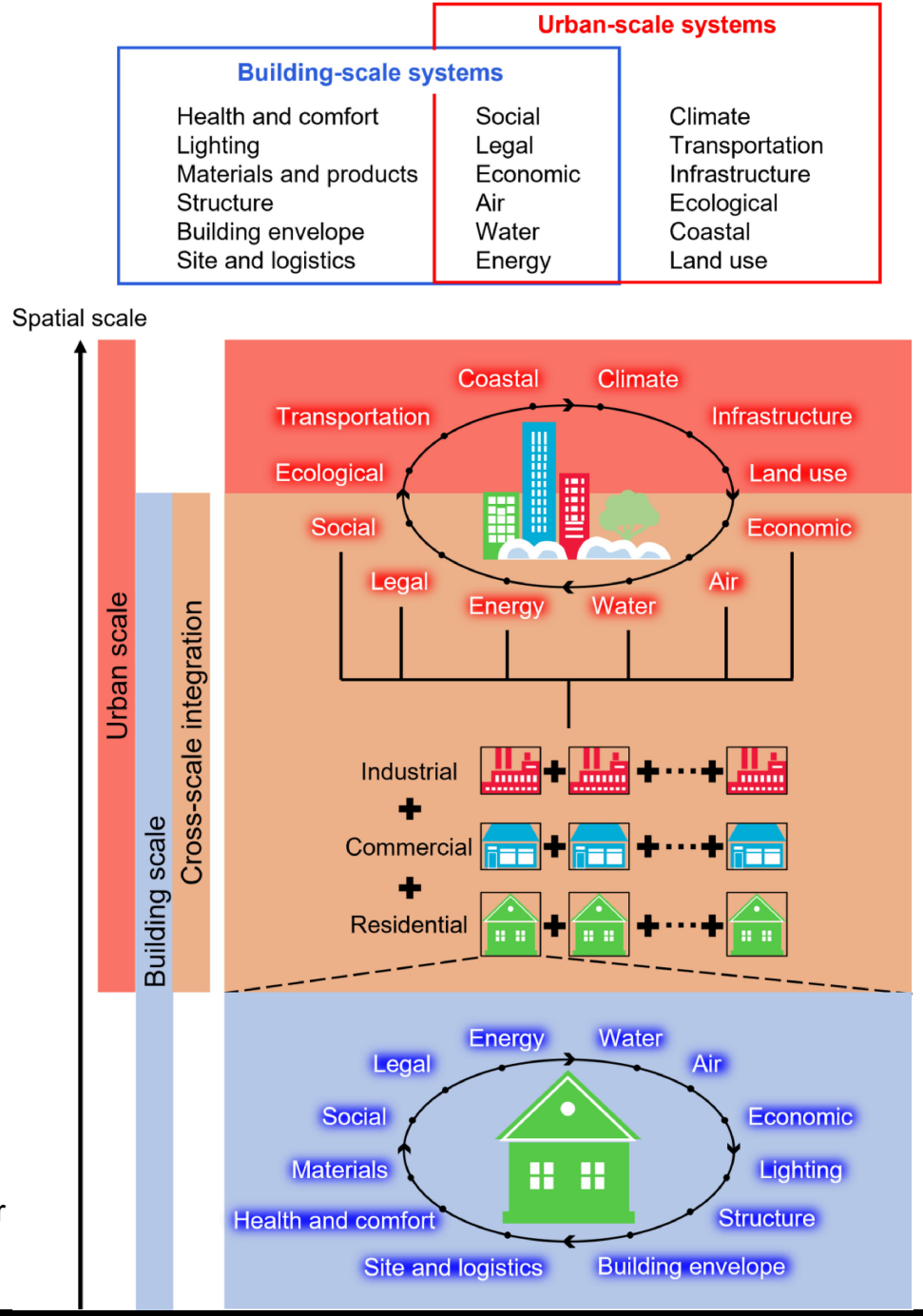
Building and urban scale assessment frameworks



C. Bi and J. C. Little, “Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach,” *Sustainable Cities and Society*, vol. 82, p. 103915, Jul. 2022, doi: 10.1016/j.scs.2022.103915.

Food for thought: Developing "**systems of systems**" approaches

- While not an easy task, researchers have proposed frameworks for linking systems and scales
- Challenges
  - Interoperability (model integration)
  - Computational costs
  - Too many systems to consider at once?



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Systems thinking review

Key concepts from Lecture 1

- What is a system?
- What makes a system complex?
- Why do cities grow?

Key concepts from Lecture 2

- What makes systems thinking different from other types of analysis?
- Systems vs. collections
- Stocks
- Flows
- Boundaries
- Object oriented programming
- Buffers
- Feedback loops (balancing and reinforcing)

Key concepts from Lecture 3

- Delays
- Multi-stock systems
- Representing systems mathematically
- Approaches for building models
- How to assess model dynamics

Key concepts from Lecture 4

- System characteristics
  - Resilience
  - Self-organization
  - Hierarchy
- Why systems surprise us
  - Structure vs. behavior
  - Nonlinearity
  - Boundaries
  - Limiting factors
  - Delays
  - Bounded rationality

Key concepts from Lecture 5 (today)

- System leverage/intervention points
- System traps and opportunities
  - Tragedy of the commons
  - Policy resistance / fixes that fail
  - Shifting the burden / addicted to interventions
  - Drift to low performance
  - Escalation
  - Success to the successful
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