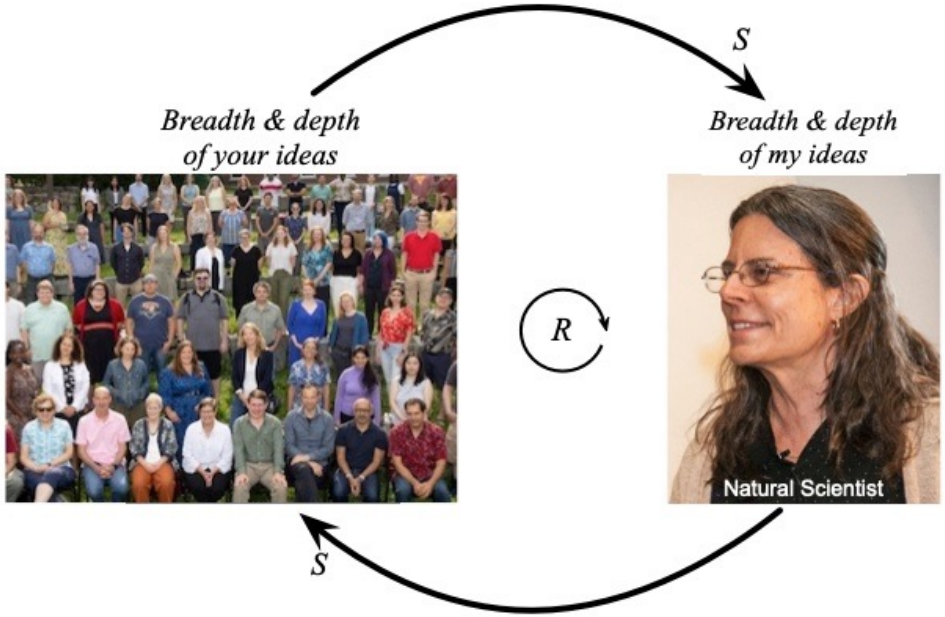
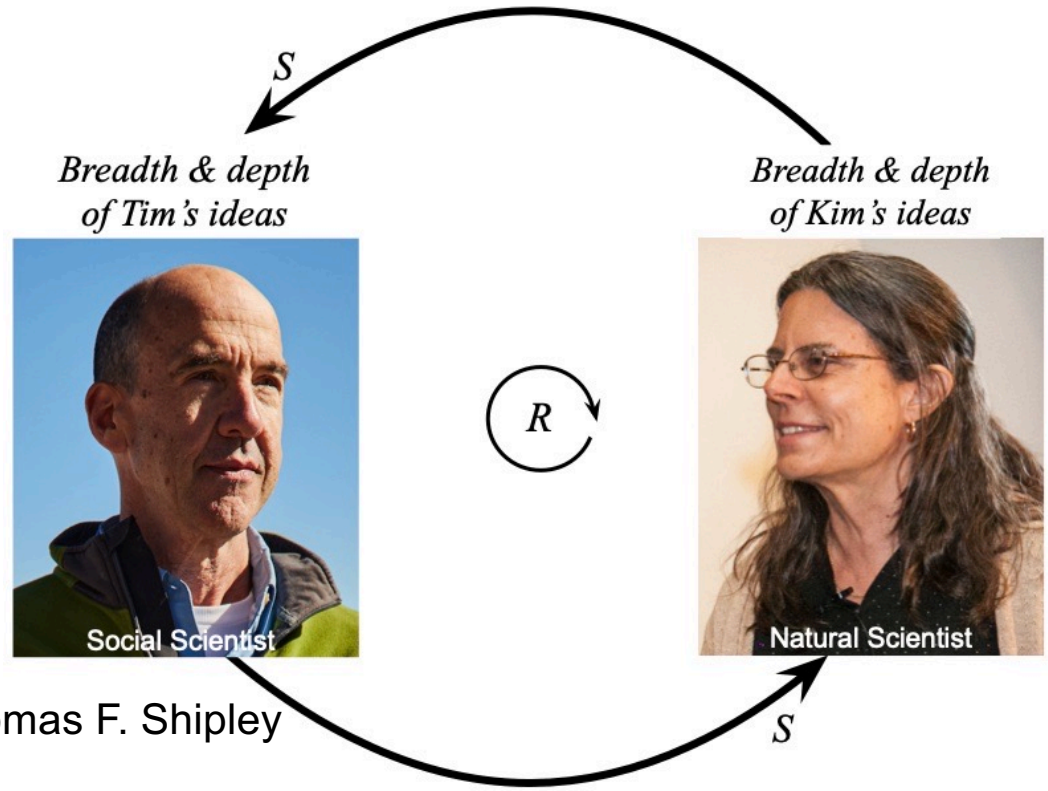
Visualizing invisible causal systems:
Using causal loop diagrams to create, improve, and convey mental models of feedback loops

Kim Kastens
Lamont-Doherty Earth Observatory
of Columbia University

Gordon Research Conference on
Visualization in Science & Education
Bates College, July 13, 2025



A team effort:



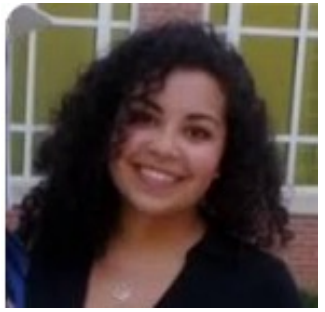
Thomas F. Shipley

Alix Davatzes

Logan Brenner

Courtney Sheckler

Mansi Shah



Rebekah Banerjee

National Science Foundation IUSE grants, *Supporting Feedback Loop Learning in Natural and Social Science Courses*: Kastens (2141939), Shipley (PI) & Davatzes (2142010), and Brenner (2141982).

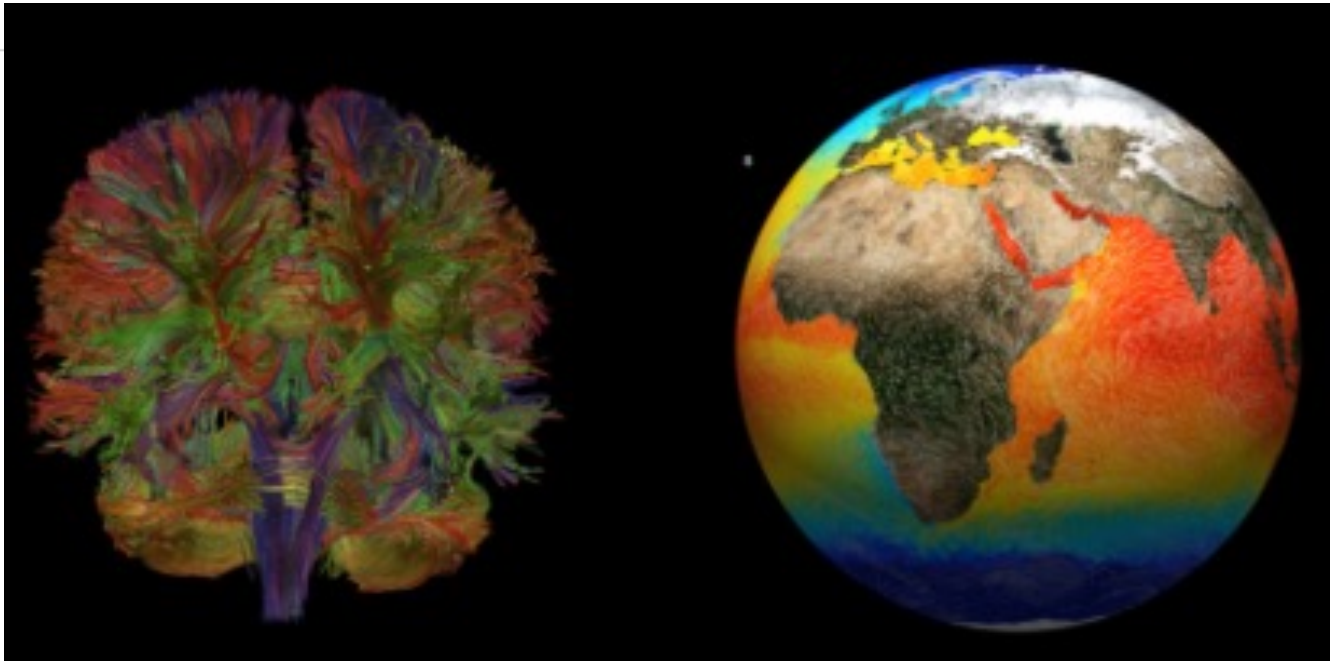
This marvelous conference, in recent years, has mostly been about data visualizations

Visualization in Science and Education

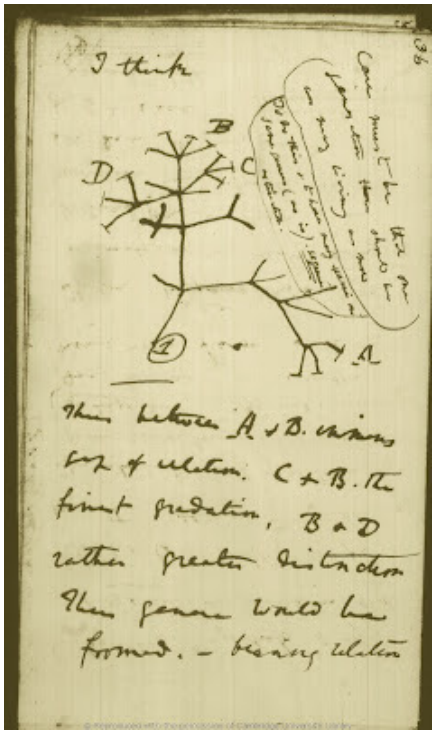
Gordon Research Conference

Visualizing Complex Systems

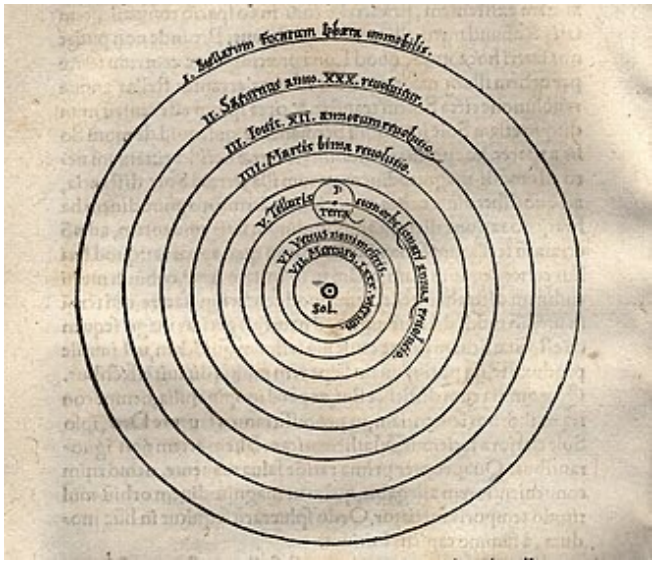
July 16 - 21, 2023



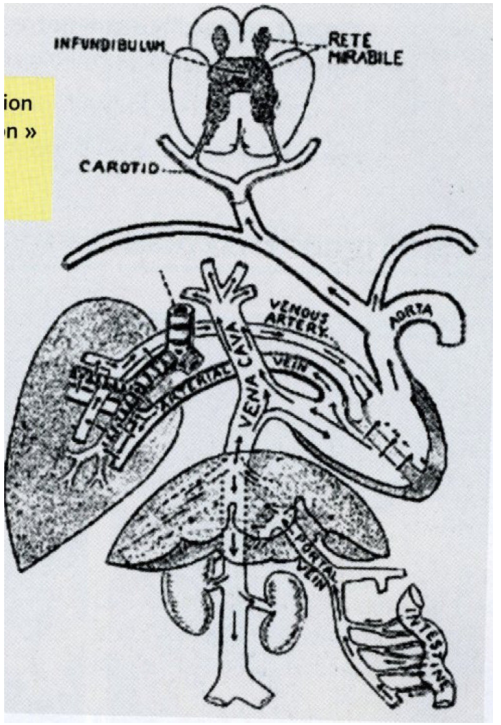
I want to push the boundaries of our conversation this week to embrace concept visualizations



Charles Darwin

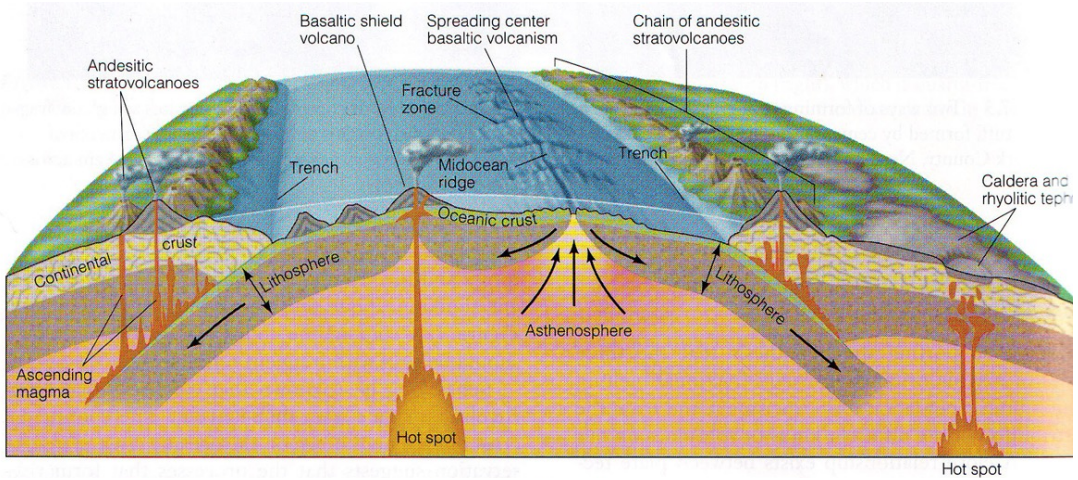


Nicolaus Copernicus

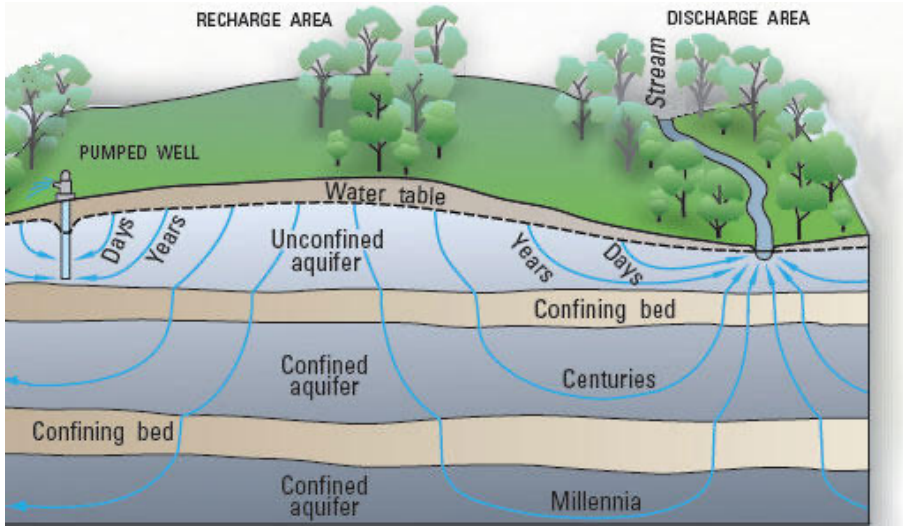


William Harvey

… concept visualizations

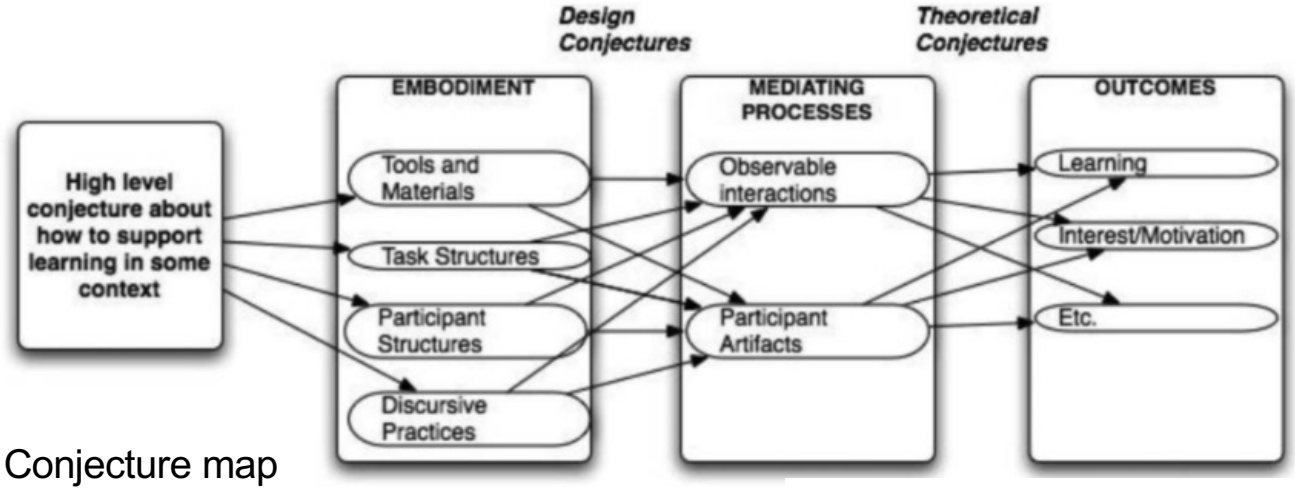


Skinner, Porter & Botkin (1995) *The Blue Planet*

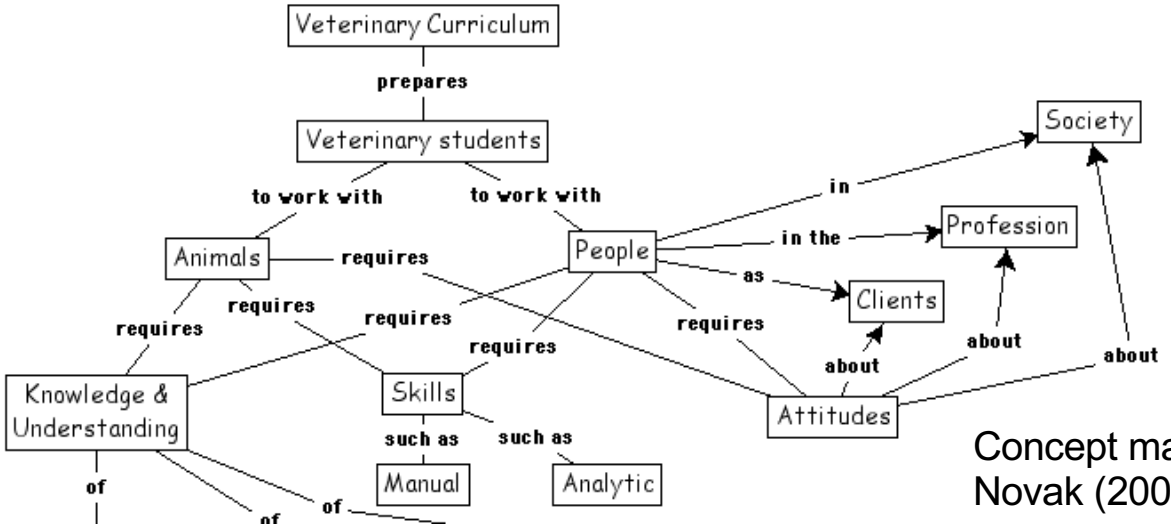


U.S. Geological Survey

… concept visualizations



Conjecture map
Sandoval (2014)



Concept map
Novak (2008)

Key attributes of concept visualizations

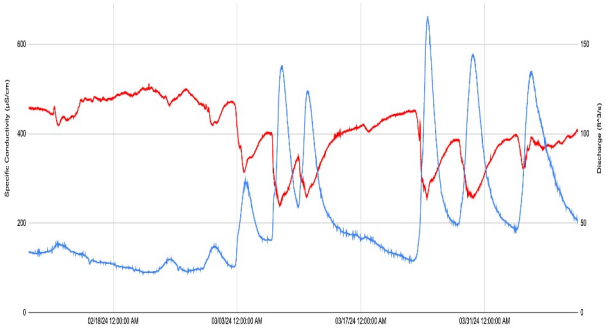
- They [can] combine a lot of information and ideas, of different kinds, into one image.
- They [usually] generalize across multiple instances, rather than depicting a single instance.
- They are good for depicting relationships: spatial, temporal, causal, hierarchical.
- They [often] support “running” a mental model, and thus are good for depicting processes.
- They [can be] valuable for “so what?” and “what next?” thinking: brainstorming explanations, predictions, interventions, solutions.
- They are tools for thinking, not just communication devices.

Why should you care about concept visualizations?

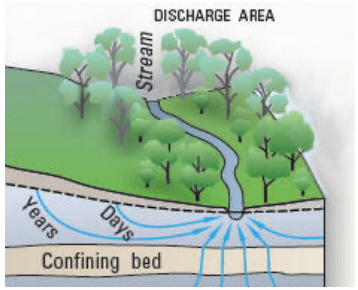
Sensors deployed in the real world

Date Time, GMT-05:00	Conductivity	Temp	Specific Conductance	S
	µS/cm	°C	µS/cm	
02/08/24 10:33:32 AM	255.9	1.34	459.3	
02/08/24 10:48:32 AM	255.8	1.35	458.9	
02/08/24 11:03:32 AM	255.8	1.39	458.4	
02/08/24 11:18:32 AM	256.6	1.44	459.1	
02/08/24 11:33:32 AM	257	1.54	458.3	
02/08/24 11:48:32 AM	257.3	1.63	457.6	
02/08/24 12:03:32 PM	258.5	1.72	458.4	
02/08/24 12:18:32 PM	259.2	1.83	458.1	
02/08/24 12:33:32 PM	260	1.96	457.6	
02/08/24 12:48:32 PM	261.1	2.08	457.9	
02/08/24 01:03:32 PM	262.3	2.2	458.2	
02/08/24 01:18:32 PM	263	2.31	457.9	
02/08/24 01:33:32 PM	263.4	2.4	457.3	
02/08/24 01:48:32 PM	264.2	2.51	457.2	
02/08/24 02:03:32 PM	264.9	2.59	457.2	
02/08/24 02:18:32 PM	265.3	2.67	456.8	
02/08/24 02:33:32 PM	266.1	2.72	457.5	

Quantitative data



Data visualization



Concept visualization

Decision

Action in the real world

Why should you care about concept visualizations?

Sensors deployed in the real world

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	µS/cm	°C	µS/cm	
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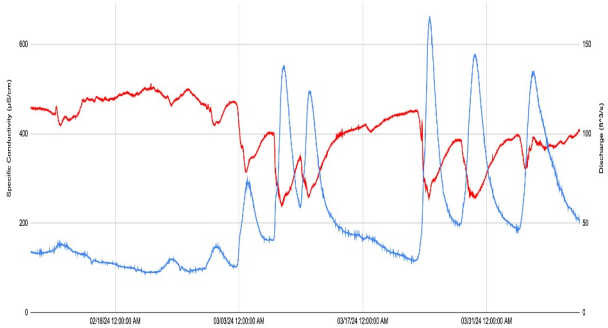
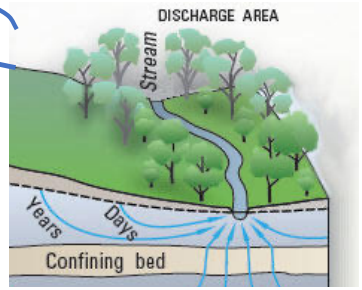


Data visualization



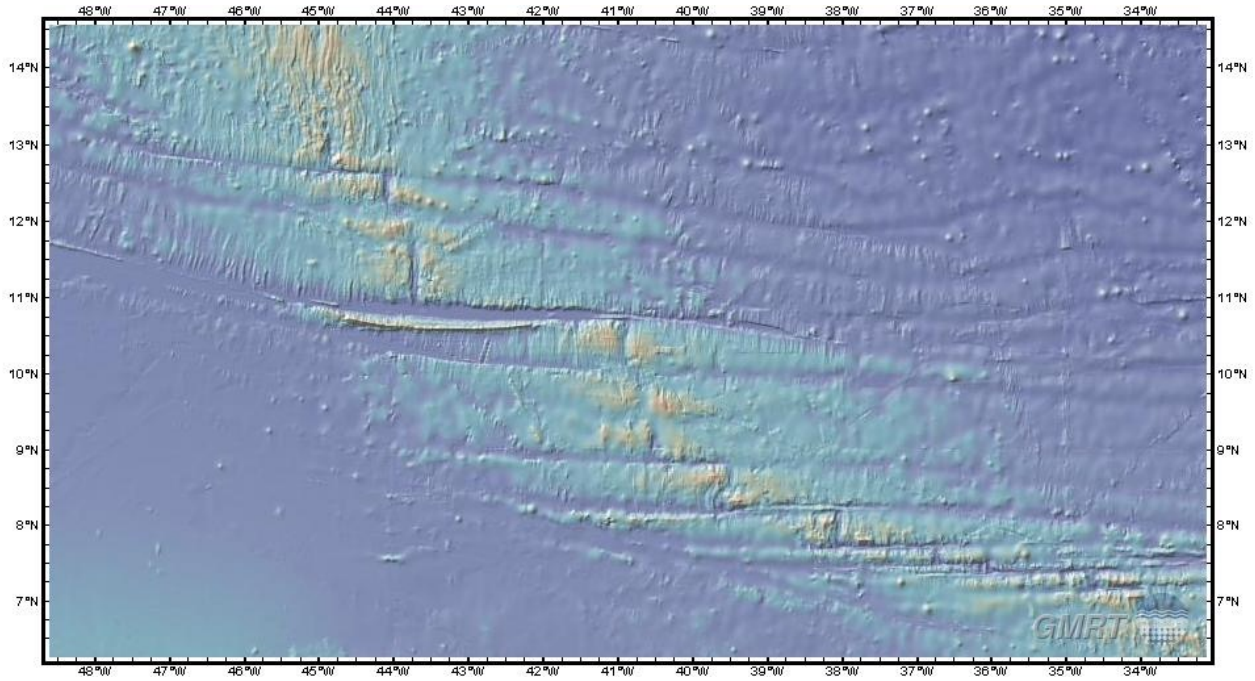
Concept visualization

Decision

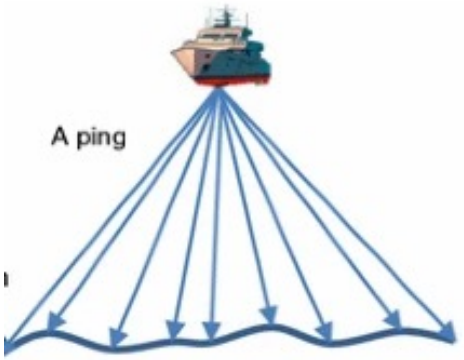
Action in the real world

Kim Kastens

Digression: Is there actually a difference? "Everything is a model"



Includes data from: Kastens, K. A. et al (2000). The Vema Transverse Ridge (Central Atlantic). *Marine Geophysical Research,* v. 20, p 533-556.



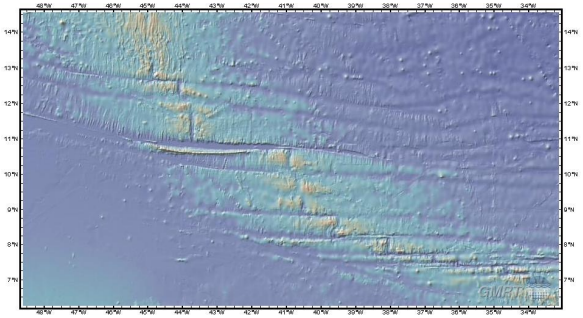
Incorporates concepts about:

- Sound
- Sound velocity
- Distance = rate * time
- Relationship among sound velocity, water temperature, salinity
- Refraction
- Latitude & longitude
- Geodetic reference frame
- Azimuth (of ship)

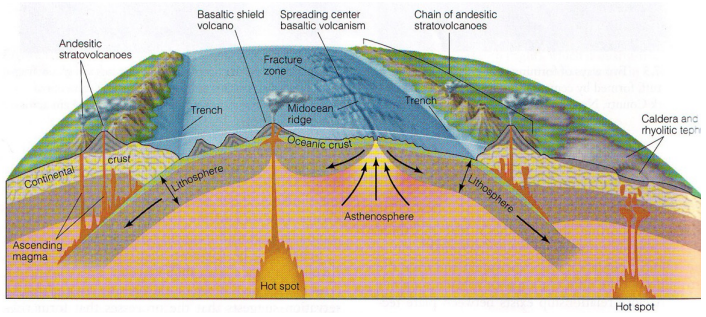
Is there actually a difference? Yes, I think so…

Data visualizations	Concept visualizations
…usually depict a specific instance, a specific place or time or population	…can depict a generalized phenomenon
…purport to convey fact (analogous to the news section of a quality newspaper)	…frankly admit to being a view conceived in a human mind (analogous to the opinion section of the same newspaper)
…usually have a “chain of custody” from the real world to the visualization, following accepted “rules” of the discipline	…sometimes have leaps of inference separating the visualization from the real world
… are well-suited for testing of hypotheses	… are well suited for conveying hypotheses, including multiple working hypotheses

Data Vis

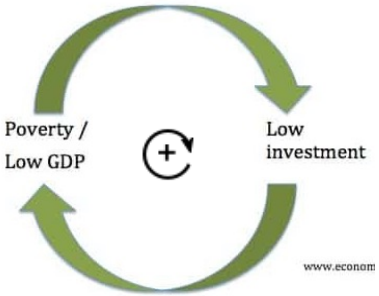


Concept Vis

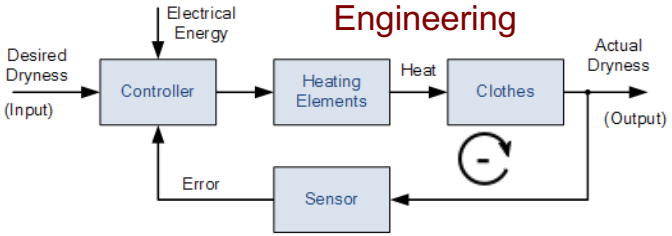


Case study: Causal Loop Diagrams (CLDs)

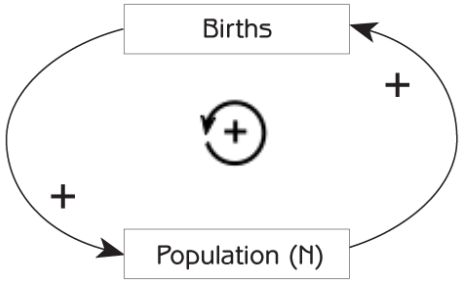
Economics



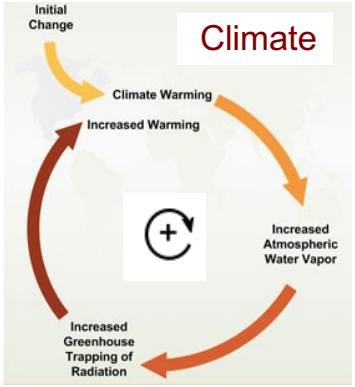
Engineering



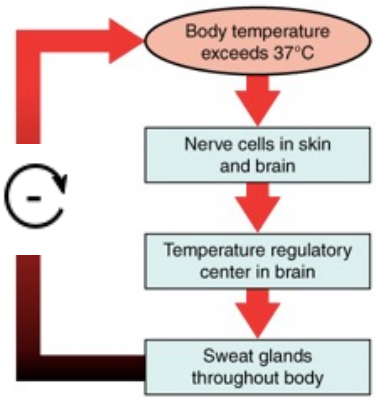
Ecology

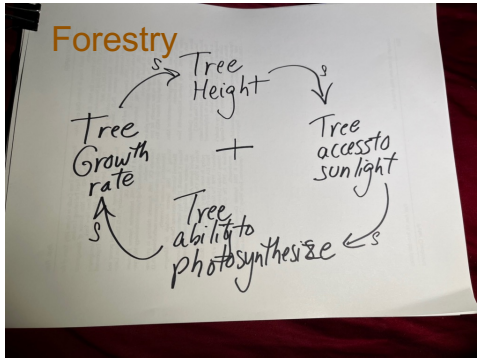


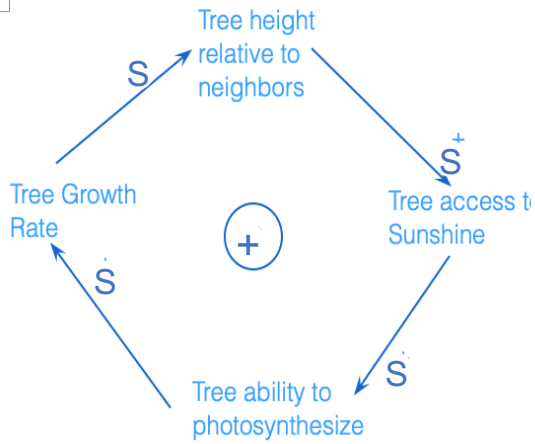
Climate



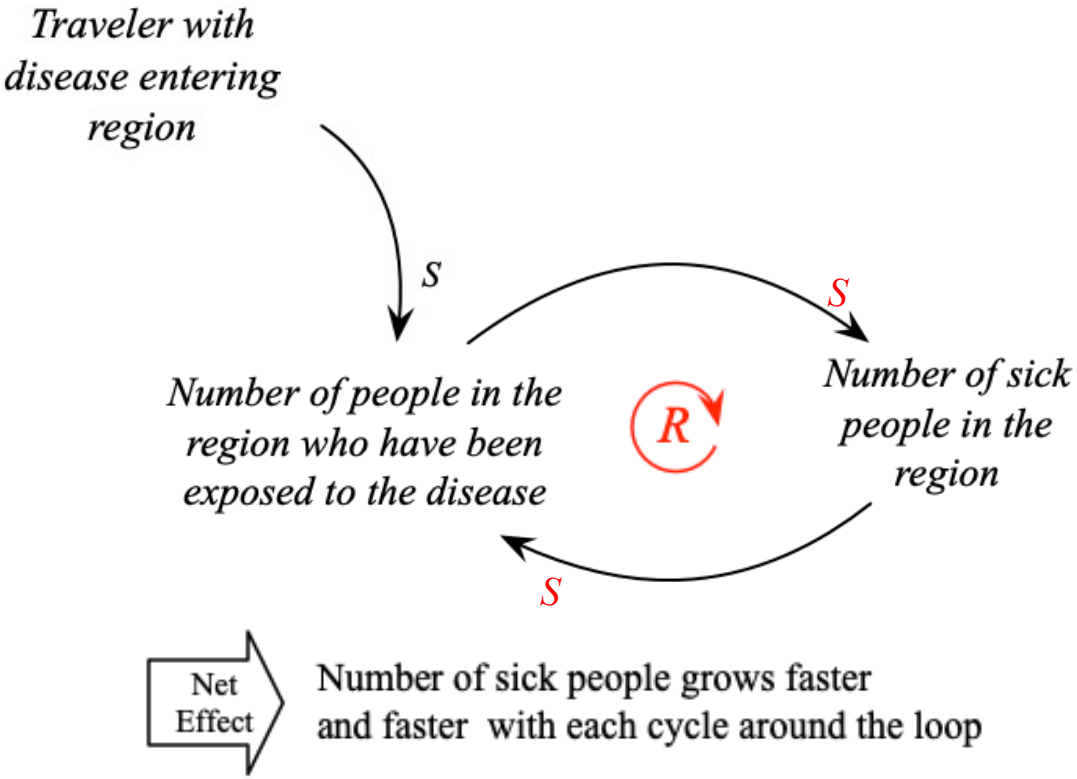
Physiology

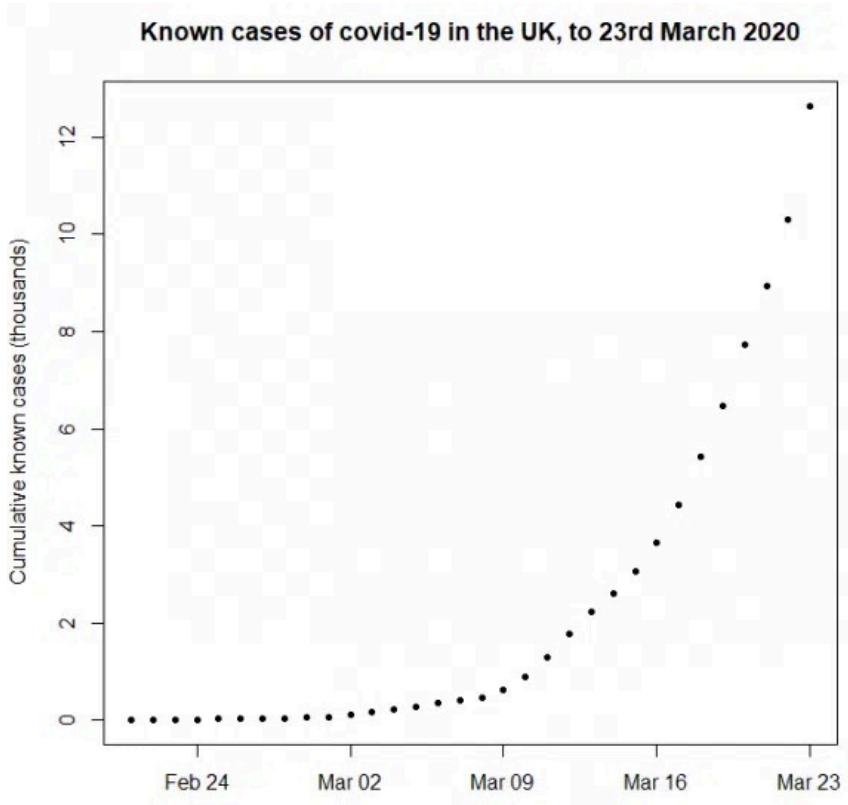






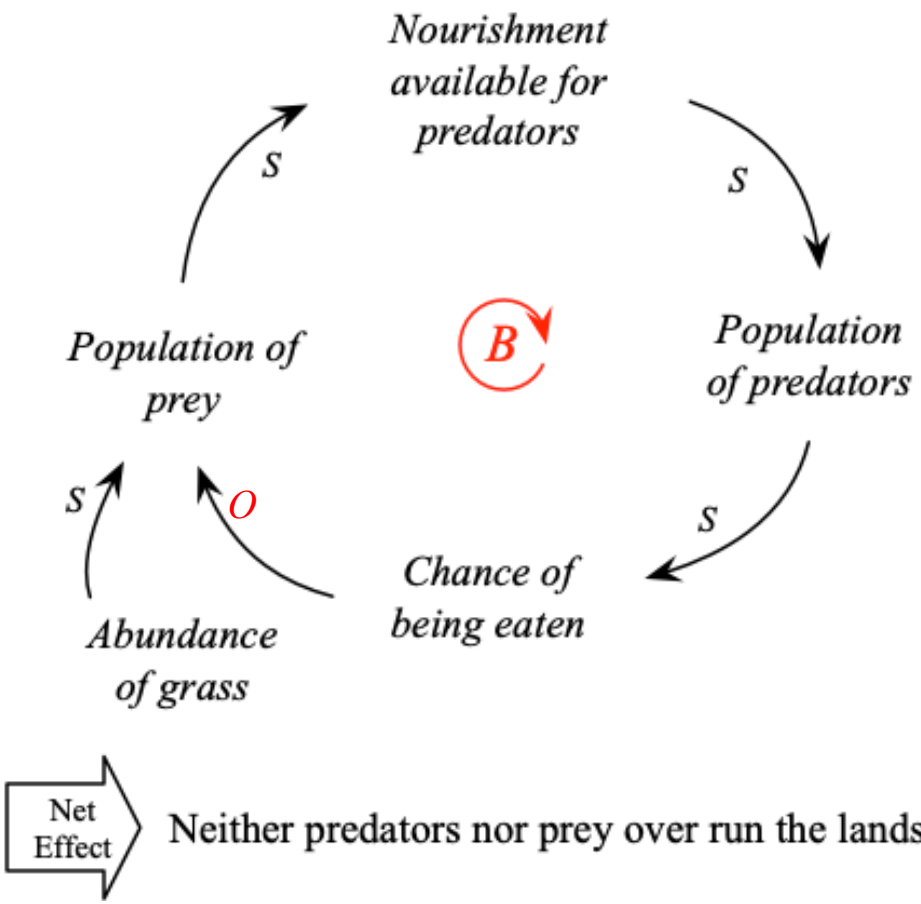
Example of a reinforcing (aka "positive") feedback loop: Pandemic spread



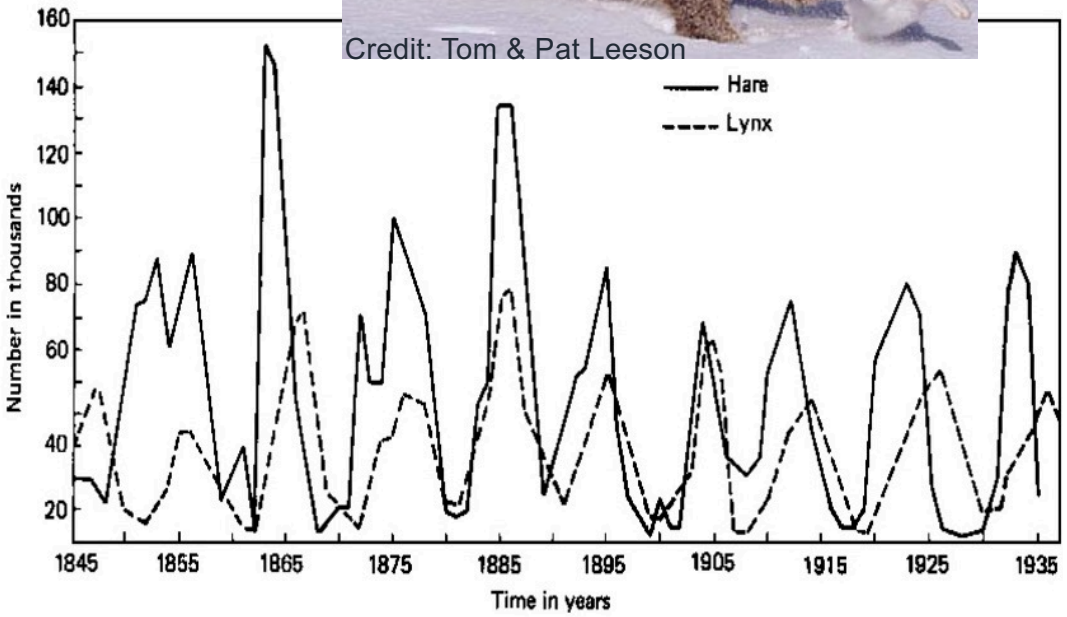


(from Stevens, et al, 2021)

Example of a balancing (aka "negative") feedback loop: Predator/prey system



Credit: Tom & Pat Leeson

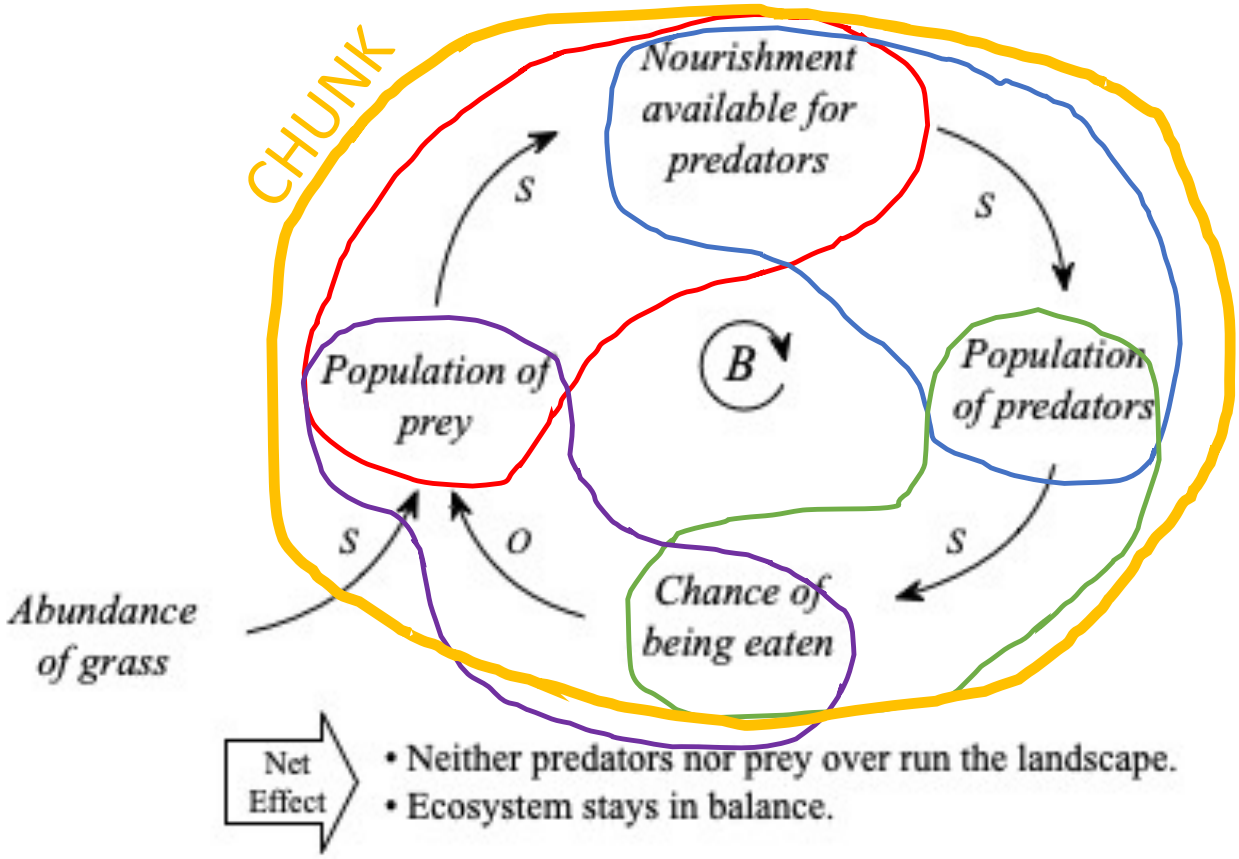


Population cycles in Lynx & its prey (MacLulich after Elton 1925)

CLD gets mental models out into public where they can be compared, combined, or co-created.

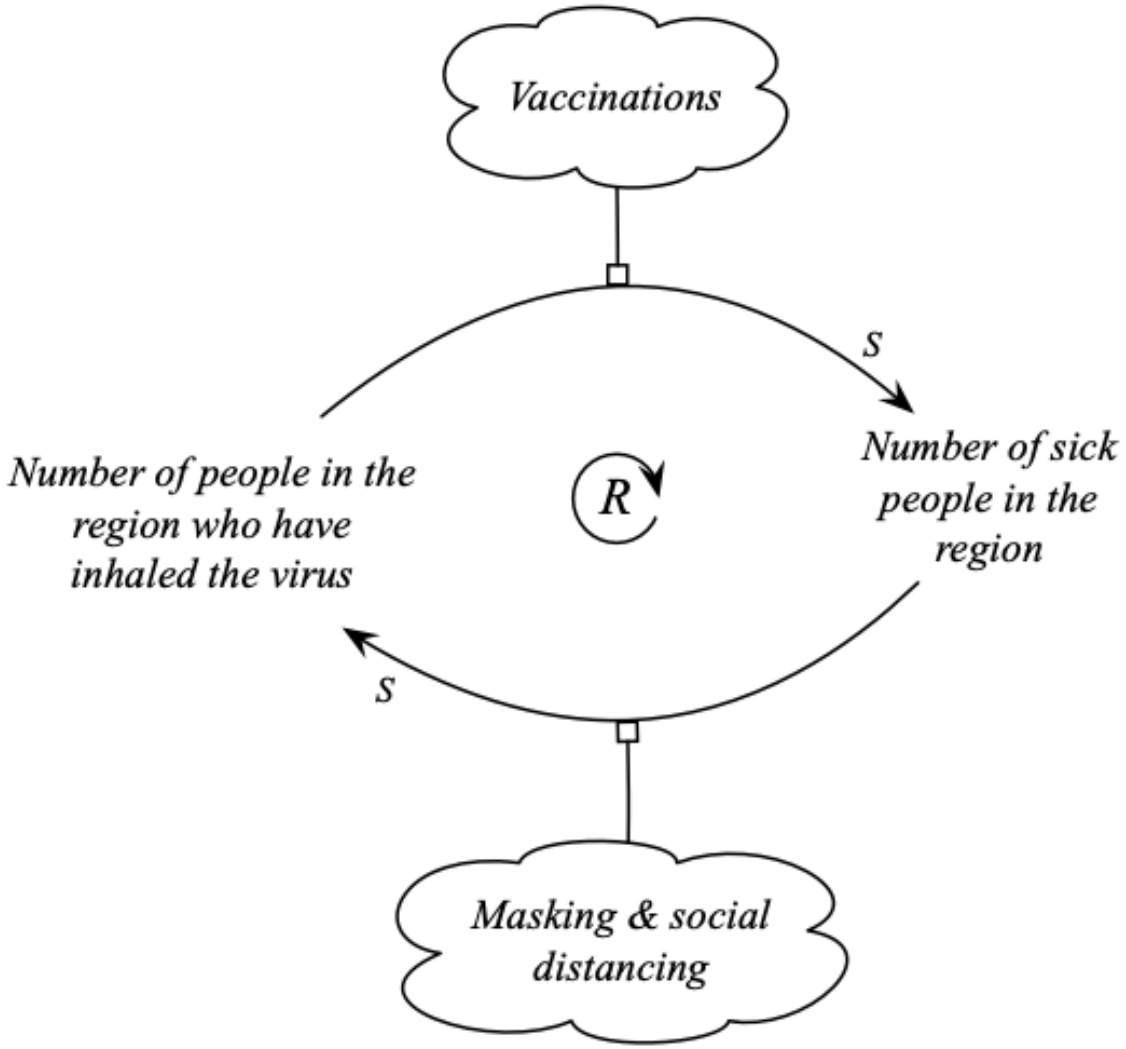
Photo from Earth Educators' Rendezvous 2024. Credit: Kim Kastens

CLD circumvents working memory limitation …

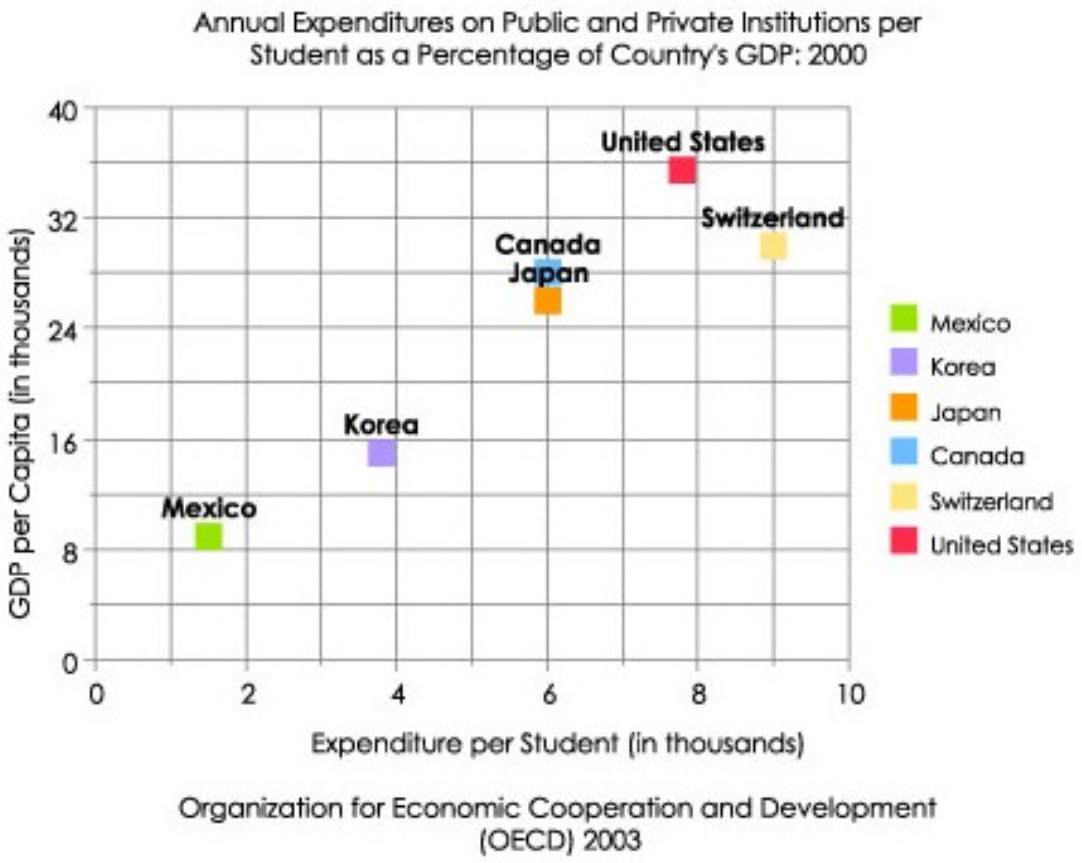


… and conveys relationship between parts & whole

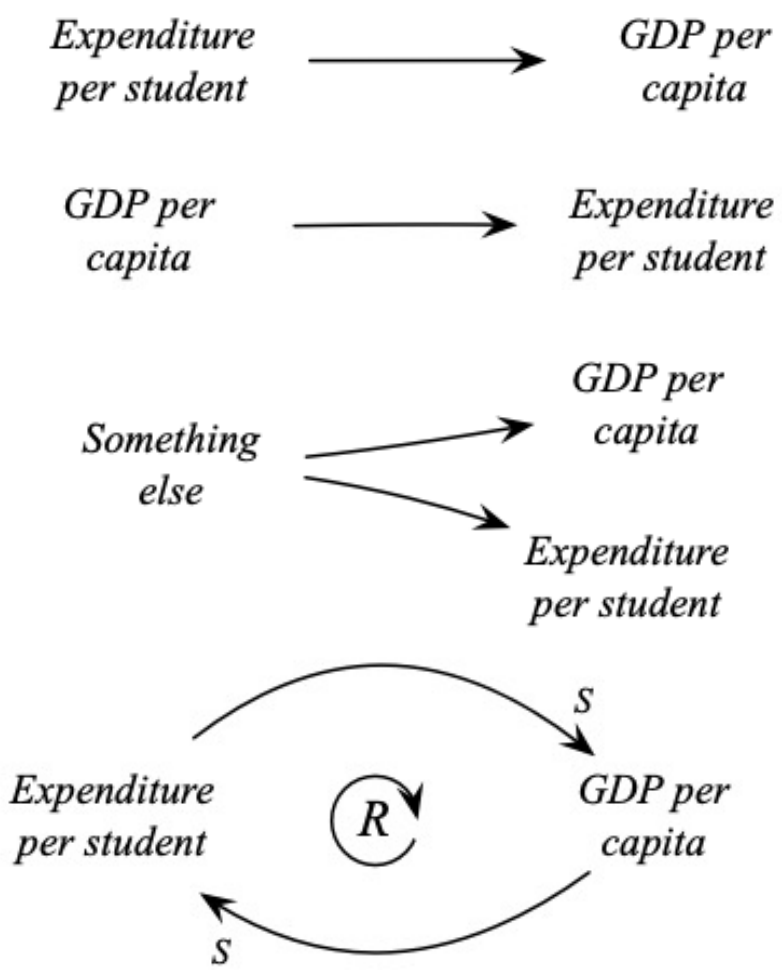
CLD makes it easier to strategize about potential interventions.



CLD makes it easier to compare competing hypotheses



(from National Center for Educational Statistics, Kid's Zone, Graphing Tutorial)



Reprise: how using CLDs strengthens one's ability to think about feedback loops

1. CLD gets mental models out into public
2. CLD circumvents working memory limitations
3. CLD captures and conveys the relationship between parts and whole,
4. CLD makes it easier to strategize about potential interventions,
5. CLD makes it easier to compare competing hypotheses.

How can you research (and thereby improve) use of concept visualizations?

1. Comprehension/Interpretation methods

2. Production methods*

* Based on Liben, L. S. (1997). Children's understanding of spatial representations of place: Mapping the methodological landscape. In N. Foreman & R. Gillett (Eds.), *A handbook of spatial research paradigms and methodologies*. (pp. 41-83). East Sussex, UK: Psychology Press, Taylor & Francis Group.

An interpretation task: What would happen if…

Based on the diagram, which of the following would increase the rate of soil erosion?

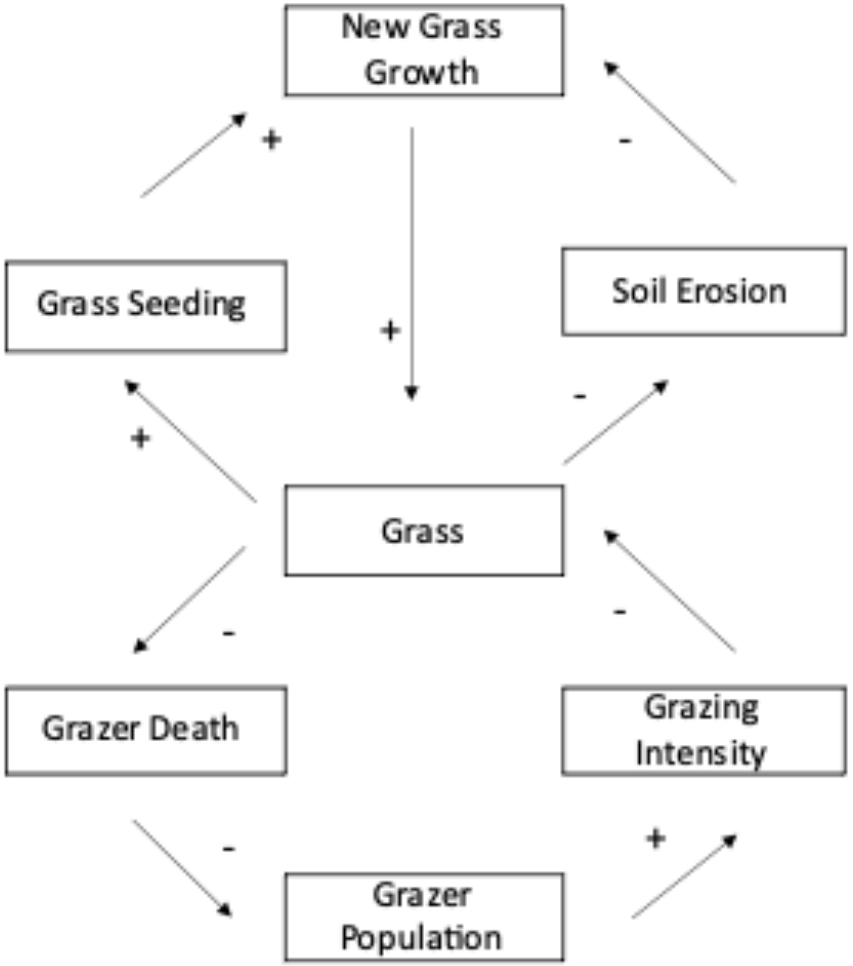
( ) Planting more grass

( ) Increasing the grazer population

( ) Introducing a fatal cow disease

( ) Adding fertilizer to enhance grass growth.

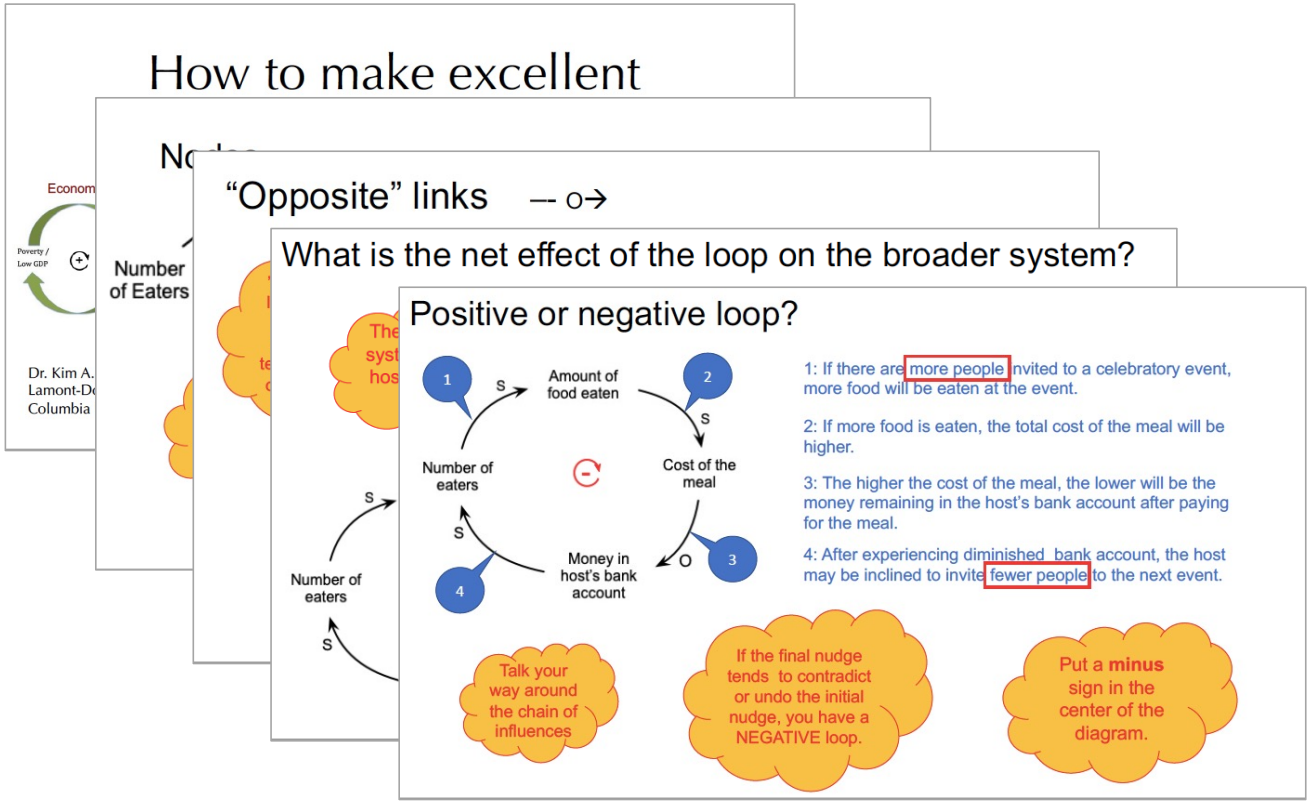
…among the best discriminators in 29-item Earth System Concept Inventory.



From Soltis, N. A., & McNeal, K. S. (2022). Development and Validation of a Concept Inventory for Earth System Thinking Skills. *Journal for STEM Education Research, 5*(1), 28-52. doi:10.1007/s41979-021-00065-z

A production task: Find and map the feedback loop in a popular media article

Participants watched an instructional video…



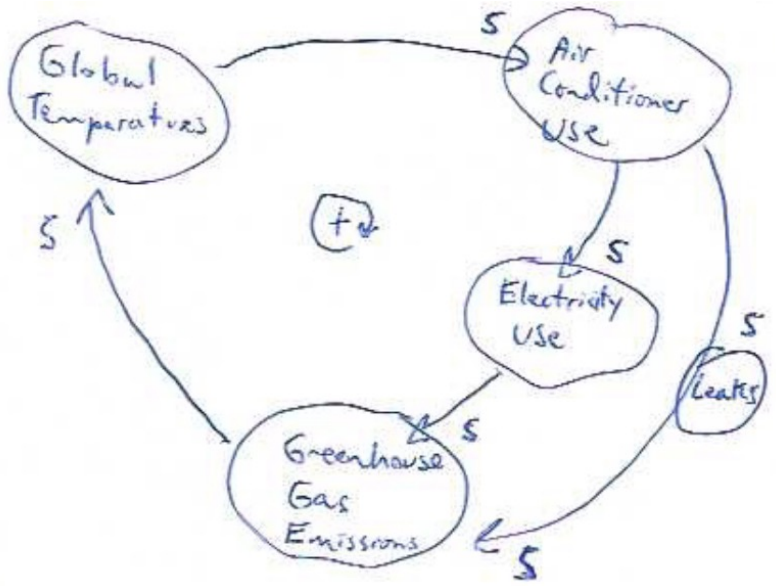
Then read a short reading passage …

excerpt from
Air-conditioning use will surge in a warming world,
by Hiroko Tabuchi. The New York Times, December 5, 2023

Sixty nations committed on Tuesday to improve the efficiency of new air-conditioners by 50 percent and reduce greenhouse gas emissions related to those cooling machines by almost 70 percent, the latest in a flurry of global promises that aim to tackle climate change.

The voluntary pledge made at the U.N. climate talks in Dubai was led by the conference hosts, the United Arab Emirates, and confronts a daunting future facing a warming planet: As global temperatures rise, more people will turn to air-conditioners to ward off the heat.

But additional air-conditioning in buildings and other spaces, which is also driven by rising incomes, population growth and urbanization, means that the world



This is a positive feedback loop. As global temperatures increase, people will tend to use air conditioning more. This increases electricity use, which in turn leads to greenhouse gas emissions, which raise global temperatures, accelerating the cycle. ~~Gases used within~~ Increased use of air conditioners also directly increase emissions by ~~increasing~~ increasing the leakage of greenhouse gases used in the air conditioners, which also enhances the cycle

… and drew a CLD and wrote an accompanying narrative

		Exceeds	Meets	Room for	Unacceptable (1)
Nodes	(1a) Node CLD				
Causal Relationships / Connections	(2a) Link the CLD				
	(2b) Narr descriptic links				
	(2c) Connection of depicted links to real-world system				
Net Effect of Loop as a Whole	(3a) Net effect of loop depicted on CLD				
	(3b) Understanding of impact of this loop on a broader system within which it is embedded.				

		Meets Expectations (5)
Nodes	(1a) Nodes on the CLD	• All nodes that are part of a loop depict something that can potentially increase or decrease, such as a quantity (e.g. # of people), state (e.g. anger, temperature), or attribute (e.g. strength), *and* • Nodes do not state or imply the direction of change.

Nodes	(1a) Nodes on the CLD
Causal Relationships/Connections	(2a) Links/arrows on the CLD
	(2b) Narrative description of causal links
	(2c) Connection of depicted links to real-world system
Net Effect of Loop as a Whole	(3a) Diagram depiction of feedback loop
	(3b) Understanding of impact of this loop on the broader system within which it is embedded.

Where undergrads need improvement

Where geoscientists may need improvement

Develop teaching materials to target discovered weaknesses

For each item, indicate the type of causal link that you think connects the two boxed nodes. For each item, there are 4 possibilities:

Draw an arrow head to indicate the direction of influence.

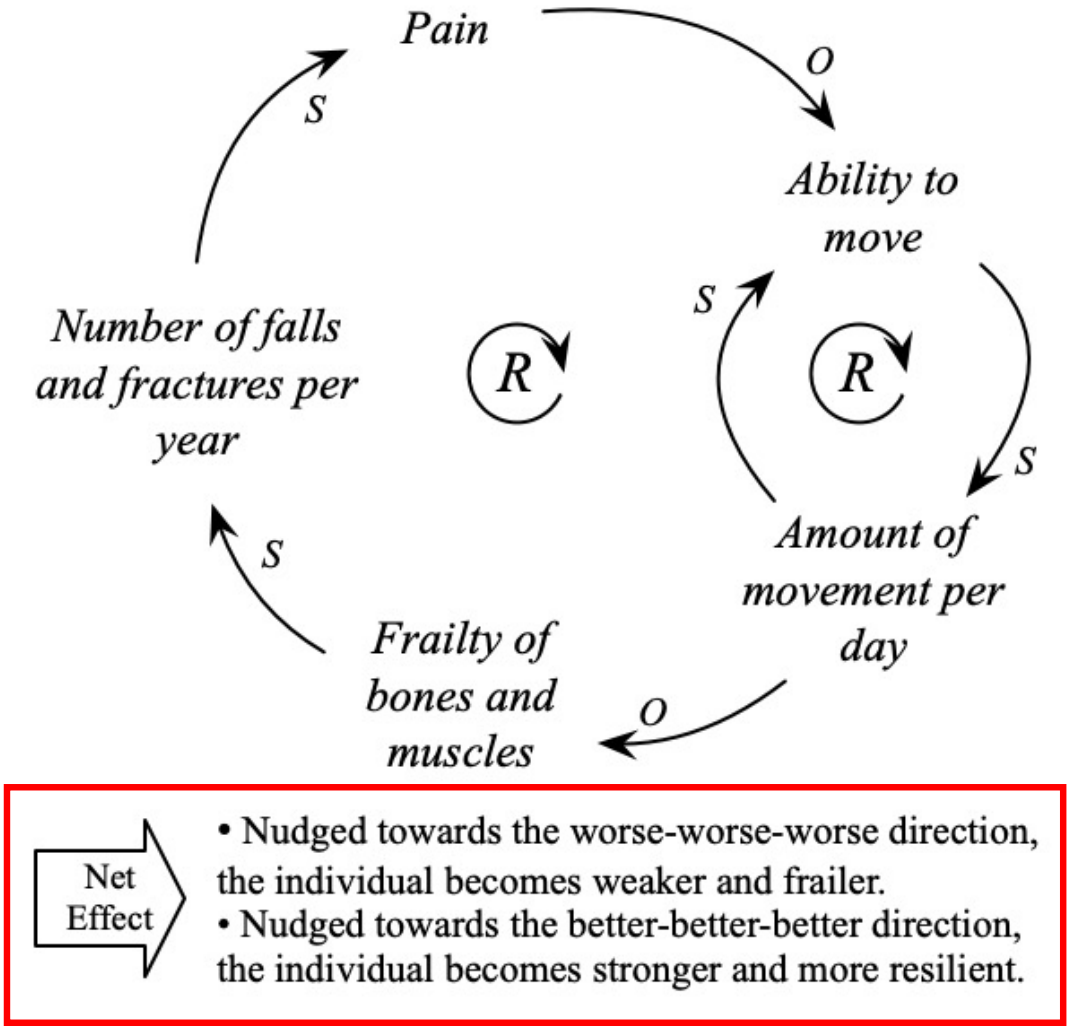
Add a "S" to the arrow if you think two nodes change in the *Same* direction. Add an "O" to the arrow if you think that the two nodes change in the *Opposite* direction.

(a) Elapsed time since last meal —S→ Hunger

(b) Ability to buy a car ←S— Money in the bank

(c) Student debt —O→ Ability to afford a house after graduation

Improve visualization to target discovered weakness



Improve instructors' materials

Check list for Causal Loop Diagrams (CLDs) & Accompanying Narrative
Earth Educators' Rendezvous 2024

_____ Nodes (text on the diagram) are things that can increase/decrease.

_____ Nodes do not state direction of change.

_____ Links (arrows) indicate direction that influence flows, and whether the upstream and downstream arrow move the same (S) or opposite (O) directions.

_____ Links represent known or plausible real-world relationships.

_____ Links form a closed loop.

_____ The type of loop is indicated: Positive (+) or negative (-).

_____ Narrative goes methodically around the loop.

_____ Narrative indicates how a change in each node influences the next node.

_____ Narrative explains the net effect of the loop: how going around influences the starting node.

_____ Narrative explains how the loop's behavior or outcome influences the broader system in which the loop is embedded.

_____ Total

Suggestions about how to research concept visualizations

- Design a challenging, holistic task in which participants do something real and important, and engage with the complexity of the world – not a toy problem.
- Make a rubric for participant-produced visualizations. This is hard, time-consuming, iterative, but deeply informative.
  - Acknowledge that concept visualizations can look different but both be correct.
  - Grapple with products that emerge from a mind in the liminal state between understanding and not-understanding the system in question.
- Look for common failure modes on the challenging, real world task.
- Design targeted, more constrained tasks that test subskills and seek to isolate sources of difficulty.
- Tap into practitioners' wisdom of people who use your type of concept visualization to teach, decide, understand or plan.

What questions or thoughts do you have?