Cognitive Analysis of a Systems Thinking Educational Assignment: Find & Map the Feedback Loop in Popular Media Articles

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Structured Abstract:

Introduction to the problem: Systems thinking draws on complex cognitive processes. Many instructors of systems thinking and systems dynamics lack expertise in cognitively-informed pedagogy, and thus may be misunderstanding their students' struggles or missing opportunities to build their students' strengths.

Approach to the work: Cognitive task analysis is the process of examining how learners process information and build understanding while completing an instructional activity. We have analyzed an assignment in which students identify a feedback loop in a reading from popular media, draw a causal loop diagram, write a narrative that describes how the loop works, and articulate the impact of the loop on the larger system within which the loop is embedded.

Results: The activity exercises analogical reasoning when identifying the loop in the reading passage, causal reasoning to create the A $\rightarrow$ B links of the diagram, facility with switching between parts and wholes at all steps of the assignment, use of external visualizations to relieve load on working memory and make essential aspects of the loop more salient, and use of sophisticated linguistic structures to convey conditionality while writing the narrative.

Discussion: Our learning goal for this assignment is that students will be able to recognize, analyze, and explain feedback loops wherever they may encounter them in their personal and professional lives. Our motivation in explicating the cognitive processes required to reach this learning goal is that instructors will be better equipped to craft effective lessons, diagnose their students' difficulties, and recognize their students' cognitive accomplishments along their learning trajectory.

Use of AI: none

Problem Statement:

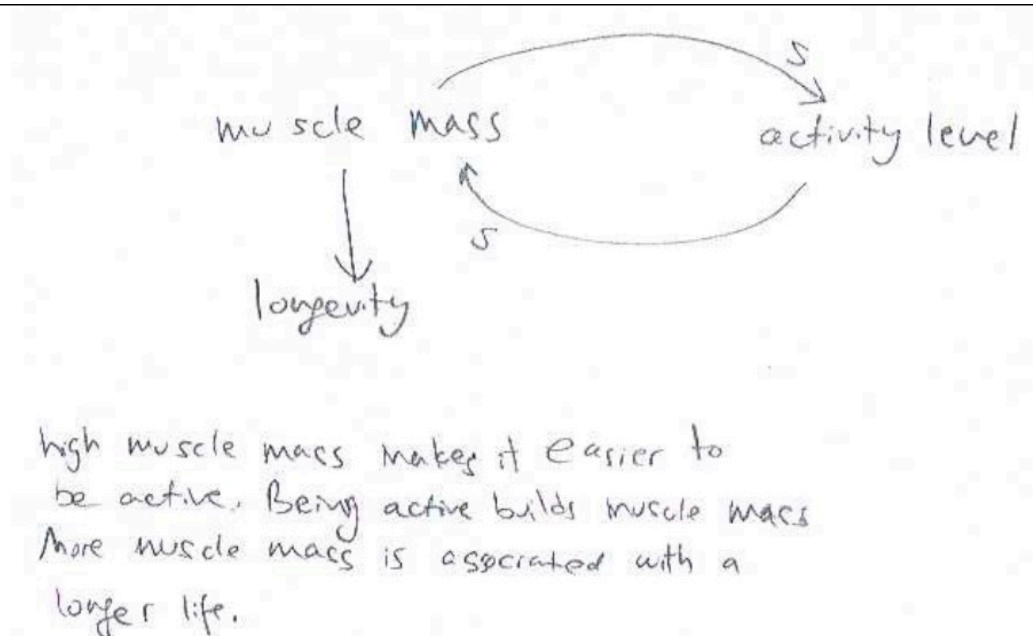
Employing systems thinking or systems dyamics requires complex cognitive processes on the part of the human practitioner (in addition to computational resources if software is involved). The problem is that most instructors teaching systems thinking and systems dynamics have little expertise or training in pedagogy, cognitive science or learning science, and thus may underestimate or misunderstand what they are asking their students to do with their human minds. This paper presents a cognitive task analysis of a learning activity that exercises many of the most important and challenging cognitive skills of systems thinking: recognizing a feedback loop when it is not explicitly pointed out, deconstructing a holistically described situation into causal relationships between entities, assembling those relationships into a reinforcing or countervailing feedback loop, conveying their mental model of that feedback loop as a visual representation (causal loop diagram), narrating the chain of influences by which the feedback loop achieves its outcome, and articulating how the feedback loop impacts the larger system within which the loop is embedded. By positioning a discussion of human thought processes in the context of cognitive tasks that instructors have themselves experienced, our goal is to help instructors teach in ways that leverage the affordances of the human mind and work around its limitations.

The assignment:

In this assignment, students read an instructor-provided article from the popular media that is relevant to the course content, and that describes a system with at least one feedback loop – but that doesn't use the term "feedback loop." Students find the feedback loop description and mark it. Then they construct a causal loop diagram (CLD) that depicts the working of the feedback loop in the article. We provide a video on how to make CLD's. Finally, they write a narrative that systematically steps around the feedback loop describing how it works. The narrative is required to end with a discussion of the impact of the loop taken as a whole on the larger system within which the loop is embedded. We provide answer keys and rubrics for scoring student products, with a student "product" comprising the CLD plus accompanying narrative.

We used this assignment to develop and field-test a rubric for evaluating student causal loop diagrams, as reported in our 2024 ISDC paper (Kastens, Shipley, and Wakeland, 2024). That 2024 paper details our rationale for basing the assignment on readings from popular media, for requiring a CLD, and for requiring an accompanying narrative. Since then, we and our collaborating instructors have used variants of this assignment in several other courses and at a summer workshop for Earth Science Educators (Kastens, Brenner, Davatzes, and Shipley, 2024). All of the teaching materials for using this assignment are now available online through the

Teach the Earth web portal (Kastens & Shipley, 2025). Figure 1 shows an example of a response to this assignment; additional examples are included in Kastens, et al., 2024.



An example of a medium-quality response to the assignment, based on a reading extracted from Attia and Gifford (2023). This response accurately captures the most prominent elements in the reading passage, and correctly connects them into a loop via "S" links. However, the reading passage also touches on strength and balance, in addition to muscle mass, which the response does not. Neither the diagram nor the narrative identifies this as a reinforcing (or positive) feedback loop, and the net effect of the loop on the larger system (the human body) is not articulated. This response offers a teachable moment to catalyze a discussion of where "longevity" fits in this model; our own inclination would be to interpret longevity as a net effect or outcome of the loop in its entirety (including balance and strength) rather than as a consequence of muscle mass alone.

About cognitive task analysis:

In learning sciences, cognitive analysis refers to the process of examining how learners process information, acquire knowledge, and build understanding, with the intent to leverage insights about how the mind works to identify more effective ways to teach and learn. Cognitive task analysis carries out this examination in the context of a particular instructional sequence (Reinhard, 2020; Wieman, 2015). Although this paper is written in the context of the assignment described in the preceding section, we think that the insights we offer will be applicable to instructional moves that many readers are employing during their own instruction.

In this paper, we will address the following higher order cognitive skills:

- *Analogical reasoning:* Used when finding the needle of the feedback loop amidst the haystack of the reading passage, this skill involves recognizing and leveraging similarities between two patterns - often a familiar situation or pattern and a newly presented situation.

- *Causal reasoning:* Used when identifying the individual A → B links that comprise the CLD, this skill involves recognizing either an empirical association or a plausible mechanism that is suggestive of a causal relationship, while avoiding common biases.
- *Distinguishing and integrating parts & wholes:* This skill involves breaking down something conceptualized as a whole into its constituent parts, or mentally assembling parts to create a new whole. This skill is used three times in the assignment: in breaking down the journalist's scenario into parts, in assembling these parts into a new whole (the feedback loop model), and then in reconceptualizing the feedback loop as a constituent part of the larger system within which it is embedded.
- *Use of external visualizations:* Used when creating the causal loop diagram, this skill involves mastering the semantics of an unfamiliar graphic language (while avoiding alternative meanings popularly associated with these same symbols), and leveraging the visualization to relieve load on working memory and make essential aspects of the represented system more salient.
- *Use of linguistic structures for hypothetical and conditional propositions*: Used when writing the narrative, this skill involves using rather subtle linguistic structures of the language of instruction, such as modal verbs and conditional mood, to express a hypothetical situation that is dependent on a certain circumstance or condition.

Some of these cognitive topics were addressed in further detail in our 2023 ISDC paper, *How does the human mind think and learn about feedback loops?* (Kastens & Shipley, 2023).

Analogical reasoning, to find the loop

We have observed that students and other novices find it relatively easy to follow along the logic of a feedback loop when it is spelled out step by step for them by an instructor, textbook, or website. They can even reproduce that logic in words or diagrams at a later time on a quiz. It is much harder for them to spot a feedback loop "in the wild," when it occurs in their personal or professional life in circumstance where there is no instructor to point it out. Yet that is the skill that we want our students to carry forth with them after they leave our classrooms or graduate from our programs. That's why we have structured the assignment so that the first challenge for students is to find a feedback loop nestled within a forest of verbiage, when the author of the writing passage did not point it out explicitly.

The instructor can calibrate the assignment to align with the time available and the students' systems skills and reading ability. In order from easiest to hardest:

- Instructor crafts a short reading passage (<200 words) in which all of the entities and links of the feedback loop are present and extraneous verbiage is minimal.
- Instructor extracts a medium length (~200 - 400 words) reading passage from an authentic article by a journalist or popular writer, in the content domain of the course. The authors may or may not have understood that they were writing about a feedback loop, but in either case they did not use the term "feedback loop" to describe the

situation. In such writing, it is typical that some elements of the feedback loop are implied rather than stated, and the elements often do not progress methodically around the loop. Sorting this out is the students' challenge. The reading passages we provide with our published version of this activity (Kastens & Shipley, 2025) are of this type.

- Instructor provides students with the entire article rather than an extracted portion. The challenge is similar to the prior situation except that the search and find process is harder and more time consuming amid the more verbose reading passage. This can be a pedagogically advantageous trade-off if the content of the article is already of high value to the course content.
- Instructor requires students to find their own article containing a feedback loop in the popular media around the course content, and continue the assignment from there. This can be a good capstone assignment after the class has done the easier versions of the assignment a few times earlier in the semester. Students can be asked to present the resultant CLDs in an oral presentation or a gallery walk (Francek, 2005); the aggregate take home message from viewing the CLD collection is that feedback loops are omnipresent in the course domain.

Regardless of the difficulty level at which the assignment is pitched, the cognitive skill used to identify the presence of the feedback loop is the same: analogical reasoning. In cognitive science, "analogs" are two or more entities or situations or events or phenomena that are similar to each other in important ways. "Analogical reasoning" refers to the process by which the human mind can notice important similarities between analogs and then use those similarities to generate new inferences (Gentner & Smith, 2012). Importantly, analogical reasoning works with similarities in structural relationships, not with surficial attributes. Analogical reasoning is a powerful cognitive capacity that is one of the ways that humans can create new hypotheses and new explanations – new knowledge that goes beyond what they have been taught by other humans (Gentner & Jeziorski, 1990).

In a form of analogical reasoning called "projective analogy," the reasoner begins with a fairly solid understanding of one familiar thing, event, situation, or phenomenon, called the "source analog." The reasoner identifies ways in which something else, called the "target analog" is aligned with the known situation. They can then project understandings from the source analog onto the target analog to create new inferences or hypotheses about the unfamiliar analog (Kurtz, Miao, & Gentner, 2001).

For example, if students are familiar with how a home thermostat works as a balancing feedback loop, they can project that understanding to the sweating/shivering thermoregulatory system of a human body to hypothesize that that system might also work as a balancing feedback loop. To activate projective analogy, a writer/speaker may use linguistic clues (Kastens & Shipley, 2021) to make the analogy explicit. For example, a journalist might say "it's **like** a thermostat" or "it works **like** the cruise control on a car." In English, "like" is a word used to telegraph to the reader/listener that the writer/speaker is making a verbal analogy between the preceding group of words and the following group of words.

In the thermoregulation example above, the source analog is a concrete single example, the thermostat. Projective analogy can also work with a more abstract source analog, which in our case would be a mental model or "schema" of feedback loops in general or of one kind of feedback loop. The broader culture (outside of the systems dynamics community) has embraced two such schema, which show up frequently in popular writings. The first is the "vicious cycle/circle" or "doom loop," a reinforcing feedback loop in which each step in the turning of the loop causes the situation to get worse. For example, a newspaper headline published in the aftermath of the Covid pandemic: "Cities are struggling. San Francisco could be in for the biggest 'doom loop' of all" (Li & Arroyo, 2023). The second is the "virtuous cycle," a reinforcing feedback loop in which each step in the turning of the loop causes the situation to get better. For example, a quote in a newspaper article: "[the interviewee] said technology-focused schools are an integral part of what he called a "virtuous cycle" that drives the city's tech industry. The schools attract faculty members and support research, both of which draw more students. The students increase and diversify the talent pool, which in turn brings more companies" (Hu, 2018).

In the absence of a linguistic pointer to the presence of a feedback loop, the user of projective analogic reasoning may begin by spotting one distinctive feature that the two analogs have in common, and then build outwards from there, testing whether additional features can also be aligned. For example, early in the "Economics of Solar Power" reading passage in the published version of this activity (Kastens & Shipley, 2025), the journalist wrote "To call solar power's rise exponential is not hyperbole." Exponential growth is a recognizable feature of reinforcing loops. The word "rise" signals the loop-savvy reader to try to align the feature in the rest of the article with a more-more-even-more variant of a reinforcing loop schema rather than with the less-less-less-even-less variant. With these clues in mind, the reader then can look for other elements of the story that align with other elements of the feedback loop schema. For example, in the solar power article, the sentence "As the cumulative production of a manufactured good increases, costs go down" can be recognized as a description of an "O" or "-" causal link.

As a student (or even an expert) first quests for the presence of feedback loops in a description of a real-world system, the initial alignment with the feedback loop concept may be fairly fuzzy, intuitive, and tentative: for example, a vague feeling of being stuck in a rut may be the initial alignment with a negative loop schema. This activity is designed so that the mapping between the real-world phenomenon and the feedback loop concept becomes more concrete and accurate as the activity progresses.

Learning scientists have documented several teaching strategies that improve students' ability to accomplish analogical mapping between a newly-presented collection of information and an already-familiar analog. One successful strategy is *progressive alignment,* in which a learning sequence begins with instances in which the conceptual gap between the two analogs is small, and then gradually moves on to less and less similar analogs (Gentner, Loewenstein, & Hung, 2007). For example, in teaching environmental science, a progressive alignment learning sequence could begin with multiple reinforcing loops all attached to the same climate nudge of increasing air temperature (e.g. wildfires, air conditioner use, permafrost, ice albedo), then move on to a balancing loop attached to the same climatic nudge (cloud cover), then progress to a loop that is in a social system rather than a physical system (e.g. economics of supply and demand for EVs). Instruction would emphasize both the similarities and the differences between these loop-driven parts of the larger human-environment system.

Analogic reasoning is unquestionably powerful, offering the ability to leapfrog across gaps in one's knowledge to create new understandings where only a blur or mishmash had existed before. But it is also fraught. The human mind seeks patterns and regularities, and there is always the danger that the reasoner will map the novel situation onto an inappropriate source analog, misalign elements of the analogs, or map by surficial features rather than underlying structure. This is one of the reasons that our activity requires that students write out a narrative as well as drawing a causal loop diagram. We aim to trigger the "self-explanation effect," in which learners perform substantially better if they are prompted to speak or write an explanation of the concept they are trying to understand or the problem they are trying to solve (Chi, et al, 1994; Chi, et al, 2000) in part because they spot and repair inconsistencies in their mental models.

Causal reasoning, to create the causal links:

Having identified and highlighted the general section of the reading passage that contains a feedback loop, the students' next step is to parse the places where the author has made a claim that when something happens, that something else will follow as result; in other words, identify the causal relationships that will become the $A \rightarrow B$ links in the CLD. In our use of this activity with undergraduates, we find that this is a notable area of weakness (Kastens, et al, 2024). Upon close scrutiny, students' CLDs contain links that were not present in the reading passage. Or they link two entities that did have a causal relationship in the reading passage, but the student's CLD has the direction of causal flow backwards.

In guiding students to identify and parse causal links, a useful teaching move is to arm them with these two questions: Is there a plausible mechanism for postulating that when A happens then B *should* follow or tend to follow? Is there empirical evidence that when A happens B *does* follow or tend to follow? The strongest causal links are backed by both empirical evidence and a plausible mechanism, but especially when the article is about pioneering science at the frontiers of knowledge, only one or the other may be available. The students' task is made harder – but also more realistic and educative – because in journalistic writing the steps in the chain of influences may not all be spelled out explicitly. In that case, the student may need to supply additional information from their knowledge of the field. Unless students are struggling at this point, we urge instructors not to succumb to the temptation to "clean up" the language of the reading passage by filling in missing links or by reordering the information in a way that strikes you as more logical. When students walk out of your classroom into the real world, their own lived experience and the accounts of stakeholders will not come to them in an order that steps neatly along a chain of influences. Working with authentic media accounts of real-world phenomena can hit the pedagogical sweet spot of hard but not too hard.

Cognitive and learning science researchers have studied human causal reasoning extensively, and have documented several common biases, two of which we think are relevant to parsing causal links in feedback loops. In lab studies of people detecting correlations amid noisy observations, participants were more successful in detecting a direct correlation than an inverse correlation of the same strength (Kareev, 1995). Although to our knowledge this bias has not been researched in the context of systems thinking, we suspect that this tendency may make it easier to detect "S" links than "O" links (or in other words "+" links rather than "-") when searching for causal relationships in the real world or in a description of the real world such as the reading passages in our learning activity.

The second well-documented bias has to do with the relative weighting of the two types of evidence for causality: empirical evidence and theory/mechanism. In an extensive series of experiments by Deanna Kuhn and her students, participants were given opportunities to explore various microworlds in which there was one observable outcome and multiple potentially causal factors. Whether the participants were middle school kids, undergraduates, jurors, or people sitting in a train station waiting room, they tended to overweight a plausible theory of why A *should* cause B, and give less credence to empirical evidence about whether A is in fact reliably followed by B ((Kuhn, 2001, 2004, 2007, 2010; Kuhn, et al, 2000).

If you structure your instructional sequence so that early instances of this activity are done in groups, you can coach your students to ask each other questions that may be protective against these types of biases: where exactly in the reading passage are you seeing the evidence for this causal link you are proposing? has the writer given us a mechanism for this proposed causal link, or are you inferring a mechanism from your other knowledge? Where in the reading passage is the evidence that this is a "same" or an "opposite" causal relationship?

Distinguishing and integrating parts and wholes

This assignment requires students to switch back and forth between considering parts and considering wholes. The reading passage presents the author's view of a system as a whole. Students must first break this system down into constituent parts, identifying the entities that will become the nodes of the CLD and the relationships that will become the links. Then they have to reassemble these parts into a new whole, a feedback loop, and represent this new whole by symbols and words. Finally, in the last step of the assignment, students must reconceptualize the feedback loop as a part of a larger whole, when they articulate the impact of the feedback loop on the larger system within which the loop is embedded.

Our first glimpse at the possibility that this scale-swapping might be causing difficulty came when our first small group of participants, expert geoscientists, skipped the last step of the assignment (Kastens, et al., 2024). That's the step in which they were asked to include in their narrative the impact of the feedback loop, taken as a whole, on the larger system in which the feedback loop was embedded. It is possible that, as experts, they felt that this impact was self-evident and didn't need to be stated.

Or it could be that switching back and forth between parts of systems and whole systems is cognitively demanding, and if a person has been focusing intently on one level (parts or wholes) it is especially difficult to switch to the other level. Students doing our assignment have just invested substantial time and mental effort in constructing a whole feedback loop; this may "prime" them to continue thinking at the level of the whole and make it difficult for them to switch over to thinking at the part level.

Navon (1977) initiated a long tradition of psychology research on this question of parts and wholes, expressing his ideas in terms of seeing the forest versus seeing the trees. As more recently summarized and advanced by Robertson (1996), participants in this research tradition view a stimulus that is one large letter made up of numerous small letters (figure 2, left); these are referred to as "global" letters and "local" letters. All the local letters are the same, but they differ from the global letter. Participants are told a pair of target letters before testing begins. Each time they see a new stimulus, they are to hit a key to indicate which of the two target letters is part of the stimulus. You can try a version of this task yourself at [https://www.psytoolkit.org/experiment-library/navon.html.](https://www.psytoolkit.org/experiment-library/navon.html)

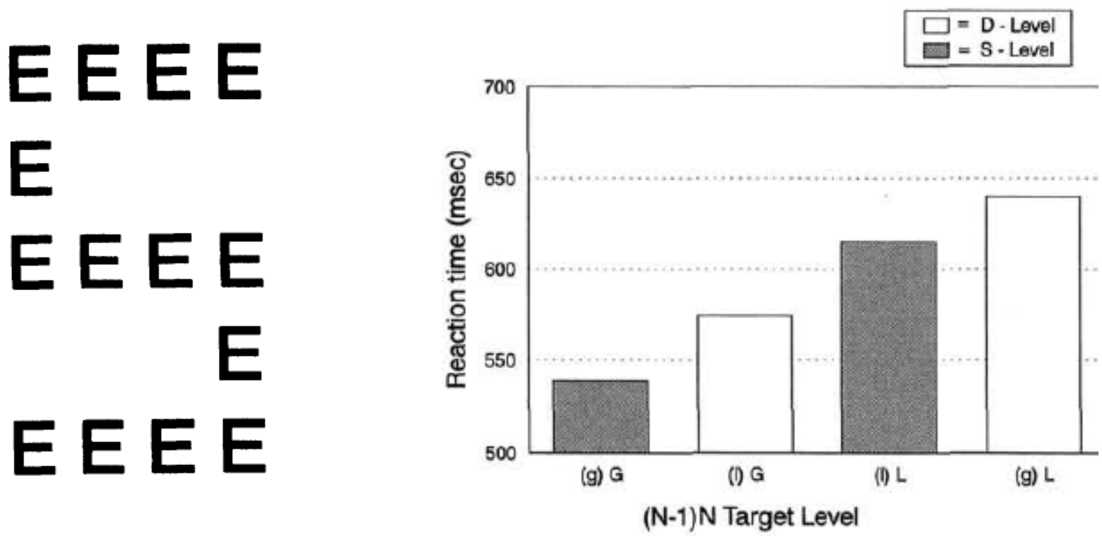


Figure 2: (left) An example of a "Navon Letter," the type of stimulus used in Robertson (1996) and other experiments on parts and wholes. The large letter (S in this example) is at the so-called "global scale" and the smaller letters (E in this example) are at the "local level." *(right)* Results from one of Robertson's (1996) experiments. G and g refer to global; L and l refer to local. Upper case refers to the current trial; lower case refers to the prior trial. The fastest reaction time (least mental demand) was for the (g)G condition, when one of the target letters was at the global scale on both the current trial and the previous trial. The slowest reaction time (most cognitive demand) was in the (g)L condition, when the participant had to switch attention from global on the prior trial to local on the current trial.

The variable of interest for the purpose of this discussion is how long the participants took (averaged over many participants and many trials) to signal their response when they had to change levels between trials (from global to local or vice versa) as opposed to staying at the same level (from global to global or from local to local). Slower reaction time in this type of experiment is interpreted as indicative of higher cognitive demand. Whether the current trial was at the local level or the global level, Robertson found that reaction time was significantly faster when the level of the target letter was the same as in the previous trial (figure 2, right). Robertson and other investigators tried many variants of this experimental design, and found that this level-specific effect is robust. The interpretation is that the step of switching attention from global scale to local scale or vice versa is cognitively demanding.

Robertson began her 1996 paper "...in the natural world, it is common for objects to be parts of other objects, which in turn can be parts of an even larger object. ... An iris is part of an eye, an eye is part of a face, a face is part of a body, and a body may be part of a crowd" (Robertson, 1996, p.227). We note that what is true of objects in nature is also true of systems: smaller systems are parts of larger systems which are parts of even larger systems. We aren't aware of empirical research on the difficulty of mentally transferring attention back and forth between a smaller system and a larger system within which the smaller system is embedded. However, we offer the hypothesis that this transition is as hard or harder for systems as for it is for objects. By having students practice going from a whole to parts to whole, to a bigger whole, this activity may help students build their capacity for a challenging aspect of systems thinking.

Use of Visual Representations, to draw the CLD

Construction of the causal loop diagram is at the heart of the activity. We now discuss reasons why constructing a CLD can be difficult, followed by reasons why doing so is educationally and cognitively powerful. Little learning science or cognitive science research has been done specifically on causal loop diagrams, so we are extrapolating from a rich literature on visual representations more broadly. In this literature, the term "referent" is used for the real-world phenomenon and "representation" is used for human-made inscriptions that are created to capture, record, or convey something about the referent.

Cognitive analysis of why making CLD's can be hard

The use of space is unfamiliar:

In many visual representations that students have encountered before – including most maps, graphs, photographs and drawings – the position, orientation, and distance between elements of the diagram carry important information about the referent. For example, in a vector diagram in a physics textbook, the length, orientation, and origin point of the line are all important. In most maps and many graphs, one or both dimensions of the space on the paper or computer screen corresponds to space in the real world (e.g. Kastens & Manduca, 2012). In causal loop diagrams, none of this is true. Position on the page, orientation, and distance between graphic elements carry no information about the referent. The only thing that matters is the linkages between elements: what is linked to what, and the nature of the linkage (i.e. the directionality of the arrows and the S/O or +/- on the arrows).

The graphic language is unfamiliar:

To experienced systems thinkers, it seems self-evident that the arrows on CLDs indicate causality: $A \rightarrow B$ means that if there is a change in A, that will cause or tend to cause a change in B. But this is not self-evident. In his treatise on visual language, Horn (1998) identified hundreds of meanings of arrows (figure 3). Tversky et al. (2000) note that a common element of all of these uses is a sense of directionality, as when a physical arrow is shot from a bow. Arrows can be used to convey the passage of time, direction in space (e.g. north arrow on a map), increase or decrease, direction of motion (including flow of a fluid, translation or rotation of a solid, travel of a person or vehicle), and as pointers to guide the viewer's eye.

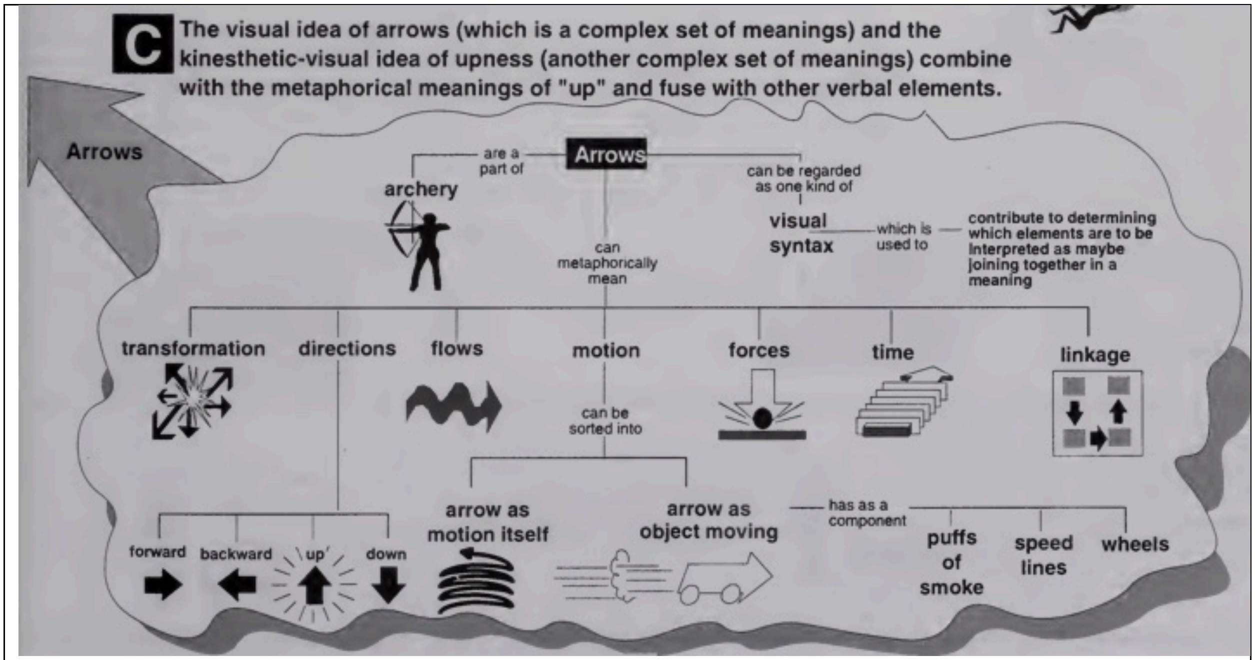


Figure 3: Horn's (1998) summary of the major uses of arrow graphics in visual language. The arrows in CLDs would fall among Horn's "Forces" grouping, as in "A forces B" or "A causes B."

The arrow confusion we see most often in dealing with causal loop diagrams is students reading or drawing arrows to indicate the passage of time rather than causal influence: "....and then..." rather than "...and so..." That's because time and causality are tightly coupled – but not perfectly so.

Every A → B causal link implies the passage of some time between the change in A and the change in B. But a temporal sequence, on the other hand, need not imply causality. For example, Wake up → Get out of bed → Get dressed → Eat breakfast → Go to work makes sense and conveys information about the real world, but the arrows carry little or no causal significance; they simply say "and then." On the third hand, temporal sequence does provide *some* constraints on causality: if we know that A happened before B, we know that A could have caused or influenced B, but B could not have caused or influenced A. Most students have never had occasion to think through these subtleties about the relationships between time and causality.

If a student is seeing arrows as conveying time, while the instructor is seeing arrows as conveying causality, two types of problems result. First, the student is seeing only part of the meaning of the arrow; yes, indeed, time does advance between the change in A and the change in B, but there is more to the story than that. Secondly, the notion that time would loop back and reconnect with an earlier moment in time may strike students as nonsensical. We continue with this idea in the next section.

Humans incline towards linear representations of temporal sequences:

People (at least in western cultures) have a strong expectation that time advances forward in one direction only (Munn, 1992). Time flows from the past, into the present, and then onto the future. Research by psychologist Barbara Tversky and colleagues has shown that people have difficulty in envisioning a series of events in time as having a looped or cyclical structure (Noel & Tversky, unpublished; Kessel, 2008; Tversky, 2019; Tversky & Jamalian, 2019, 2021). Tversky's team presented undergraduates with a verbal description of four events that formed a temporal *sequence* (e.g. Break eggs in bowl; Add milk; Stir; Cook in frying pan) or a temporal *cycle* (e.g. Wake up; Go to work; Come home; Go to sleep.) Students were asked to draw a simple diagram conveying the information presented. For the temporal sequence, ninety-five percent of students' drawings showed the four events as pictures or boxes, connected by lines or arrows, arranged in a progression from beginning to end of the written series. More surprisingly, 80% of students produced similarly linear drawings when asked to depict the events that formed a temporal cycle. The researchers tried several manipulations to make the cyclic nature of the repeating cycles more salient (for example, adding "Wake up" to the end of the temporal sequence), but a strong majority of participants persisted in making linear depictions.

The researchers' interpretation is that participants in these studies conceptualized time as unidirectional and resisted the idea of time as a cycle that can repeat. We further hypothesize that because of the strong association between time and causality, some students likewise resist the idea that causality can loop back upon itself and connect to an earlier node to form a loop. Some evidence of this resistance comes from one of our earliest (as yet unpublished) feedback loop studies in which we gave undergraduates a definition of a feedback loop and one example of a feedback loop diagram, and asked them to draw any other feedback loop from their own knowledge. Their most common error was to fail to close the loop in their diagram.

Cognitive analysis of why CLDs are powerful

Note that our goal in this section is not to persuade you to use CLDs in your instruction; many readers may already do that. Our goal is to offer some cognitive insights that may help you make your instructional use of CLDs more effective.

CLDs make the relationship between parts and wholes more salient:

In an earlier section, we discussed evidence of significant cognitive burden involved in shifting attention back and forth between local and global levels of information, which we generalized to apply to the parts of a system and the system as a whole. The CLD visual representation supports this mental effort by making the relationship between the parts of the loop (depicted as nodes and arrows), and the entirety of the loop more salient: the parts connect in a chain of influences, which loops around self-referentially. This relationship is almost invisible when the feedback loop is depicted in sentences: sentences have a beginning, middle, and end, and the end never connects to the beginning.

CLDs help overcome working memory limitation:

"Working memory" refers to the small amount of information that can be held in mind in a readily accessible form and actively manipulated during the execution of cognitive tasks (Burmester, 2017; Cowan, 2014). Inferring mechanisms, predicting behaviors, and evaluating evidence are examples of loop-relevant tasks that draw on working memory. Unfortunately, humans' working memory capacity is very limited, in the range of three to five items. Even the simplest feedback loop, one with two nodes plus two links, may tax the capacity of working memory. Constructing a casual loop diagram enables the reasoner to build a feedback loop in smaller chunks, each of which can be handled within working memory. The mind can focus on the A→ B link: identify its directionality ("S" or "O"), gauge its conditionality (e.g. "causes" or "encourages"), evaluate its evidence, step through its mechanism. Then, when the link is pretty well understood, it can be pinned down graphically onto the paper or computer screen, after which the mind can move onto contemplation of the B → C link, the C→ D link, and then eventually back to the loop-closing X → A link. Note that the causal loop diagram, as we are describing its use here, is not merely a communication tool or an assessment instrument. It is a thinking tool that actively supports the construction of an internally consistent model that is too large to keep in mind all at once.

Repeated use of CLDs facilitates extraction of a feedback loop schema:

We wrote above about "projective" analogic reasoning, in which the reasoner projects understanding from a specific familiar situation onto a newly encountered situation, based on discerning an analogic mapping between the two situations; we offered projective analogic reasoning as a way that learners can identify feedback loops in real world settings. There is another form of analogic reasoning that we think comes into play as the learner works with many different feedback loops over an extended course of instruction, called "extracting the schema."

This form of learning can arise when a learner is exposed to multiple instances of phenomena that have a similar suite of interconnected and important attributes and relationships. Over the course of exposure to multiple instances, the learner discerns the nature of these relationships and attributes, called the "schema." This is a foundational form of learning: think of how a child builds a schema for "dog," through exposure to multiple instances of dogs and non-dogs. Schemata built in this way tend to be more flexible and more powerful for problem solving, than a mere description or definition offered by an instructor or textbook (Gentner, 2010; Gick & Holyoak, 1980, 1983).

We hypothesize that working with causal loop diagrams facilitates the process of extracting a powerful, resilient feedback loop schema from exposure to multiple instances of feedback loops. Envision a television news clip of a pandemic, a wild fire, and a confrontation between police and protestors. Now envision a print newspaper account of those three situations. Finally, envision causal loop diagrams of pandemic spread, wildfire frequency under conditions of climate change, and escalation of hostilities. The three CLDs, with their loop structure, are visually similar to each other in a way that the TV clips and print accounts are not, leading us to conclude that a generalized, reusable schema for a reinforcing feedback loop may be easier to extract from among the three CLDs than among the alternate representations.

Language structures for conditionals and hypotheticals, used to write the narrative:

Writing accurately and grammatically about feedback loops calls for the use of linguistic structures that may never have been taught to your students, notably the conditional mood, modal verbs, and action verbs of varying strength. We don't advise that systems instructors explicitly teach these grammar bits, but we do advise that you attend to the shades of meaning conveyed by your own use of language, and be sensitive to the possibility that students whose native tongue is other than the language of instruction may struggle to find the words to externalize their understanding of a system into language.

"Modal verbs" are little verbs that accompany a main verb and give additional information about the proposition being expressed by the sentence. For systems thinking, an important use of modal verbs is to convey the speaker's/writer's assessment of the certainty or robustness of a proposed causal link. English language modal verbs include "can," "could," "should," "will," "would," "may," "might," "must." Students who are not skilled in English could easily miss the information conveyed by these inconspicuous little words. Consider the difference among: "when people are happy, they will throw a party," "...they can throw a party," ".... they might throw a party," and "... they should throw a party." The first conveys certainty; the second, capacity; the third, probability; and the fourth, a value judgement. In communicating about the causal structure of systems, modal verbs can convey subtle differences in how and why links between nodes are effectuated.

"Mood" refers to the devices that language uses to convey the writer's or speaker's attitude or intention towards the stated proposition, including the relationship of a statement to reality. Most conversation happens in the indicative mood (also called "declarative," used to declare or assert a fact, opinion or idea), the imperative mood (used to give orders), and the interrogative mood (used to seek information or clarification). But feedback loops are models, which is to say they are an expression of the speaker's/writer's hypotheses about how the world works, or might have worked in the past, or might work in the future under various conditions, including conditions that are counterfactual to present conditions. For expressing these "maybe" sorts of statements, language offers the less familiar "conditional" mood.

As well explained by LanGeek (accessed Dec. 12, 2024), the conditional mood "is used to express a hypothetical or uncertain situation that is ... dependent on a certain condition or circumstance. The situation is not necessarily real or has not yet happened, but may happen in the future." Conditional sentences usually have two parts: an if-clause or when-clause expresses the condition, and the "result" clause expresses the consequences that would follow if the condition were met. In place of "if" or "when," system thinkers often say "as," for example, "As people age, their muscle mass declines."

- *Zero conditional:* The "zero conditional" is used for facts or situations that the speaker/writer considers will *always* be true if the condition is met. In English, zero conditional is constructed as an if- or when- (or as-) clause, followed by a results clause in simple present tense. For example: "As greenhouse gas concentrations rise, the temperature also increases."
- *Conditional I:* The "first conditional" is used to discuss a possible situation with a result that the speaker/writer thinks is *likely* to occur if the condition is met. First conditional is used in expressing predictions about the future. In English, the first conditional has an if/when/as clause in a present tense, and a results clause made up of a modal verb (will, can, may) followed by the base form of the verb. For example: "If microbakeries increase, there will be more generation of jobs and income."
- *Conditional II:* The second conditional is used to describe a situation where speaker/writer considers the result to be unlikely or purely hypothetical. In English, the second conditional has an if/when/as clause in the past simple tense and a result clause made up of a modal verb (would, could, might) followed by the base form of the verb. For example: "If they exercised more, they would be stronger." The past tense in this construction doesn't indicate a time in the past; it indicates distance from reality.

In addition to modal verbs, English offers main verbs that can convey shades of probability or certainty that a result will happen under a given condition. In approximate level of decreasing certainty, "causes," "leads to," "tends to cause," "increases the chances of," or "favors" carry shades of meaning that are compatible with an "S" or "+" link in a causal loop diagram. An "O" or "-" link could equate to "prevents," "decreases the chances of" or "inhibits." To convey that the speaker or writer believes that there is a causal connection but they aren't sure of the direction or strength of the connection, an English speaker can use the verb "influences."

It may be tempting to move quickly away from natural language into software, where all of these subtleties can be rendered into unambiguous equations. However, eventually your thinking must be explained to stakeholders, at which point the need for natural language to explain the shades of causality becomes inevitable.

In conclusion:

For instructors: We hope that this tour through some of the thinking processes that your students employ helps you craft more effective lessons, and better handle your students' learning challenges as they arise. With your guidance, students should be better able to:

- use projective analogy to recognize unfamiliar feedback loops,
- use causal reasoning to identify and defend the causal links they find in a description of a real world situation,
- use a visual representation (diagram) to off-load mental effort while working through the chain of influences in an unfamiliar loop,
- go back and forth faciley between parts and wholes of systems and subsystems,
- extract an accurate and flexible generalized feedback loop schema as they work with multiple loop-driven systems,
- use natural language to accurately convey the conditionality of the various causal links that comprise a feedback loop of interest.

We especially hope that the insights provided in this paper have equipped you with concrete ideas for constructive critiques and encouragements that you can offer students who are swimming in that difficult liminal zone where they sort of understand, but not really. We hope that some of you, faced with a student product that mixes up a confusing mixture of good and bad aspects, will now think to say something like: "I like the way you have broken down the journalist's description into its constituent parts and relationships; you weren't doing that so well earlier in the semester." Or "the challenge you need to work on next is to focus in on the causal reasoning that you are using to justify each link in your CLD; what was the empirical evidence or plausible mechanism that you had in mind when you drew that [ ] → [ ] link?"

For students: We hope that this cognitively-informed instructional sequence will help build your capacity for recognizing, analyzing, and explaining feedback loops wherever you may encounter them in your personal and professional lives.

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References:

Attia, P., with Gifford, B. (2023). *Outlive: The Science and Art of Longevity.* Harmony, 496pp.

Burmester, A. (2017). Working memory: How you keep things "in mind" over the short term. *The Conversation*. Retrieved from https://theconversation.com/working-memory-how-you-keep-things-in-mind-over-the-short-term-75960.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in Instructional Psychology: Volume 5 Educational Design & Cognitive Science* (pp. 161-238). Mahwah, NJ: Lawrence Erlbaum Associates.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in Instructional Psychology* (pp. 161-238). Mahwah, NJ: Lawrence Erlbaum Associates.

Chi, M. T. H., de Leeuw, N., Chiu, M. H. , & LaVancher, C. (1994) . Eliciting self-explanations improves understanding. *Cognitive Science*, 18,439-477.

Cowan, N. (2014). Working memory underpins cognitive development, learning, and education. *Educ. Psychol. Rev.,* 26, 197-223.

Francek, M. (2005) Gallery Walk, Science Education Resource Center, online at: https://serc/carleton.edu/introgeo/gallerywalk/index.html

Gentner, D. (2010). Bootstrapping the mind: Analogical processes and symbol systems. *Cognitive Science,* 34(5), 752-775.

Gentner, D., & Colhoun, J. (2010). Analogical processes in human thinking and learning. In B. Glatzeder, V. Goel, & A. v. Muller (Eds.), *On Thinking: Volume 2. Towards a Theory of Thinking* (pp. 35-48). Berlin: Springer-Verlag.

Gentner, D., & Jeziorski, M. (1990). *Historical shifts in the use of analogy in science*. Technical Report no. 498, Center for the Study of Reading, University of Illinois at Urbana-Champaign.

Gentner, D., Loewenstein, J., & Hung, B. (2007). Comparison Facilitates Children's Learning of Names for Parts. *Journal of Cognition and Development*, 8(3), 285–307. https://doi-org.libproxy.temple.edu/10.1080/15248370701446434

Gentner, D., & Smith, L. (2012). Analogical Reasoning. *In Encyclopedia of Human Behavior (Second Edition)* (pp. 130-136): Elsevier. Online at: https://groups.psych.northwestern.edu/gentner/papers/gentnerSmith_2012.pdf.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology,* 12, 306-355.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology,* 15, 1-38.

Horn, R.E, 1998, *Visual Language.* Bambridge Island, WA. MacroVu, Inc.online at: https://dn720705.ca.archive.org/0/items/visuallanguagegl00horn/visuallanguagegl00horn.pdf

Hu, W. (2018). An island nesting ground for new technology, in the *New York Times*. Online at: https://www.nytimes.com/2018/12/17/nyregion/cornell-tech-startup-jobs-amazon.html

Kastens, K.A., L. Brenner, A. Davatzes, and T.F. Shipley (2024). Wrapping your head around environmental problems by leveraging feedback loop thinking. Website for Earth Educators' Rendezvous. Online at: https://serc.carleton.edu/earth_rendezvous/2024/program/morning_workshops/w6/index.html

Kastens, K. A., & Mandua, C. A. (2012). Fostering knowledge integration in geoscience education. In K. A. Kastens & C. Manduca (Eds.), *Earth & Mind II: Synthesis of Research on Thinking and Learning in the Geosciences, Geological Society of America Special Publication* (pp. 183-206). Boulder: Geological Society of America.

Kastens, K. A., and T. F. Shipley (June 2021). Linguistic clues for spotting feedback loops in the wild. *Creative Learning Exchange Newsletter* **30**(2). Online at http://static.clexchange.org/ftp/documents/x-curricular/CC2021_LinguisticClues.pdf

Kastens, K. A., and T. F. Shipley (2023). How does the human mind think and learn about feedback loops? *Proceedings of the International Conference on Systems Dynamics, Chicago, IL, Systems Dynamics Society.* Online at: https://proceedings.systemdynamics.org/2023/papers/P1208.pdf

Kastens, K. A., and T. F. Shipley (2025). Find the Feedback Loop teaching activity. *Teach the Earth web portal.* Online at: https://serc.carleton.edu/teachearth/activities/287189.html

Kastens, K. A., T. F. Shipley and W. Wakeland (2024). Developing and field-testing a rubric for evaluating students' causal loop diagrams. *Proceedings of the International Systems Dynamics Conference,* Bergen, Norway. Online at: https://proceedings.systemdynamics.org/2024/papers/P1354.pdf

Kareev, Y. (1995). Positive bias in the perception of covariation. *Psychological Review, 102*(3), 490-502.

Kessel, A. M. (2008). *Cognitive methods for information visualization: Linear and cyclic events.* (PhD), Stanford University, Palo Alto, CA.

Kuhn, D. (2001). How do people know? *Psychological Science, 12(1),* 1-8.

Kuhn, D. (2004). Developing Reason. *Thinking and Reasoning*, 10(2), 197-219.

Kuhn, D. (2007). Jumping to conclusions. *Scientific American Mind, Feb/March*, 44-51.

Kuhn, D. (2010). What is scientific thinking and how does it develop? In U. Goswami (Ed.), *Handbook of Childhood Cognitive Development* (pp. 497-523): Blackwell.

Kuhn, D., Black, J., Keselman, A., & Kaplan, D. (2000). The development of cognitive skills to support inquiry learning. *Cognition & Instructions, 18*(4), 495-523.

Kurtz, K., Miao, C.-H. M., & Gentner, D. (2001). Learning by analogical bootstrapping. *Journal of the Learning Sciences,* 10(4), 417-446.

LanGeek (accessed Dec. 12, 2024).

- Modals. https://langeek.co/en/grammar/course/450/modals
- Moods: https://langeek.co/en/grammar/course/548/moods
- Conditional mood: https://langeek.co/en/grammar/course/504/conditional-mood
- Zero conditional: https://langeek.co/en/grammar/course/110/zero-conditional
- Conditional I: https://langeek.co/en/grammar/course/36/conditional-i

Li, R., and N. Arroyo (2023). Cities are struggling. San Francisco could be in for the biggest 'doom loop' of all. *San Francisco Chronicle*. Online at: https://www.sfchronicle.com/sf/article/city-economy-doom-loop-17846412.php

Munn, N. D. (1992). The cultural anthropology of time: A critical essay. *Annual review of anthropology*, 21(1), 93-123.

Navon, D. (1977). Forests before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9*, 353-383.

Noel, A. M., & Tversky, B. (2020). Linear and circular thinking about time. *unpublished manuscript.*

Reinhart, A. (2020). Cognitive task analysis. Online at: https://www.refsmmat.com/notebooks/cognitive-task-analysis.html#:~:text=Cognitive%20task%20analysis%20is%20a%20way%20of,determine%20what%20cognitive%20skills%20real%20people%20use.

Robertson, L. C. (1996). Attentional persistence for features of hierarchical patterns. *Journal of Experimental Psychology: General, 125*, 277-249.

Tversky, B. (2019). *Mind in motion: How action shapes thought*: Basic Books

Tversky, B., & Jamalian, A. (2019). *Gestures alter thinking about time*. Paper presented at the Conference of the Cognitive Science Society. https://www.researchgate.net/publication/255961613_Gestures_Alter_Thinking_About_Time

Tversky, B., & Jamalian, A. (2021). Thinking Tools: Gestures change thought about time. *Topics in cognitive science, 13*, 750-776. doi: https://doi.org/10.1111/tops.12566

Tversky, B., Zacks, J., Lee, P., & Heiser, J. (2000). Lines, Blobs, Crosses and Arrows: Diagrammatic communications with schematic figures. In *Theory and application of diagrams* (Vol. 1889, pp. 389-408). Heidelberg: Springer.

Wieman, C. (2015). Comparative cognitive task analyses of experimental science and instructional laboratory courses. *The Physics Teacher, 53*, 349-351. doi:10.1119/1.4928349