Concept Mapping: A Technique for Teaching about Systems and Complex Problems

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Concept mapping is an educational technique that has been used in a wide variety of educational contexts in the past several decades (Novak and Canus 2008). Within the context of teaching about socio-environmental (S-E) synthesis, the use concept maps has emerged as a common and useful practice: a large number of SESYNC case studies incorporate concept mapping as a core activity and assessment (see Appendix A). Here, we discuss why concept mapping is a particularly powerful teaching technique for teaching about S-E systems and complex S-E problems, and describe how it has been and can be used in S-E synthesis case studies.

The appeal of the concept mapping technique lies partly in its flexibility and simplicity; it has a low entry threshold for students, yet is also useful for experts. A concept map is basically a diagram that displays concepts and ideas, along with the ways they are connected or influence one another. It provides a visual means to consolidate, organize, and document connections between ideas, issues, or causal forces, and thus is an effective method for helping students visualize and explore the complexity of a given S-E issue.

Concept maps are powerful tools for facilitating collaborative work. The process of creating concept maps provides a good opportunity for students to work together in groups and to practice integrating diverse viewpoints of a problem into a single coherent story. The concept maps themselves provide a useful artifact for students to explain their understanding of a complex issue: the maps act as a "boundary negotiating object" (Pennington et al. 2016) that provides tangible representation of the group's mental model by which a team can visualize, discuss, and refine their collective understanding of the problem. Thus, concept mapping is a powerful technique for ***providing direction and focus on interdisciplinary and transdisciplinary teams***, and a powerful activity for helping students to develop collaborative, interdisciplinary competencies.

In an S-E synthesis case study, concept maps can be a powerful medium through which students can continually refine how they are ***framing the problem*** presented in the case. By "framing the problem", we refer to the process of answering questions such as: What sort of expertise (scientific and local contextual expertise) is relevant to this problem? What understanding of the problem do these domains bring? What are the temporal and spatial boundaries of the problem? Who are the main players and what roles do they play? How do those players interact with one another and collectively to impact the problem? To explore these questions, students will necessarily cast a wide net of inquiry and gather information from a wide variety of domains (social, natural scientific, local context) in order to familiarize themselves with the problem and its context. They must develop a sense of how these domains shape their view of the problem and how these views collectively provide a more holistic understanding of the problem. In this way, a concept map is an excellent tool for students to explore, organize, and express a holistic description of the problem.

Concept maps are also useful in ***helping students to develop an understanding of a system***. A common activity to introduce students to a particular system that may be the focus of a case study is to ask them to create a concept map that describes the system by mapping the various parts of the system and their interactions. In these cases, the concept maps are often described as "systems maps." As a visual description of a system, a systems map describes a collection of actors and forces that work together to create and sustain a given socio-environmental phenomenon. The system map shows the causal relationships among those actors and forces. A concept map, on the other hand, describes interrelationships among ideas or concepts. Thus, while concept maps and systems maps share fundamental similarities, there are distinctions: while a system map can be thought of as a particular kind of concept map, not all concept maps are system maps. Likewise, not all systems maps are concept maps. For example, one might create a concept map to show the knowledge domains or disciplines that are relevant to a particular socio-environmental issue and how those domains inform one

another and our understanding of the issue. A system map might show the different actors involved in that same issue and highlight how their actions impact the issue and the other actors.

Finally, concept maps can be a highly effective storytelling platform for communicating with others outside the team about how the problem has been framed, what has been learned, and what information is still missing. In the context of a classroom, a concept map and accompanying map story helps the team showcase their thinking about the problem and provides a rich means of ***assessing student work and understanding***.

What are some best practices for teaching students to use concept maps?

- ***All concept maps should have a clearly-stated purpose***. This purpose serves as an important filter for including or excluding concepts, groups, or information. It also helps avoid a "spaghetti map" that is difficult to interpret or evaluate. By having a clearly stated purpose, one has something to evaluate the map against: How well does the map accomplish this purpose?
  One way of providing a clear purpose is to specify a question that the map is designed to answer. For example, the following questions (all about the same problem) lead to its own concept map. While all the maps may have some things in common, they will also be distinct from one another.
  - *What factors have worked together over the past 50 years to create the severe water shortage in the region surrounding Atlanta, Georgia?*
  - *Who are the main players who have impacted the water shortage in Atlanta, GA over the past 50 years, and what roles have they played?*
  - *What areas of knowledge are relevant for understanding the water crisis in Atlanta, GA over the past 50 years, and how do they inform our understanding of the problem?*
- ***Prominently display the purpose somewhere on the map***. It might be the title to the map, or it might be the central "concept" on the map. By displaying the purpose, the authors are reminded of the "filter" they should use for what to include or not include on the map. This also helps others understand the purpose of the map when they view it.
- ***Provide adequate scaffolding***. If students have little or no experience with concept mapping, it is important to give them practice before they attempt to make a map related to their case study. This scaffolding can be done by first using a simple, easily accessible and readily familiar example. The idea is to reduce the cognitive load (see Paas et al. 2003) by first focusing on the mechanics of making a useful concept map and later adding the task of synthesizing new information about the S-E problem into a concept map.
- ***Provide structure and limitations to the concept map activity, especially with novices***. Otherwise, novice students will likely generate maps that are highly specific, detailed, cluttered, and hard to understand. The instructor can provide structure by:
  - Limiting the number of concepts on the map: generally, novice maps with more than 10-15 concepts look more like "data dumps" where students included everything they could think of and where little consolidation or synthesis was done.
  - Clarifying the purpose of the map (see the item above)
  - Giving rough guidelines about the main categories of information to consider: i.e. giving rough boundaries for the scope of topics or concepts to consider)
- ***Label all arrows on the maps*** so that the concept - arrow - concept triad forms a logical statement of the relationship. (Note: some concept maps label arrows with +/- notation, as on each arrow, but this implies

that all the concepts on the maps are quantities that can increase or decrease over time. Such maps are primitive system maps that are more specialized and serve as precursors to exploring feedback dynamics and for building running simulators of the system associated with a problem).

- ***Require an accompanying narrative***. A concept map is a visual story. In order to fully grasp the story (and in order to help students figure out what the story is), it is important to require them to write a short narrative. This narrative should tell the story about the map, i.e. What is the answer to the main question that the map is designed to address?
- ***Ask students to reflect on their process of creating the concept map***. This can be a short written piece in which students describe their thought process and the process of negotiation that was used within the team. Through this reflection, students could develop more self-awareness about their learning and about how to work effectively on a team.
- ***Consider using a jigsaw team format for developing a holistic concept map***. For example, one student could explore the role of the social or political elements of the problem. Another student might do research on the natural ecosystem(s) involved in the problem. Another may do research on stakeholders. Each student could develop a separate concept map explaining their analysis and findings. The entire team could meet to integrate these individual maps into a more comprehensive map and associated story.
- ***Use pre and post concept maps as a means of self-reflection and as a way to assess student progress***. This helps highlight how student understanding of the problem has changed as a result of the exercise or case study.
- ***Teach by wandering around***. Give students time to work on their maps during class. Use this as an opportunity to wander around and observe their work. Ask them to explain their ideas and the maps as they develop them. Keep pointing them back to the purpose of the map, and help them find ways to eliminate unnecessary redundancy and clutter.

What are some common challenges (and fixes) to using concept maps?

It is often disappointing to see students' first efforts at creating a concept map. Beginner maps are sometimes overly complicated, and students have difficulty "telling the story" that their map represents. Early maps will sometimes provide little new insight as students struggle with this mode of communication and analysis. Be patient and plan on using this tool over and over in order to build proficiency and sophistication. Below are some common challenges, with suggestions on how to address them.

- ***Overwhelming maps***. Novice map builders tend to have too many components. It is often the case that several "concepts" on the map are so closely related that they can be consolidated into fewer concepts. This process of consolidation is a constant balancing act between too much detail and too little. By setting limitations on the map complexity, having a clear map purpose, and teaching by wandering around, this problem can be addressed.
- ***Questionable/undefined connections***. Novices tend to draw connections everywhere without defining or explaining the connections and relationship. By requiring each connecting arrow to be labeled so that each concept-arrow-concept triad is a clear statement of the relationship, this problem can be addressed. (See the best practices list in the previous section.)
- ***Ambiguity about the meaning of "+/-" designations***. In some software, concept maps (or mind maps) can be created for doing simple simulations. In order to do this, the arrows are labeled with "+" or "-" designations, instead of word phrases to describe the relationship between the connected concepts. In such

a case, the concept map is no longer primarily a communication tool (to clarify one's thinking about a problem and to communicate it to others), but is instead a simulation tool (to evaluate how the system might behave over time). The simulation use is extremely important and powerful, but should not be confused with the structural analysis that comes from the creation of a concept map and associated narrative. Too often, students can create simulators but they are unclear about what "story" or assumptions underlie the map they have created. This reduces the map to a kind of black box. It is best to use the simulation approach after first spending time creating a series of concept maps and narratives.

- ***Where to start?*** Students often have difficulty figuring out "where to start" when drawing their concept maps. A process for doing this is described in ***Appendix B: A process for making a concept map***.
- ***Assessment: How can I evaluate the quality of a concept map?*** Assessing the quality of a concept map is difficult because there are so many different aspects to consider. Instructors have found that it is helpful to prioritize what you are looking for in the map. Some options are listed below. The next section provides several rubrics that could be adopted for evaluating concept maps in your case study.
    - Look for progress in expanding the boundary of relevant factors affecting the problem. Compare pre- and post- maps to see if students have progressed in their understanding of the breadth of factors involved in the problem. For example, before the case study, students might have thought that problem or issue is rooted in the actions of a single group (the "bad guys") and failed to see that there are economic, social, and maybe even natural forces at work that also contribute to the issue. When evaluating expanding boundaries, less focus is on the actual structure of the concept map, but rather the scope of issues that are included in the map.
    - Evaluate the map syntax, by evaluating whether the map follows the rules for constructing such an artifact. Is the map's purpose displayed prominently? Are the arrows labeled so that each concept-arrow-concept triad forms a logical statement describing the relationship? Are the arrows logical? Are there redundant arrows or concepts that could be eliminated or consolidated?
    - Evaluate how well the map explains interdependencies by examining the focus and logical integrity of the map. Does the map address its primary purpose? Do the connections make sense? Do the concept-labeled arrow-concept triads form logically correct statements about the interrelationships? Are important relationships missing or misrepresented? It is important early on to evaluate the logical integrity and validity of the map: How well do the cause-effect relationships correspond to what students ought to know about the problem?
    - Evaluate concept map narrative. Concentrate on how the narrative and the map itself "go together." Is the narrative a holistic description of how the map addresses the main question, or is it a mechanistic "walk around" the map, explaining every connection and its meaning?

What are some useful resources for making and evaluating concept maps?

Free concept map utilities

- ***VUE (Visual Understanding Environment)*** **-** from Tufts university; very powerful, with story-telling capabilities, imbedding images and documents, etc
- ***Mental modeler*** - Provides some nice rudimentary simulation of system maps based on fuzzy logic.
- ***CMAP*** **-** Powerful, lots of features, international development community

Rubrics for evaluating concept maps

- ***This document gives a collection*** of useful rubrics from the University of Iowa.
- Below is a rubric from one of our case studies (A Pipeline in Paradise, Part 1: Learning the Relevant Science (2014-6). This evaluates both the map itself and the accompanying narrative.

Evaluation Rubric: Integrated Concept Map and Narrative

Criterion (CM = "Concept Map"; N = "Narrative")	0 - Missing	1 Unnaccep-table; major errors	2	3 Acceptable; many minor errors	4	5 Outstanding; no notable errors
CM: Neat and easy to read						
CM: Connected concept and labeled arrows form meaningful and correct statements						
CM: Considers concepts from all relevant knowledge domains						
CM: No obvious missing connections						
N: Focuses on answering the main question						
N: Easy to follow; well written						
N: Consistent with the Concept Map						

References

Novak, J.D. and Canas, A.J. 2008. The Theory Underlying Concept Maps and How to Construct and Use Them. Technical Report IHMC CmapTools 2006-01 Rev 01-2008. www.ihmc.us

Paas, et al. 2003. Cognitive Load Theory and Instructional Design: Recent Developments. *Educational Psychologist, 38(1)*, pp. 1-4. Lawrence Erlbaum Associates, Inc.

Pennington, D.A. et al. 2016. The EMBeRS Project: employing model-based reasoning in socio-environmental synthesis. J Environ Stud Sci. 6:278–286 DOI 10.1007/s13412-015-0335-8

Appendix A: SESYNC Case Studies Using Concept Mapping

The following is a list of case studies in the SESYNC Case Study Collection that use concept mapping. This is a sample, and is not comprehensive.

From Tropical Plantations to K-Cups: A socio-environmental analysis of the global journey of coffee (2015-10) by Madhusudan Katti, Andrew Rhys Jones, Mara Brady, and Beth Weinman

Social-Hydrological Risk in the Mexico City Basin (2015-9)
Author(s): Hallie Eakin, Ana Elena Escalante, Elizabeth Tellman, and Lakshmi Charli-Joseph

Up in the Air: Understanding Vulnerability when Toilets Fly (2015-7)
Author(s): Amy Krakowka Richmond, Suzanne Pierce, and Gautam Sethi

Balancing economic and environmental tradeoffs for dairy production in California and New Zealand (2015-6) by Rachael Garrett and Meredith Niles

The Fish, the People, the Tradeoffs: Social-Ecological Coupling in the Wetfish Fishery of Monterey Bay, California (2015-2) by Stacy Aguilera and Rachel Zuercher

A Pipeline in Paradise, Part 1: Learning the Relevant Science (2014-6) by Shannon N. Conley, Kathryn De Ridder-Vignone, Mary K. Handley, and Michael L. Deaton

When It Rains, It Pours: A Socio-environmental Approach to Understanding Coastal Flooding (2014-5) by Elizabeth A. Albright, Emily Eisenhauer, Melissa A. Kenney, and Ariana E. Sutton-Grier

Designing an Urban Green Infrastructure Network: Balancing Biodiversity and Stakeholder Needs (2014-4) by Emilie Stander and Myla Aronson

Using System Maps to Analyze Complex Social-Environmental Issues: A Case Study of Geoduck Aquaculture in the Puget Sound (2014-2)) by Kate Mulvaney, Simone Pulver, Clare Ryan, and Yen-Chu Weng

The Blind Spot in the Green Revolution: Temples, Terraces & Rice Farmers of Bali (2013-14) by Cynthia Wei, William Burnside, and Judy Che-Castaldo

Appendix B: Introduction to Concept Mapping from A Pipeline in Paradise, Part 1: Learning the Relevant Science (2014-6)

By Shannon Conley, Michael L. Deaton, Mary Handley, Kathryn de Ridder-Vignone

What is a concept map?

A concept map is a diagram that displays concepts and ideas, along with the ways they are connected or influence one another. To make a concept map, you need to have a purpose for it. That purpose can be stated as a question that the map is designed to answer. It should be prominently displayed on the map (either as the title or as a central concept on the map).

A plan for making a concept map that integrates the five knowledge domains

Begin by first identify the question you wish to answer through the concept map. It's not appropriate to use a "yes/no" question or a question that has a single answer. Instead, think of questions that prompt you tell a story. One way to do this is to use questions that ask you to explain how to make a decision or find a particular answer. For example, instead of using *"How much money do I need for my spring break trip?"* (question with a single answer), use *"What considerations should I keep in mind as I decide how much money to take?"* Instead of asking *"Should I change my major?"* (a yes/no question), ask instead: "*How will I go about deciding whether to change my major?"*

Begin by getting a stack of 30 or 40 post-it notes of different colors on which to write your ideas. Go some place where you can have a big board to write on. Then on that board, begin by drawing a big oval in the center of the board. Inside the oval, write down the primary question that the map is designed to address. This is the start of your concept diagram.

Now, use post-it notes to add your diagram those concepts, ideas or issues that your team has identified that would be important to answering the question. Write one concept, idea, or issue on each post-it note. Then place the post-it notes on the board. Think about arranging similar ideas/concepts/issues close to one another on the board, but leave lots of space for drawing arrows.

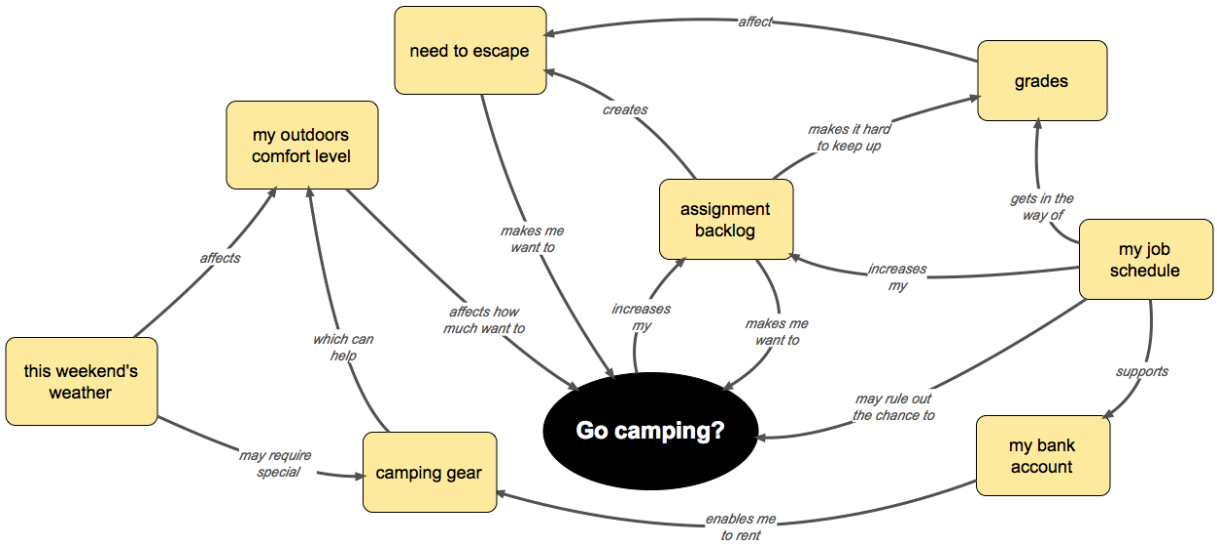
Adding and labeling connecting arrows

As you add post-it notes (concepts) to your diagram, draw arrows that show the interdependencies among the

concepts. The arrows should point from a concept into another concept that in some way is affected by or depends on the first.

See the concept map below. This map addresses the question *"How will I decide if I should go camping with my friends this weekend?"* Notice how the main purpose (question) that the map addresses is shown prominently in the large black oval near the center. Each "node" (oval or rectangle) either has an arrow leading into it or out of it (a node with no arrows into or out of it would not, by definition, be relevant to your story).

Also notice how the arrows are labeled with verb phrases (action phrases) that describe the relationship between the two connected nodes. You can check yourself to see if your nodes and connections make sense by seeing if each pair of connected nodes and the labeled arrow can form a sentence that makes sense. For example, the arrow from "my job schedule" to "my bank account" can be translated to say "My job schedule supports my bank account." The relationship between "my outdoors comfort level" and the "go camping?" concepts is this: "My outdoors comfort level affects how much I want to go camping."



Writing a narrative to explain the "story" your concept map is telling

It is important that you supplement your concept map with a written or oral narrative to help a viewer (and you!) understand the big picture - what the concept map is designed to represent. To do this, you need to "tell the story": explaining how your map addresses the question in the central oval. For example, if you examine the above diagram, you can hopefully see that it's telling a story...the story about all the things this student is considering as they think about going camping.

In order to create this narrative, step back and ask "what story are we trying to tell with this map?" If you can tell this story in a concise way, it will help a viewer interpret the diagram and understand the main ideas you wish to communicate. BE CAREFUL! Your story narrative should provide something more informative than a simple bulleted list of disconnected sentences (one sentence for every pair of connected nodes). Instead, the narrative should provide a focused "Cliff Notes" summary of the main ideas and relationships you wish to communicate through the concept map.

Here's one example of a narrative that could go along with the above diagram. We will write the story in 1st person, since the diagram refers to "my bank account," etc.

As I think about going camping this weekend, I'm trying to consider three main things: (1) how comfortable I

feel about being outside all weekend (given the weather conditions and the camping gear I have), (2) my need to escape and unwind (because I've had lots of homework lately, and my grades are suffering) , and (3) my job schedule (which needs to take priority so I can pay my bills...but which also makes it hard to keep up my grades). What shall I do? The jury is still out on this one!

Notice that the story does not refer to every single detail in the diagram, but it captures the essence of main ideas and their relationships. Also, the story has a focus. In this case, the story focuses on answering this question: *"How will I decide if I should go camping with my friends this weekend?"* The story addresses the details in map only as they bear on that main question.

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