# A Novel Approach to Teaching and Understanding Transformations of Matter in Dynamic Earth Systems

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## ABSTRACT

The need to engage K-12 and post-secondary students in considering the Earth as a dynamic system requires explicit discussion of system characteristics. Fundamentally, dynamic systems involve the movement and change of matter, often through processes that are difficult to see and comprehend. We introduce a novel instructional method, termed Cause-MaP, designed to enhance non-science major undergraduates' understanding of complex Earth systems. Students are provided with a mechanism for explicitly following matter as it moves through the environment, and are encouraged to describe this movement both verbally, in response to a structured set of questions, and pictorially, in box-and-arrow diagrams. This approach raises awareness of the underlying causes for the dynamic nature of systems, and encourages reasoning, thoroughness, and transferability of skills. Preliminary data suggest that this method is effective with post-secondary students and we encourage adaptation of Cause-MaP to other courses at both the post-secondary and K-12 levels. A follow-up, more rigorous investigation of the impact of this approach on student learning will clarify the effectiveness of this instructional method.

## INTRODUCTION

Earth is a complex and dynamic system comprised of numerous, interacting subsystems, commonly considered as the geosphere, hydrosphere, atmosphere, and biosphere (Orion, 2002). In recent years, the importance of the interrelatedness of these spheres has led to the emergence of Earth System Science (ESS) both as a research venue and an approach to integrated instruction (Herbert, 2006; Mayer, 1991, 1995; Orion, 2002; Rankey and Ruzek, 2006). A critical aspect of ESS literacy is the ability to apply "systems thinking", which can be defined as "a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots" (Senge, 1990, p. 69). Each sphere is interwoven with all others through processes and exchanges of matter. At the same time, each sphere derives its characteristics from the matter within the sphere and the processes that transform that matter. For example, $CO_2$ in the atmosphere can come from $CO_2$ erupted from volcanoes (rock cycle), diffuse and dissolve into raindrops or directly into the oceans (water cycle) and react to form new rocks (rock cycle) or organic molecules via photosynthesis (bio cycle). Students often do not realize that a single method of reasoning can be applied to studying processes in all Earth spheres. This unfortunate, non-systematic view may be reinforced when the spheres (or cycles) are presented separately in textbooks or classrooms. Whereas scientists are flexible in their thinking and easily recognize processes that transform matter within or between spheres, students may become lost when instruction does not explicitly delineate matter, process characteristics, and relationships amongst spheres.

In this paper, we outline an instructional method that we term Cause-MaP, for Cause, Matter, and Process. We developed the Cause-MaP method to expose students to systems thinking, encourage reasoning about transformations that occur in Earth systems, and to recognize the importance of the causes driving transformative processes that generate Earth change through time. The Cause-MaP method promotes student visualization of matter, processes, and underlying causes within Earth systems via a framework that breaks down complicated processes into component parts, effectively sorting vital from non-vital ideas for teachers and students, and providing a context in which students can practice scientific reasoning skills. Utilizing a single method to reason across different systems has significant benefits, including: 1) complete, thoughtful consideration of processes, as opposed to rote use of technical terms; 2) transferability of skills across what the student may perceive as disparate Earth systems; 3) heightened awareness of why systems remain dynamic over time; and 4) potential for application of scientific reasoning to both scientific issues and to life outside the science classroom. We demonstrate the application of this method to the water cycle, and present exemplars of student work. It is our expectation that this method will direct students to reason about interactions between matter and processes rather than practice rote memorization of terms or see systems as non-integrated, isolated pieces. This expectation is in line with studies of related instructional approaches, such as concept mapping and constructivist activities (Bodner, 1986; Bransford et al., 2000; diSessa et al., 2004; Novak and Cañas, 2006).

## CONTEXT

Previous work has shown that many students have conceptual difficulties understanding dynamic systems (e.g., Sell et al., 2006), especially when the matter is in an unobservable part of the system, such as groundwater flow (Orion, 2002; Sibley et al., 2007), when a process is not readily apparent, such as condensation (Sibley et al., 2007; Wilson et al., 2006), or when the instructional context of the system is not directly relevant to the students' previous experiences (Shepardson et al., 2009). In stark contrast to the practice of scientists, who generally visualize the entire system and apply reasoning to constrain system properties, many students try to learn

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about systems by remembering isolated pieces of information (Raia, 2005). The science education community, particularly physics education, has long recognized the presence of fragmented or loosely-coherent ideas in student explanations of phenomena (e.g., diSessa, 1988; McDermott, 1984; Redish, 2004; Reiner et al., 2000). In the geosciences, researchers have observed students who perceive the water cycle as a set of unrelated facts, understanding various hydrobiogeological processes, but lacking "dynamic, cyclic, and systemic perceptions of the system" (Ben-Zvi-Assaraf and Orion, 2005, p. 366). Similarly, Libarkin and Kurdziel (2006) noted that students possess facility with isolated, technical ideas, but demonstrate limited recognition of underlying processes responsible for Earth phenomena. They suggest that, while the majority of students perceive that something causes a transformation of matter, most students are unable to provide an explanation of why the transformation (or process) is occurring. Overall, students seem to be focusing on changes that occur to matter without recognizing causal relationships. In a post-secondary physical science class for non-science majors, Sibley et al. (2007) noted that even though processes were a focus of rock cycle instruction, post-instruction student interviews revealed students could describe basic rock types but never mentioned the processes by which matter moves or changes in the rock cycle (Sibley et al., 2007, p. 144). In addition to focusing on matter over process, Sibley et al. (2007) found that many post-secondary-level students do not apply scientific principles in their responses to science questions. Clearly, students are more comfortable focusing on matter as isolated pieces of information than they are with processes responsible for transformation of matter. Attempts to improve instruction by focusing on these processes have not been entirely successful (Raia, 2005; Sibley et al., 2007).

Teaching post-secondary students to apply reasoning to the task of tracing matter through a system, coupled with explicit attention to what drives processes (e.g., force, energy, cause, impetus), provides a structure around which students can practice thinking scientifically. Unraveling events into the three fundamental components of matter, process, and cause encourages students to recognize that diverse processes can be understood through a common reasoning framework. Students can be influenced to build new knowledge on top of existing knowledge by repeatedly applying the same reasoning to processes occurring across an array of dynamic systems. This can help students to recognize the repetition of common patterns in the fundamental structures of all systems.

## CAUSE, MATTER, AND PROCESS METHOD (Cause-MaP)

The importance of tracing matter (Wilson et al., 2006), of distinguishing between matter and process (Libarkin and Kurdziel, 2006), and of causality (Raia, 2005, 2008) in understanding fundamental earth systems is well recognized. To target these core concepts, we developed Cause-MaP. The Cause-MaP method has two overarching goals: 1) to provide a mechanism for students to track the movements and changes of matter through sequential processes; and, 2) to provide the instructor with clear guidelines for determining which material is relevant and necessary to a particular concept. Utilizing only relevant material and applying a backwards design approach (Wiggins and McTighe, 2006) helps instructors to be consistent, and encourages development of clear and concise curricula and instruction. Two aspects of *Understanding by Design* described by Wiggins and McTighe (2006) are explicitly addressed in Cause-MaP: 1) promoting transfer of learning; and, 2) providing a conceptual framework for helping students make sense of discrete facts and skills.

Students engaging in the Cause-MaP method develop basic reasoning skills through careful scaffolding of three tasks:

1) *Answering a set of five questions for each process in a system.* These questions encourage explicit tracing of matter through a system, as well as recognition of the underlying cause for transformation or movement of matter.
2) *Tabulating the answers into a structured argument table.* Transferring answers to a table, with each row being a reasoned response, provides a stepwise pattern to connect each process to the subsequent one, helping the student to avoid skipping steps and the instructor from introducing irrelevant material.
3) *Using the table to construct a box-and-arrow diagram.* This diagram offers a pictorial representation of relevant processes. Students can easily identify processes that are irrelevant to the specific system being studied, and missing connections in the diagram indicate processes or matter that need to be considered.

*Population and Setting.* The Cause-Map method was developed and evaluated for undergraduates enrolled in a science for non-science majors course (n=69) at a large state university in the Midwestern US. The course is designed to provide students with a basic understanding of global change throughout Earth's history, and across many environments. The students enrolled in this course were mostly third-year post-secondary students, with 9%, 17%, 44%, and 29% in their first, second, third, and fourth years, respectively. One additional student was enrolled as non-degree seeking. Other demographics were not collected from the students in this class. However, the typical university-wide enrollment during this semester was: 58% female and 42% male; 72% Caucasian, 9% black, 6% Asian/Pacific Islander, 3% Hispanic, 0.7% American Indian/Alaska Native, and 8.4% international. We have also introduced Cause-MaP in other similar courses; these experiences influenced the development of the method as presented.

## IMPLEMENTING Cause-MaP

Bridging curriculum with prior knowledge can aid in the transition from familiar to unfamiliar concepts. Initial applications of the Cause-MaP method have been most successful in our classrooms when we first introduce students' to tangible, seemingly non-scientific and everyday examples These examples serve as a guide when considering more complicated, less familiar processes and systems. For example, students are generally more experienced with the phase transformations of water changing from gas to liquid to solid than they are with transformations occurring within the carbon cycle. Given the familiarity and ease with which most students discuss water processes, such as melting, freezing and precipitation, the transformation and movement of water in a familiar setting lends itself to encouraging systems thinking, particularly in students who may be reluctant or even afraid to engage in science.

In our courses, we first introduce students to Cause-MaP with a brief lecture reviewing and expanding on water cycle processes. Following a discussion of the processes of evaporation and condensation, that water vapor in the atmosphere is invisible, and that clouds consist of tiny droplets of liquid water, students were shown a picture of a steaming hot cup of coffee. Students were asked to explain all the 'driving forces' (i.e., causes), forms of matter, and processes (Cause-MaP) involved in transforming water molecules in the hot coffee into water vapor dispersed in the atmosphere. Students collaborated in groups of three or four to explain the processes involved. This is a good introductory exercise for the students because it can be observed in daily life, involves water cycle processes, and the system is more complicated than many people initially expect. Our example problem is a fairly simple system to scientists, and most faculty teaching about these phenomena would easily recognize that the water evaporates, condenses to form visible water droplets (i.e., a mist), and then, as it advects, the water evaporates and disperses into the atmosphere. These processes may seem obvious and intuitive to faculty, but until a student is explicitly cognizant of each, many of the processes will remain unintuitive. The familiarity of a steaming cup of coffee belies the inherent complexity of this system. After students gain confidence and experience with this familiar system, faculty can then introduce more complicated, cross-sphere phenomena. As appropriate for a given course, this can then lead into discussions on geological processes important for understanding the significant role of fluxes in Earth processes (Wood, 1997).

## STEP1: ANSWERING THE QUESTIONS

The question of how water moves from being a liquid in a cup of coffee to being a gas in the atmosphere requires consideration of what, where, and why the water is moving. The Cause-MaP method pulls apart abstract ideas that are often taught implicitly by first asking the series of questions listed below.

Cause-MaP users should first clearly define what, a water molecule or an entire cup of coffee, is being traced through the environment. Subsequent questions elicit explicit details that students (and perhaps faculty teaching a new subject) need in order to understand how processes in systems operate. We encourage the answers to questions 2 through 4 to consist of only one or two words to avoid inclusion of irrelevant details and to facilitate easy transfer to the tabulated format.

**Question #1: What MATTER is being traced?** The first question provides the foundational focus of the exercise and it needs to be formally stated. Whether the matter of interest is a hypothetical carbon atom in an atmospheric $CO_2$ molecule that becomes bound in a shell fragment and deposited at the bottom of the sea, or a water molecule leaving a cup of coffee and entering the atmosphere, students need to clearly state what entity is being followed through the environment.

**Question #2: Where is the PROCESS occurring?** Geoscientists consider processes that occur within and across multiple spatial boundaries. Therefore, it is important for students to visualize where a process is occurring. We also need to acknowledge that the vocabulary may itself be a barrier for some students. For example, 'biosphere' does not define a unique location, but is rather a sphere that encompasses any location where life exists. This may not be obvious to students, and we argue that recognizing the importance of spatial location in processes is a necessary step to developing a meaningful Earth systems understanding.

**Question #3: What is CAUSING the process to occur?** This is a critical question that is often bypassed by students, textbooks, and instructors. Only with a conceptual appreciation of why a process occurs, can students gain a proficiency in understanding the process itself (Libarkin and Kurdziel, 2006). We chose to have students answer the "why" of matter transfer and transformation by articulating a "cause" to the process. In our discussions, we originally contemplated having students determine the underlying 'driving force" of changes to matter. However, the phrase 'driving force' may misdirect or confuse some students if they are thinking of a term, such as gravitational potential, that they know to be energy, not a force. Energy and force are difficult and abstract concepts for many students, and are often confused with one another (Hestenes et al., 1992; Trumper et al., 2000). Thus we have chosen the more general term, "cause" which can encompass both force and energy. Focusing on the concept of a cause, instructors can emphasize causal relationships while maintaining the freedom to address the causes at whatever level they deem appropriate for their students.

**Questions #4 & #5: What is the scientific TERMINOLOGY for the process?; and, What is changing or moving?** These two questions address the processes involved in the change or movement of matter either within or between reservoirs or spheres. Answers to question 4 are the technical terminology, such as "evaporation", typically associated with the processes in box-and-arrow diagrams (Sibley et al., 2007). In answering question 5, students provide an explanation of, or definition for, the scientific terminology used to describe the process. This helps students to associate technical words with the process and form a deeper cognitive understanding rather than allowing them to potentially discuss processes using only procedural display (Bloome et al., 1989).

**TABLE 1.** STRUCTURED SET OF QUESTIONS WITH EXAMPLE.

| QUESTION | EXAMPLE |
|---|---|
| Q1. What MATTER is being traced? | **Q1 answer.** Water |
| Q2. What is the LOCATION where the process is occurring? (Matter is moving within a sphere, or from where to where?) | STRUCTURED ARGUMENT:<br>*In / From the **Q2 answer**, the **Q3 answer** drives **Q4 answer**, which is / of **Q5 answer**.* |
| Q3. What is CAUSING the process to occur? | |
| Q4. What is the scientific TERMINOLOGY for the PROCESS? | EXAMPLE:<br>From the **coffee to the atmosphere**, **heat** drives **evaporation** of **liquid water to water vapor**. |
| Q5. What is changing or moving? (EXPLAIN what is happening to matter.) | |

## STEP 2: TABULATING THE ANSWERS

The responses to the five questions are combined to form a logical statement about a single process (Table 1). The five answers are inserted into a structured argument table (Table 2), providing a mechanism for recognizing the relationship between sequential processes and building a model for a complex series of processes. A tabular format encourages students to be thorough in their answers. If the matter described by "What is changing or moving?" in one row can't be linked directly to the matter in the subsequent row through a single process, then the student will know that a process has been skipped. The student must list processes as they relate to each event and detail the causes for each event. We also have found that encouraging students to include mental cues helps them to link colloquial understanding with scientific models. Students can scan down the Q4 and Q5 columns to confirm that the matter output from one process is the correct input matter for the subsequent process. It is the responses to questions 4 and 5 that are displayed graphically as a box-and-arrow diagram (Fig. 1).

## STEP 3: CONSTRUCTING THE BOX-AND-ARROW DIAGRAM

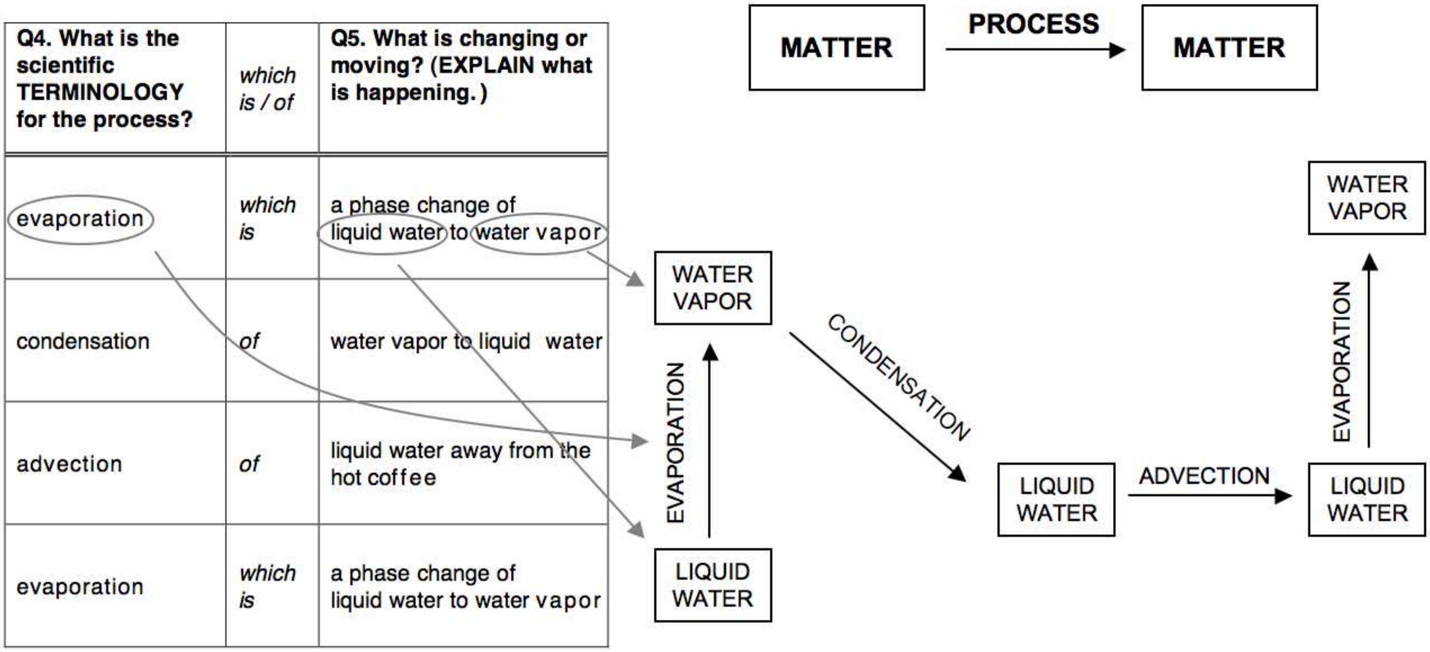
In the third and final step, tabulated responses are used to construct a cyclic concept map (Safayeni et al., 2005) called a box-and-arrow diagram (Fig. 1). In a typical concept map, concepts, which are typically encircled or boxed, are linked by words or phases and lines to other concepts to form meaningful relationships (Novak and Cañas, 2006; Novak and Gowin, 1984). In box-and-arrow diagrams, reservoirs or forms of matter are linked by processes that indicate functional relationships (Sibley et al., 2007). These processes are typically unidirectional and, as such, are indicated by arrows. Though not specifically called box-and-arrow diagrams, these kinds of figures have represented geological systems, such as the rock cycle and water cycle, in introductory-level geoscience textbooks since at least the 1930s (Croneis and Krumbein, 1936).

The first box in a box-and-arrow diagram should state the matter in its initial form. In the case of our hot coffee example, the initial matter is liquid water. The process of evaporation connects liquid water to water vapor in the atmosphere; condensation turns this gas back into a liquid; advection moves the liquid water into a zone of lower saturation; and a final evaporation step changes suspended droplets of liquid water back into water vapor. Coupled with the table (Table 2) that states the underlying cause and defines each process, this method yields a model that students can use to reason about phase transformation. Although explicitly stating each step may

**TABLE 2.** TABULATION OF PROCESSES INVOLVED IN MOVEMENT OF WATER IN A COFFEE-AIR SYSTEM
**Q1. What MATTER is being traced?** Water from a hot cup of coffee into the air

| *In / From the* | **Q2. What is the LOCATION where the process is occurring? (Matter is moving within a sphere, or from where to where?)** | **Q3. What is CAUSING the process to occur?**[1] | *drives* | **Q4. What is the scientific TERMINOLOGY for the process?** | *which is / of* | **Q5. What is changing or moving? (EXPLAIN what is happening.)** | **Mental cues and details (assessable knowledge)** |
|---|---|---|---|---|---|---|---|
| *From the* | hot cup of coffee to the air | heat | *drives* | evaporation | *which is* | a phase change of liquid water to water vapor | water vapor is invisible |
| *In the* | atmosphere | heat loss | *drives* | condensation | *of* | water vapor to liquid water | liquid water is visible |
| *In the* | atmosphere | thermal variations | *drives* | advection | *of* | liquid water away from the hot coffee | convection of air over hot coffee |
| *In the* | atmosphere | vapor pressure | *drives* | evaporation | *which is* | a phase change of liquid water to water vapor | |

Note:
[1] The level to which causes are described will depend upon the nature of the course objectives and the student population



| Q4. What is the scientific TERMINOLOGY for the process? | which is / of | Q5. What is changing or moving? (EXPLAIN what is happening.) |
|---|---|---|
| evaporation | which is | a phase change of liquid water to water vapor |
| condensation | of | water vapor to liquid water |
| advection | of | liquid water away from the hot coffee |
| evaporation | which is | a phase change of liquid water to water vapor |

**FIGURE 1.** **Box-and-arrow diagram for water evaporating from a hot cup of coffee. The responses to questions 4 and 5 are used by the student to construct the box-and-arrow diagram. Note that the cause for each process could be added to the arrow and the location could be included in the reservoir box, if an instructor wishes. We caution that too much text can overloaded the diagram and take away from its effectiveness in communicating its key point about changing and moving matter.**

appear overly detailed and unnecessary to some faculty, we believe that these details are necessary until students gain the ability to recognize system components and visualize emerging patterns of systems. Once students become proficient at explicitly recognizing matter and important processes occurring in a system, rigidly following the Cause-MaP steps may become unnecessary. For example, the structured set of questions themselves can become second nature and tacitly applied.

During in-class activities, we have observed that some students prefer to complete the box-and-arrow diagram prior to tabulating their answers to the questions. We are not concerned that this might detract from the strengths of the Cause-MaP method, and note that this may be indicative of differing learning styles. The Cause-MaP method enhances box-and-arrow diagrams by providing an avenue for connecting matter to processes, and processes to causes. Students must also define each term in the structured argument. If used correctly, box-and-arrow diagrams actually define this scientific terminology. For example, the process of evaporation appears on an arrow pointing from a box containing liquid water to a box containing water vapor (Fig. 1). Evaporation *is* the transformation of a liquid into a gas.

Box-and-arrow diagrams can be constructed as in Figure 1, or more details can be added to pinpoint specific locations (cf. Sibley et al., 2007). The desire to provide a complete picture of the processes involved in a system needs to be weighed against the limited amount of information that students can absorb (e.g., Johnson and Aragon, 2003). We recommend taking advantage of the strengths of this method by simplifying each step, such that the box-and-arrow diagram illustrates a systems approach to how matter is transformed and the table emphasizes causation and relates each transformation to a location.

Finally, flexibility in how students are allowed to construct structured arguments is necessary, as instructors will have different concepts that they wish to emphasize. For example, one instructor might feel it is important to emphasize vapor pressure conditions whereas another instructor may want students to focus on the more conceptually accessible concept of thermal energy as the cause of evaporation. Regardless of the specific focus, the Cause-MaP method encourages consistency within any class, so that students are reapplying the same causal relationships and processes in multiple contexts.

## EVALUATION OF CAUSE-MaP

We have analyzed exam data that suggest Cause-MaP is an effective tool for encouraging explicit consideration of the movement and change of matter within dynamic systems. In addition, these data illustrate limitations of the method. These data were collected for standard student assessment purposes in a course taught by one of the authors with questions that were not written explicitly with research objectives in mind. Following five in-class and homework activities in which students applied the Cause-MaP method to water and carbon cycle processes, students (n=69) were provided two opportunities to apply the Cause-MaP method on a mid-term exam. While both questions related to movement of material in a system, one question explicitly asked students to use the Cause-MaP tools, while the other did not:

1) Summer is upon us and it is frequently muggy (i.e., hot and sticky) outside. The mugginess is due to

heat and water vapor in the air. **What is the main way for that water vapor to leave the atmosphere?** (Include all necessary steps.)

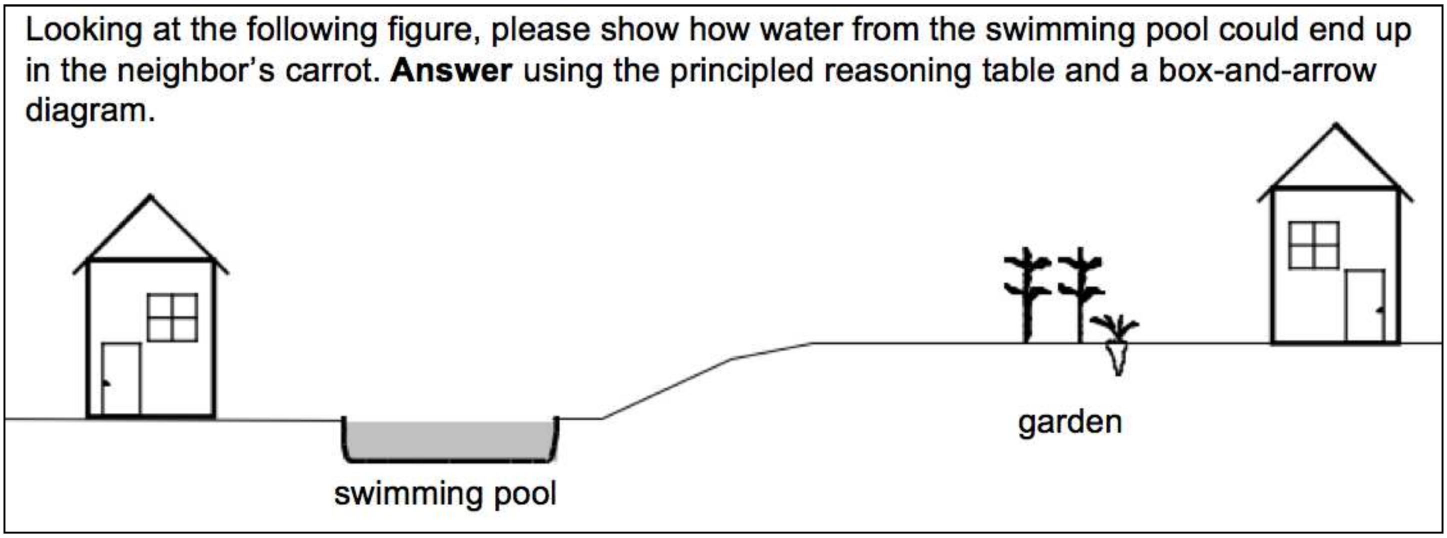
2) Looking at the following figure, **please show how water from the swimming pool could end up in the neighbor's carrot**. Answer using the structured argument table and a box-and-arrow diagram. [*Note: This question was accompanied by the figure as shown in Fig. 2, as well as a blank table, similar to Table 2.]*

The first question is the simpler of the two, requiring only two steps to explain the movement of water vapor out of the atmosphere (condensation and precipitation). The second question (Fig. 2) requires five or six steps: evaporation, advection (not required in assessment), condensation, precipitation, infiltration, and absorption. In addition, this more difficult second question explicitly encourages students to use the Cause-MaP method, while the first question makes no mention of Cause-MaP.

While every student presented some form of a box-and-arrow diagram when explicitly told to use Cause-MaP on question 2, only one out of five students included a box-and-arrow diagram in their responses to question 1. The average instructor-generated score for all students was 67.5% ± 36.5% ($1\sigma$) and 82.5% ± 16.7% ($1\sigma$) for questions 1 and 2, respectively. Even though the difference between scores on these two questions were not statistically different based on a non-parametric Mann-Whitney U-test ($p=0.58$, two-tailed) this contrast is striking given that the second question contained three times as many processes as the first. Similarly, the average score for those students ($n=13$) who included a box-and-arrow diagram in their response to question 1 was almost 15 points higher than those students who did not. These differences also are not statistically significant based on a non-parametric Mann-Whitney U-test ($p = 0.35$, two-tailed); this lack of significance is attributable to the large variance in the data as well as the small data set. While we acknowledge that differences in text-only versus box-and-arrow scores could be the result of scorer bias (e.g., if box-and-arrows were simply given higher scores than text alone), an analysis of the lower half of the scores ($n = 35$) reveals scores of 36.7% ± 25.6% ($1\sigma$) and 70.9% ± 16.0% ($1\sigma$) for questions 1 and 2, respectively. These averages are significantly different from each other based on a non-parametric Mann-Whitney U-test ($p<0.001$, two-tailed). We interpret this to mean that the explicitly directed use of Cause-MaP can help those students who are most at risk for poor performance on process-related questions. Also, our evaluation of the responses suggests that students who did not use box-and-arrow diagrams were much less explicit. For example, two of the students who responded to question 1 with text-only answers stated:

> Student A: *"The main way for the water vapor to leave the atmosphere is through precipitation."*
>
> Student B: *"Condensation, water in its gaseous form converts to water in its liquid form as a result of a temperature decrease, & rises to atmosphere. Evaporation is already occurring (hence the water vapor) but cannot rise."*

These quotes illustrate the difficulties some students have in constructing a logical explanation when they provide short answer responses to open-ended questions. Student A omitted condensation of the water vapor, whereas Student B included condensation but omitted precipitation. If these students had formulated their explanations using Cause-MaP, they might have recognized the disconnect between the starting and ending points. Although these two examples demonstrate the inabilities of some students to provide complete explanations, we should point out that many students did provide a complete two-step process using text, alone. Finally, the inclusion of a box-and-arrow diagram can provide details that a student might omit from their written explanation. For example, one of the few students to provide both a short written answer and a box-and-arrow diagram stated only, *"Precipitation is the main way for water vapor to leave the atmosphere."* However, this

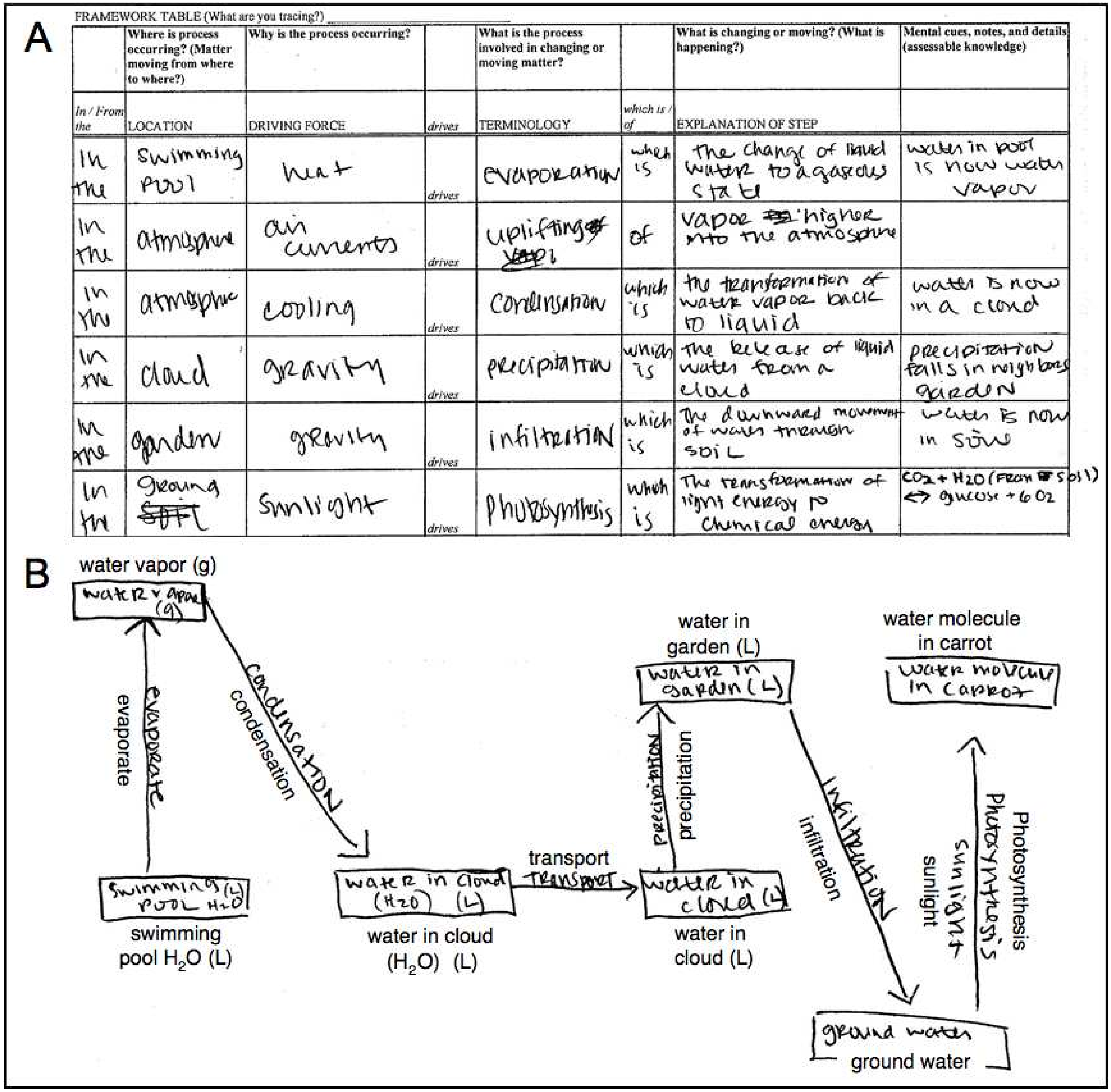


Looking at the following figure, please show how water from the swimming pool could end up in the neighbor's carrot. **Answer** using the principled reasoning table and a box-and-arrow diagram.

**FIGURE 2**. **An exam question used to evaluate student understanding of system dynamics as illustrated in their use of the Cause -MaP method.**

student included condensation in their box-and-arrow diagram, providing evidence for student understanding of the complete process that was not demonstrated in the text.

A typical, appropriate response from a student, including both the table of responses (Fig. 3A) and the box-and-arrow diagram (Fig. 3B) illustrates the facility with which students can visualize the movement and change of matter, even under complex conditions. The overall student performance on the more complicated question 2 was much higher than on the similar, simpler question where students did not generally apply Cause-MaP. In fact, scores on question 2 (83% ±17%, 1σ) are nearly identical to the scores achieved by the select students who applied a box-and-arrow approach to the first question (80% ± 27%, 1σ). We are encouraged by these preliminary data as suggestive of the efficacy of the Cause-MaP method for promoting student reasoning about Earth systems. Overall, results from these questions suggest that students who use Cause-MaP provide a clearer depiction



FRAMEWORK TABLE (What are you tracing?) ____________

| | Where is process occurring? (Matter moving from where to where?) | Why is the process occurring? | | What is the process involved in changing or moving matter? | | What is changing or moving? (What is happening?) | Mental cues, notes, and details (assessable knowledge) |
|---|---|---|---|---|---|---|---|
| *In / From the* | LOCATION | DRIVING FORCE | *drives* | TERMINOLOGY | *which is / of* | EXPLANATION OF STEP | |
| In the | swimming pool | heat | *drives* | evaporation | which is | the change of liquid water to a gaseous state | water in pool is now water vapor |
| In the | atmosphere | air currents | *drives* | uplifting ~~of~~ ~~vapo~~ | of | vapor ~~is~~ higher into the atmosphere | |
| In the | atmosphere | cooling | *drives* | condensation | which is | the transformation of water vapor back to liquid | water is now in a cloud |
| In the | cloud | gravity | *drives* | precipitation | which is | the release of liquid water from a cloud | precipitation falls in neighbors garden |
| In the | garden | gravity | *drives* | infiltration | which is | the downward movement of water through soil | water is now in soil |
| In the | ground ~~soil~~ | sunlight | *drives* | photosynthesis | which is | The transformation of light energy to chemical energy | $CO_2 + H_2O$ (from soil) ↔ glucose + $6O_2$ |

**FIGURE 3. Artifacts of a typical response to exam question in Fig. 2. A. Tabulated responses, including causes of processes. B. Box-and-arrow diagram illustrating movement of water through the environment.**

of

fundamental processes than students who do not. At the same time, it appears that students are not always able to recognize when a question requires explicit discussion of processes. In general, students seemed most likely to provide verbal, inexact responses unless explicitly told to apply Cause-MaP

## CONCLUSIONS

Cause-MaP provides an explicit and thorough method for students to reason about Earth systems. This tool encourages both student learning and faculty reflection on teaching. For students, this method encourages learning by repetition, meaningful learning of terminology, and the association of matter with processes their causes. In addition, because students are often familiar with these processes in a narrow setting, this approach encourages transfer of pre-existing knowledge across spheres. For faculty, Cause-MaP can provide a metric for prioritizing the wide array of material that might be taught in a specific course. Faculty can easily identify and exclude non-relevant concepts that may detract from the main objective of the lesson, while simultaneously recognizing key details that might otherwise be taught implicitly.

Overall, the data presented here suggest that the Cause-MaP method encourages students to clearly relate processes at work in a system. A more thorough, research-focused evaluation of Cause-MaP as an instructional intervention would provide much deeper insight into the ways in which this method does, and does not, encourage systems thinking across ESS spheres. Investigation of student thinking through use of semi-structured interviews and post-intervention surveys would provide concrete evidence of the effectiveness and limitations of the Cause-MaP method. Our initial results also suggest that a link may exist between learning styles and the effectiveness of Cause-MaP. In particular, we are intrigued by the fact that some students completed the table before the box-and-arrow diagram while others completed the box-and-arrow diagram first.

Although it is our expectation that students will extend Cause-MaP to novel systems, exposure to this method in only one course was not enough to encourage most students to apply the technique when not explicitly instructed to do so. In the future, we would like to explore how to teach students to apply the reasoning inherent to the Cause-MaP method to all Earth systems. The fundamental differences in problem-solving approaches taken by those students who applied Cause-MaP independently and those students who did not is an area worthy of investigation.

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## REFERENCES

Ben-Zvi-Assaraf, O., and Orion, N., 2005, A Study of Junior High Students’ Perceptions of the Water Cycle: Journal of Geoscience Education, v. 53, p. 366-373.

Bloome, D., Puro, P., and Theodorou, E., 1989, Procedural display and classroom lessons: Curriculum Inquiry, v. 19, p. 265-291.

Bodner, G.M., 1986, Constructivism: A theory of knowledge: Journal of Chemical Education, v. 63, p. 873-878.

Bransford, J.D., Brown, A.L., and Cocking, R.R., 2000, How people learn: Brain, mind, experience, and school: Washington, DC, National Academy Press, 374 p.

Croneis, C., and Krumbein, W.C., 1936, Down to Earth: An Introduction to Geology: Chicago, University of Chicago Press, 501 p.

diSessa, A.A., 1988, Knowledge in pieces, *in* Forman, G., and Pufall, P.B., eds., Constructivism in the Computer Age: Hillsdale, NJ, Lawrence Erlbaum Associates, p. 49-70.

diSessa, A.A., Gillespie, N.M., and Esterly, J.B., 2004, Coherence versus fragmentation in the development of the concept of force: Cognitive Science, v. 28, p. 843-900.

Herbert, B.E., 2006, Student understanding of complex earth systems, *in* Manduca, C.A., and Mogk, D.W., eds., Earth and Mind: How Geologists Think and Learn about the Earth, Volume Special paper 413: Boulder, CO, Geological Society of America, p. 95-104.

Hestenes, D., Wells, M., and Swackhamer, G., 1992, Force Concept Inventory: The Physics Teacher, v. 30, p. 141-158.

Johnson, S.D., and Aragon, S.A., 2003, An instructional strategy framework for online learning environments, *in* Aragon, S.A., ed., Facilitating Learning in Online Environments, New Directions for Adult and Continuing Education: San Francisco, Jossey-Bass, p. 31-44.

Libarkin, J.C., and Kurdziel, J.P., 2006, Ontology and the teaching of earth system science: Journal of Geoscience Education, v. 54, p. 408-413.

Mayer, V.J., 1991, Earth-systems science: The Science Teacher, v. 58, p. 34-39.

Mayer, V.J., 1995, Using the Earth system for integrating the science curriculum: Science Education, v. 79, p. 375-391.

McDermott, L.C., 1984, Research on conceptual understanding in mechanics: Physics Today, v. 37, p. 24-32.

Novak, J.D., and Cañas, A.J., 2006, The Theory Underlying Concept Maps and How to Construct Them, Florida Institute for Human and Machine Cognition, 33 p.

Novak, J.D., and Gowin, D.B., 1984, Learning How to Learn: Cambridge, Cambridge University Press, 199 p.

Orion, N., 2002, An Earth systems curriculum development model, *in* Mayer, V.J., ed., Global Science Literacy, Kluwer Academic Publisher, p. 159-168.

Raia, F., 2005, Students' understanding of complex dynamic systems: Journal of Geoscience Education, v. 53, p. 297-308.

Raia, F., 2008, Causality in complex dynamic systems: A challenge in Earth Systems Science education: Journal of Geoscience Education, v. 56, p. 81-94.

Rankey, E.C., and Ruzek, M., 2006, Symphony of the spheres: Perspectives on Earth system science education: Journal of Geoscience Education, v. 54, p. 197-201.

Redish, E.F., 2004, A theoretical framework for physics education research: Modeling student thinking, *in* Redish, E.F., and Vicentini, M., eds., Proceedings of the Enrico Fermi summer school, course CLVI: Bologna, Italy, Italian Physical Scoiety, p. 1-63.

Reiner, M., Slotta, J.D., Chi, M.T.H., and Resnick, L.B., 2000, Naive Physics Reasoning: A Commitment to Substance-Based Conceptions: Cognition and Instruction, v. 18, p. 1-34.

Safayeni, F., Derbentseva, N., and Cañas, A.J., 2005, A theoretical note on concepts and the need for cyclic concept maps: Journal of Research in Science Teaching, v. 42, p. 741-766.

Sell, K.S., Herbert, B.E., Stuessy, C.L., and Schielack, J., 2006, Supporting student conceptual model development of complex systems through the use of multiple representations and inquiry: Journal of Geoscience Education, v. 54, p. 396-407.

Senge, P.M., 1990, The Fifth Discipline: The Art and Practice of the Learning Oganization: New York, Doubleday, 424 p.

Shepardson, D.P., Wee, B., Priddy, M., Schellenberger, L., and Harbor, J., 2009, Water transformation and storage in the mountains and at the coast: Midwest students' disconnected conceptions of the hydrologic cycle: International Journal of Science Education, v. 31, p. 1447-1471.

Sibley, D.F., Anderson, C.W., Heidemann, M., Merrill, J.E., Parker, J.M., and Szymanski, D.W., 2007, Box diagrams to assess students’ systems thinking about the rock, water and carbon cycles: Journal of Geoscience Education, v. 55, p. 138-146.

Trumper, R., Raviolo, A., and Shnersch, A.M., 2000, A cross-cultural survey of conceptions of energy among elementary school teachers in training - empirical results from Israel and Argentina: Teaching and Teacher Education, v. 16, p. 697-714.

Wiggins, G., and McTighe, J., 2006, Understanding by Design: Upper Saddle River, NJ, Pearson Education, Inc., 370 p.

Wilson, C.D., Anderson, C.W., Heidemann, M., Merrill, J.E., Merritt, B.W., Richmond, G., Sibley, D.F., and Parker, J.M., 2006, Assessing students’ ability to trace matter in dynamic systems in cell biology: Cell Biology Education, v. 5, p. 323-331.

Wood, W.W., 1997, Fluxes: A new paradigm for geologic education: Ground Water, v. 35, p. 1.