# LEARNING A SECONDARY DISCOURSE: SHIFTS FROM FORCE-DYNAMIC TO MODEL-BASED REASONING IN UNDERSTANDING WATER IN SOCIO-ECOLOGICAL SYSTEMS

Changes in student thinking across a learning progression can be described as the process of learning a new Discourse. According to Gee (1991), a Discourse is defined as the ways of talking, thinking, and acting that link people to socially meaningful groups. Embedded within Discourses are the practices and knowledge from which people draw when engaging in the various roles they play in their lives. Work on developing a learning progression for understanding water in complex socio-ecological systems identifies and describes changes in student thinking as they learn the scientific knowledge and practices of the Discourse of environmentally literate citizens. These changes include shifts from using informal, force-dynamic reasoning characteristic of students' primary Discourses to using scientific model-based reasoning characteristic of the new, secondary Discourse. This paper describes the framework developed to identify changes in student knowledge and practices as they learn a new secondary Discourse and provides examples in the context of the learning progression on water in socio-ecological systems.

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Learning progressions are heralded as powerful tools that have the potential to connect research on student thinking to development of curriculum, curriculum materials, large-scale summative assessment, classroom-scale formative assessments, and classroom teaching (Smith, Wiser, Anderson, & Krajcik, 2006). As a new field of research, however, the conversation about what constitutes a learning progression and how it will achieve its promise is still taking place.

The term "learning progression" inspires a broad range of possible definitions. In a report on learning progressions to the Council of Chief State School Officers, Heritage (2008) defined learning progressions as descriptions of learning trajectories that are intended to provide teachers with a big picture view of how learning goals are linked across grade levels and a small scale tool that teachers can use to track student progress towards achieving learning goals.

In contrast, the often cited definition of learning progressions from the NRC Report *Taking Science to School* views learning progressions not as benchmark statements, but as descriptions of changes in students' thinking as they participate in and progress through school. "Learning progressions are descriptions of successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (National Research Council, 2007, p. 219).

This and similar definitions (e.g. National Research Council, 2005; Smith, et al., 2006) limit learning progressions to those descriptions of student thinking that are grounded in empirical data on students' reasoning rather than just logical ordering of ideas from the perspective of expert thinkers. Others see learning progressions as more dynamic. Alonzo & Steedle (2009) for example, note that because learning progressions are grounded in empirical data, they are hypotheses about student thinking that can be revised as understanding about student thinking changes.

Whether viewed as a descriptive or hypothetical framework, these definitions remain vague in terms of what progresses in student thinking, what time span learning progressions should cover, at what grain-size learning progressions should be described, and how learning progressions should be validated (Corcoran, Mosher, & Rogat, 2009). This paper provides a perspective on answers to these questions in the context of a project to define a learning progression for student understanding of water in environmental systems.

## The Environmental Literacy Project

The learning progression on water is part of the broader Environmental Literacy Project to research and develop learning progressions for environmental science literacy. This project focuses on envisioning and defining a curriculum framework for upper elementary through college grades that supports students in developing the knowledge and practices necessary to be informed and effective citizens. We define environmental science literacy as the capacity to understand and participate in evidence-based discussions of environmental systems and to make informed decisions about appropriate actions and policies (Anderson, 2009). In our framework, we view environmental systems as connected natural and human systems, which we refer to as socio-ecological systems.

Learning progressions are organized around big ideas in a discipline (Smith, et al., 2006). Big ideas offer explanatory power that link experiences with phenomena, laws, principles, theories, and models into a coherent structure. The Environmental Literacy Project is developing four learning progressions addressing the big ideas that are necessary for environmental science literacy. In addition to the water cycle learning progression (Covitt, Gunckel, & Anderson, 2009; Gunckel, Covitt, Dionise, Dudek, & Anderson, 2009), working groups in the Environmental Literacy Project are concurrently developing learning progressions for the big ideas of carbon cycling (Mohan, Chen, & Anderson, in press) and biodiversity (Zesaguli, et al., 2009). A fourth working group is exploring students' decision-making practices in citizenship roles (Covitt, Tan, Tsurusaki, & Anderson, 2009). The work on citizenship practices is relevant to all of the other strands of the project because it explores what progresses as students develop greater capacities to use the big ideas of water cycling, carbon cycling, and biodiversity to make informed and responsible decisions about socio-ecological issues.

The NRC (2007) *Taking Science to School* report and a report by the Center for Continuous Instructional Improvement (Corcoran, et al., 2009) both note the importance of grounding learning progressions in empirical studies on student learning. Both reports identify key characteristics of learning progressions including that learning progressions are anchored on one end by what students bring to learning and on the other end by the target learning goals. In between these lower and upper anchors are intermediate levels of achievement, identified by characteristics of student learning that change over time, called progress variables, and defined in terms of student learning performances on assessment tasks. The environmental literacy learning progressions all include these key characteristics.

In their review, Corcoran, Mosher, & Rogat (2009) describe learning progressions in terms of students' cognitive development. Example learning progressions included in the review often highlighted the common errors and misconceptions that students make at the various levels of achievement. Identifying these errors and misconceptions are important for helping teachers support students in re-organizing their ideas into the more complex understandings represented by higher levels. However, the learning progression frameworks developed by all strands of the Environmental Literacy Project encompass a wider sociocultural perspective on students' developing ideas. Instead of just asking, "What do students' learning performances suggest they do not understand?" we also ask, "Why do these students' responses make sense to the students who gave them?" We want to understand not just the cognitive aspects of students' learning, but also how their developing world views shape their learning. Our goal is to develop a framework that not only identifies and describes patterns in student thinking, but also explains and situates these patterns in the communities in which students participate. The next section describes the Discourses, Practices, Knowledge framework that we use to explain patterns of progress in student thinking. This framework is described using the water cycle learning progression as an example context, although the framework applies to all of the learning progressions in the Environmental Literacy Project.

## Discourses Practices Knowledge Framework

Our work conceptualizes learning as the process of mastering a new Discourse (Cobb & Hodge, 2002; Wenger, 1998). Discourses are the ways of talking, thinking, and acting that identify a socially meaningful group. Discourses are enacted in communities through the practices in which members of the community engage (Gee, 1991). Participating in the practices of a community, in turn, requires specific knowledge. Figure 1 shows the embedded relationship of knowledge in practices in Discourses. Tracking students' progress as they learn new Discourses requires tracing changes in student knowledge as students engage in new practices. In this section, we describe the Discourses Practices Knowledge framework for tracking changes in student thinking.

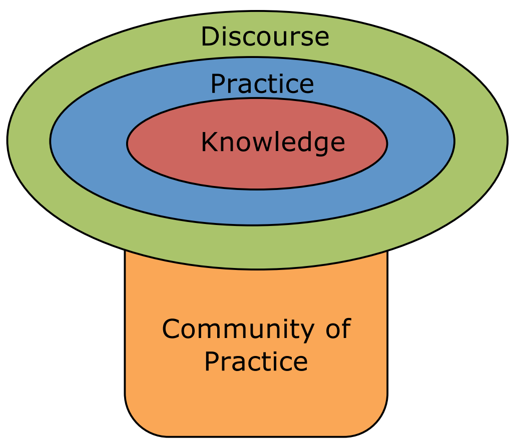


Figure 1: Relationship among Discourses, practices, knowledge, and communities.

### Discourses

Discourses provide the broad framework for how people interact together in groups. Discourses describe the ways language use defines the perspectives, values, and identities that link people together in social networks. In short, they provide the lenses through which people see and make sense of their world.

People participate in many different communities at any given time, and can thus draw on many Discourses as they move through their daily lives. Everyone starts life with a primary Discourse.

> All humans … get one form of discourse free, so to speak... This is our socioculturally determined way of using language in face-to-face communication with intimates… (Gee, 1991, p. 7)

As people expand their communities of participation, they learn new, or secondary Discourses.

> Beyond the primary discourse, however, there are other discourses which crucially involve institutions beyond the family…. Let us refer to these institutions as secondary institutions (such as schools, workplaces, stores, government offices, businesses, or churches)…. Thus we will refer to them as "secondary discourses." (Gee, 1991, p. 8)

In our framework, students' primary Discourses anchor the lower end of our learning progression. The process of learning involves mastering the ways of talking, thinking, and acting of secondary Discourses. The target secondary Discourse for the Environmental Literacy Project learning progressions is the Discourse of environmentally-literate citizens capable of reasoning scientifically about water in socio-ecological systems as they participate in the many roles of democratic citizenship(Covitt, Gunckel, et al., 2009; Covitt, Tan, et al., 2009; Mohan, et al., in press). With respect to the water cycle, environmentally literate citizens participate in the collective decision-making processes necessary to maintain and protect adequate fresh water quality and quantity for people and the natural ecosystems on which humans depend.

*Primary Discourse: Force-Dynamic Reasoning.* Students' primary Discourses provide insight into how students make sense of their world. Understanding students' primary Discourses is about more than just determining what students do and do not know about the world; it also involves understanding the frameworks that structure how students view the world and their experiences in the world.

Although there are many different primary Discourses rooted in diverse sociocultural communities, one common feature of many primary Discourses is a force-dynamic view of explaining the events of the world. Linguist Stephen (2007) and developmental psychologist Leonard Talmy (1988) argue that there is a "theory of the world" built into the basic grammar of many languages, including English. We must learn that theory in order to speak grammatical English, and this theory of the world, in turn shapes how we view and explain events.

> There is a theory of space and time embedded in the way we use words. There is a theory of matter and causality, too. … These conceptions… add up to a distinctively human model of reality, which differs in major ways from the objective understanding of reality eked out by our best science and logic. Though these ideas are woven into language, their roots are deeper than language itself. They lay out the ground rules for how we understand our surroundings. (Pinker, 2007, p. vii)

Talmy and Pinker label this theory of the world force-dynamic reasoning. Force-dynamic reasoning explains the events of the world in terms of actors who have certain abilities and who perform against the backdrop of landscape. Actors have purposes they try to fulfill and needs they must have met in order to fulfill those purposes. Characteristics of force dynamic reasoning include:

- *Actors and abilities*. The events of the world are largely caused by actors in accord with their abilities. Humans have the most abilities, followed by animals, then plants. Dead things have no abilities, so they decay away or are acted on by other actors. Non-living entities such machines can be actors with limited abilities. Depending on the situation, water can also be an actor, such as when a river carves a canyon.

- *Purposes and results.* Actors have goals or purposes, and the results of events are generally the fulfillment of the actors' purposes. Higher level actors can have many purposes, so animals grow, move, think, etc. Lower level actors have fewer purposes, so the main purpose of a tree is to grow. Water can also have purposes, or natural tendencies. One such purpose or tendency of water, for example, is to flow downhill.
- *Needs or enablers.* In order to use their abilities and fulfill their purposes, actors have needs. For example, a tree needs soil, water, air, and sunlight to grow. Conversely, actors can also have inhibitors or antagonists that prevent them from fulfilling their purpose. Thus, a concrete sidewalk inhibits water from soaking into the ground. Water can also be an enabler or an inhibitor for another actor, such a person who needs clean water to drink.
- *Events or actions.* The events of the world take place when actors have all of their needs met or all the conditions are present. For example, water can go from one lake to another lake if there is a river connecting them.
- *Settings or scenes* for the action. Finally, there are settings or scenes for the action, including air, earth, stones, etc. These settings provide the background landscape or the stage for the actors to act and events to happen. Water is often the background landscape against which other events happen.

*Secondary Discourse – Scientific Reasoning.* The secondary Discourse of environmentally-literate citizens that anchors the upper end of our learning progression includes a different type of reasoning from the force-dynamic reasoning of students' primary Discourses. The Discourse of environmentally-literate citizens relies on scientific reasoning, which views all phenomena as parts of connected and dynamic systems that operate at multiple scales and are governed by fundamental principles. Scientific reasoning relies on models that are grounded in observations (data) and applied in consistent ways to explain the events of the world (Anderson, 2003; National Research Council, 2007; Sharma & Anderson, 2003). For example, model-based reasoning about water in socio-ecological systems involves recognizing that water and other substances are parts of connected systems (e.g. watersheds, groundwater, municipal water systems, etc.), and that the movement of water and other substances through these systems is governed by natural laws and principles, such as the law of conservation of matter and the law of gravity.

Practices

Discourses are the overarching frameworks that guide how we make sense of the world. Discourses are enacted, however, through the practices of the communities in which people participate (Cobb & Hodge, 2002; Wenger, 1998). We define practice as a pattern in activity, an activity that is engaged in repeatedly. Discourses shape or mediate the activities in which members of a group participate (Cobb & Hodge, 2003; Wertsch, 1991).

We are interested in the practices that are essential for environmentally responsible citizenship. Figure 2 represents citizens' decisions and actions in public and private roles:

- Public roles: voter, advocate, volunteer, elected official
- Private roles: consumer, owner, worker, learner

We would like students to become informed citizens who are aware of the possible environmental consequences of their actions and take those consequences into account. Citizens' decisions and actions always can- and should- be based on considerations and values other than scientific knowledge and environmental consequences. Environmental science literacy is about giving people real choices – helping them to understand possible alternative actions and their consequences – rather than leaving them trapped by ignorance.

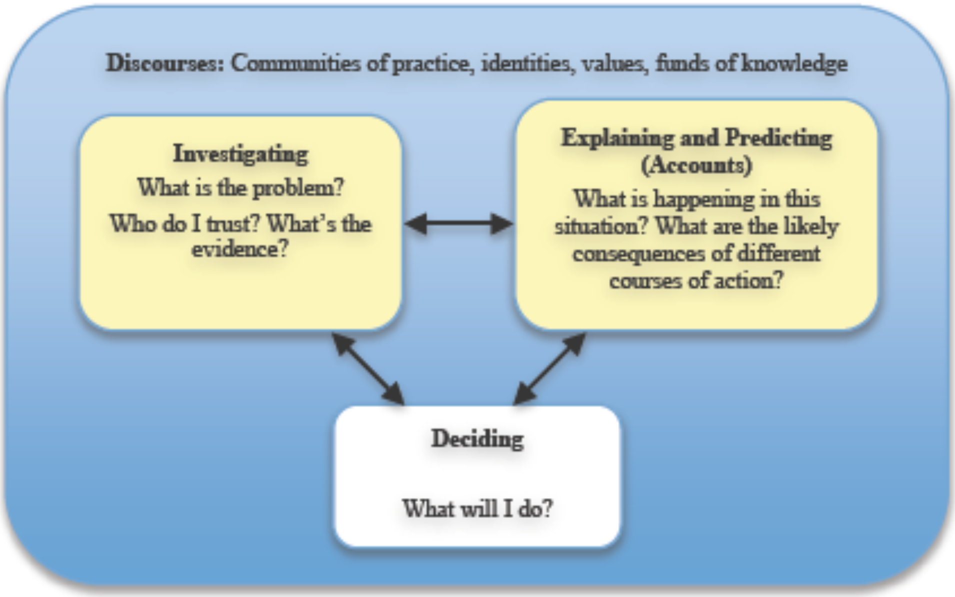


Figure 2: Citizenship practices (from Covitt, et al, 2009)

Figure 2 is our framework for citizenship practices. It suggests that the decisions we make in public and private citizens' roles involve four kinds of practices, two of which we have typically grouped together in our work:

1. *Inquiry (Investigating):* learning from experience, developing and evaluating arguments from evidence. Inquiry includes evaluating both sources of evidence and the evidence itself. Citizens must be able to learn about and understand the specifics of particular water quality and supply issues and situations. They must be able to identify and understand pertinent evidence and then analyze and evaluate the quality of evidence and arguments presented by multiple stakeholders.
2. *Accounts:* describing, explaining, and predicting outcomes of processes in socio-ecological systems.
    - *Explaining* processes in systems. Citizens must combine scientific and social-scientific models and theories (i.e., general knowledge) with specific facts of the case (i.e., local knowledge) to explain what is happening to water in the socio-ecological systems in which they live, and how these systems are affected by human actions.
    - *Predicting* effects of disturbances or human policies and actions on processes in systems. When making informed decisions, citizens must use their understanding of socio-ecological systems to make predictions about the potential consequences of possible courses of action on the local water system.

3. *Deciding*: making choices (conscious or unconscious) about personal lifestyles or courses of action in private roles, people or policies to support in public roles.

In the Environmental Literacy Project, the citizenship strand focuses on students' inquiry and deciding practices. The water cycle learning progression (as well as the carbon cycle and biodiversity learning progressions) focuses on the two accounting practices: explaining and predicting. In particular, we concentrate on changes in students' practices as they develop greater sophistication over time. They move from explaining and predicting practices that rely on force dynamic perspectives of the material world, toward explaining and predicting practices that rely on model-based reasoning about the material world.

Knowledge

Each of these practices requires that citizens understand and use knowledge. Such knowledge ranges from understanding general principles, such as conservation of matter, to specific knowledge of local situations. Figure 3, adapted from the Loop Diagram from the Long Term Ecological Research Network (Long Term Ecological Research Network Research Initiatives, 2007), shows the domain of general knowledge about water in socio-ecological systems necessary for environmentally-literate citizens to engage in the practices listed above. The boxes show the natural environmental systems and human social and economic systems that comprise a global, connected socio-ecological system. Within each box are the structures through which water and substances move, and the processes responsible for moving the water and altering the composition of the water. The arrows represent connections between the human social/economic systems and the natural environmental systems. Fundamental to our framework is the recognition that the systems in neither box exist in isolation. Human social and economic systems depend on natural systems for freshwater; the processes that take place within the human social and economic systems have significant impacts on the quality and distribution of water in environmental systems.

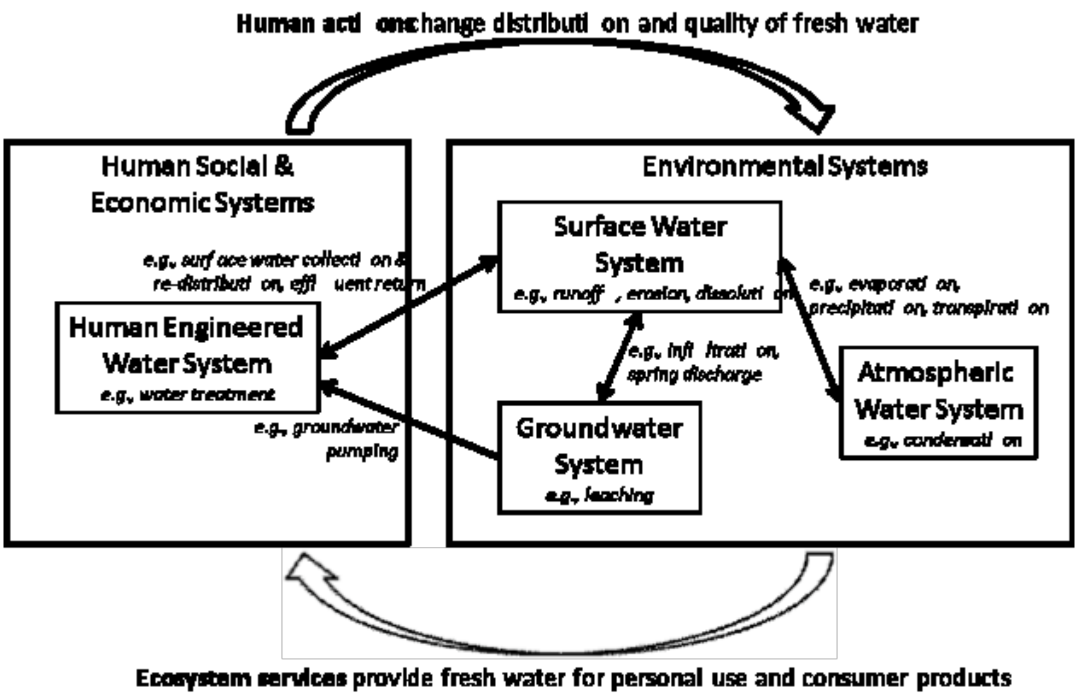


Figure 3: Loop diagram for water in socio-ecological systems.

## A Learning Progression for Water in Environmental Systems

This section provides an overview of the general framework for the learning progressions in the Environmental Literacy Project (Anderson, 2009) and an example of a learning progression in the context of water in socio-ecological systems.

### A General Framework for Learning Progressions

The Environmental Literacy Project learning progression frameworks have the same general structure, represented in Table 1. This framework identifies a unit of analysis: Learning performances. It organizes students' learning performances according to (a) Progress Variables, and (b) Levels of Achievement.

Table 1: General Learning Progression Framework

| *Levels of Achievement* | *Progress Variables* | | |
|---|---|---|---|
| | Systems & Scale | Movement of Water | Movement of Substances |
| 4: Qualitative model-based accounts | | | |
| 3: "School science" narratives | Learning performances for specific Progress Variables and Levels of Achievement | | |
| 2: Force-dynamic with hidden mechanisms | | | |
| 1: Force-dynamic narratives | | | |

*Progress Variables* are aspects of knowledge and practice that are present in some form at all Levels of Achievement, so that their development can be traced across Levels. Progress variables are derived partly from theories about how knowledge and practice are organized and partly from empirical research on assessment and student reasoning (Briggs, Alonzo, Schwab, & Wilson, 2004; Wilson, 2005; Draney & Wilson, 2007).

*Levels of Achievement* are patterns in learners' knowledge and practice that extend across progress variables (see Mohan, et al., in press). The four Levels of Achievement in our learning progressions describe performances we have seen in students from elementary through high school grades.

*Learning Performances* are the contents of the individual cells of Table 1: the specific practices characteristic of students who are at a particular Level of Achievement and reasoning about a particular Progress Variable. Learning performances also provide specific predictions about student reasoning and student learning that can be tested empirically. Thus, it is through Learning Performances that we can link the learning progressions framework to empirical data from assessments.

## Learning Progression for Water in Socio-ecological Systems

The development of the water cycle learning progression has involved four cycles of iterative design research (Barab & Squire, 2004; Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003). We began by identifying the target knowledge and practices necessary to understand and reason about water and other substances moving through complex socio-ecological systems. As our research progressed, this framework developed into a description of the target secondary Discourse.

Next, we designed short-answer assessments for $2^{nd}$-$12^{th}$ grade students to elicit their understandings about water in environmental systems. We also conducted extended interviews with a sample of students to better understand their ideas. We selected a sample of student responses for each question and ranked responses from least sophisticated to most sophisticated. We grouped the ranked student responses to identify similar features in the responses. This process allowed us to identify features in student responses that were changing from less to more sophisticated answers. From these features we were able to identify progress variables, levels of achievement, and indicators of levels of achievement for each progress variable in student learning performances. Progress variables and levels of achievement are described below.

In each iteration of development, we designed new assessment questions that tested our framework and probed new areas of student thinking. Each round of analysis resulted in refinement of the frameworks. Our progress variables and the descriptions of the levels of achievement are thus developed partly by theory and partly from the empirical evidence in student responses to assessments (Briggs, Alonzo, Schwab, & Wilson, 2004; Draney, 2007; National Research Council, 2005).

## Progress Variables

We have identified three progress variables that are present at every level of achievement and therefore can be used to trace the development of student thinking. The learning progression framework for water in socio-ecological focuses on accounting practices. Therefore, we describe the progress variables as elements of a complete account about water and substances in water moving through socio-ecological systems. Our assessment questions probe different aspects of these progress variables in different contexts. That is, not every assessment question elicits complete accounts. Some questions focus more on structures of systems (e.g. where groundwater is stored or types of water pollution) and other questions focus more on processes (e.g. evaporation of water from a puddle or distillation of salt water).

1. Systems & Scale – Focuses on whether or not students consider hidden or invisible parts of systems (e.g., groundwater) and the scale at which students describe and reason about water, substances in water, and structures of systems (from atomic-molecular scale through landscape scale).
2. Movement of Water – Focuses on how students identify and describe processes that move water through connected systems. Considers whether or not students recognize and apply constraints on processes such as conservation of matter, gravitational control of water flow, and permeability of materials.
3. Movement of Substances – Focuses on how students identify and describe processes that mix and move substances with water through connected systems. Considers students' conceptions of water quality and changes in water quality, including reasoning about how substances may be separated from water. Also focuses on whether or not students

recognize and apply constraints on processes, including conservation of matter, gravity, and permeability of materials.

Levels of Achievement

We have identified four levels of achievement in the water learning progression. These levels trace student accounts from a force-dynamic to a model-based view of the world. Our assessment questions probe different aspects of water in socio-ecological systems, such as water and substances moving across the land surface or water and substances moving underground. The Levels of Achievement have been developed based on student responses to approximately 20 questions addressing different aspects of the hydrologic system. The descriptions provided below use examples of student responses from a subset of these 20 questions.

Questions focusing on movement of water

1. Puddles Question: After it rains you notice puddles in the middle of the soccer field. After a few days you notice that the puddles are gone. Where did the water go?
2. Bathtub Question: Could the water (from the puddles) get in your bathtub?
3. Groundwater Question: Draw a picture of what you think it looks like underground where there is water.
4. Watershed Pollution Question: If a water pollutant is put into the river at town C, which towns (if any) would be affected by the pollution? Explain how the pollution would get to the towns you circled.

Questions focusing on substances in water

1. Water Pollution Question: What are examples of water pollution?
2. Salt Dissolving Question: What happens to salt when it dissolves in water?
3. Treatment Question: Describe the different treatments that are used to make sure water is safe.
4. Ocean Water Question: If you had to make ocean water drinkable, how would you go about doing it?
5. Salty Rain Question: If you live by an ocean, will your rain be salty? Why or why not?

*Level 1: Force-Dynamic Narratives.*

Level 1 students explain and predict using the language and theories of force-dynamic Discourse. They identify the key elements that determine the course of an event, including the setting, the actors and their abilities, purposes, and needs. They predict whether actors achieve their purposes. Actors can achieve their purposes if they have all the necessary enablers and if there are no antagonists or opposing actors. If there are antagonists, then the outcome depends on which actor has greater powers.

*Moving Water: Water in the Background Landscape.* Level 1 responses indicate that students consider water to be part of the background landscape. Water can disappear from the landscape, going someplace else where it is not available or useful anymore. Level 1 responses to the Puddles Question included, "I think the water went to the grund [sic]." For students at this level, water that is invisible is not connected to water in other locations. For example, a response to the Bathtub Question was, "No. It already disappeared into the air." When asked to draw water in places they cannot see, such as underground, Level 1 students imagine water in locations they can see and translate those images to places they cannot see. For example, they draw pictures of groundwater as water in underground pipes or tanks.

*Substances in Water: Macroscopic Accounts of Types of Water.* Level 1 students recognize water quality in terms of types of water or qualitative descriptors. For example, one student's examples of water pollution included, "Lake water, ocean water, sea water, well water, pond water." Another student wrote, "black merkey [sic] water." Level 1 students focus on macroscopic scale and on human actors as agents. Thus, one response to the Water Pollution Question focused on a human action rather than matter, "Some examples are throughing [sic] bottles and pop cans." When asked about materials in water that are not visible, Level 1 students tend to express that the materials have gone away. Answering the Salt Dissolving Question, one student wrote, "…the water overpowers the salt by making it disappear." Level 1 students think of changes in water quality as not possible, as something that changes water from one type to another, or as something that humans do without need for a process. For example, in response to the Ocean Water Question, one student wrote, "I would not be happy because I would have to drink uncleaned water." Another wrote, "Cleaning it and making sure it's clean."

*Level 2: Force-Dynamic with Hidden Mechanisms.* Level 2 students still explain and predict using force-dynamic reasoning, but students are now giving more attention to hidden mechanisms in their accounts. They recognize that events have causes and often describe simple mechanisms that they use to explain or predict events. Students at Level 2 are beginning to trace water and substances, recognizing that water and substances that are no longer visible go someplace else.

*Moving Water: Natural Tendencies with Conditions.* At level 2, students still think about water as part of the background landscape, but their conception of the size of the background landscape is larger. Level 2 students think about rivers as connected to other rivers and groundwater as layers of water underground. Level 2 students think about the movement of water as a natural tendency of water and they identify possible enablers and antagonists to movement. For example, Level 2 responses to the Bathtub Question included, "Yes. If it was a rainy day and if there were puddles saved from yesterday and you open the door it could go in to the bath tub then there would be puddles in the bathtub." And, "Yes. If you had a window in your bathroom like I do, if you happened to have it open it would condensate." These responses identify an action that a person must take to enable water to move from the puddle into the bathtub.

*Substances in Water: Objects and Unspecified Stuff in Water.* At Level 2, students recognize that water can mix with other materials. Water pollution is thought of as harmful things put in water, often by people. These may be objects (e.g., "garbage," "dead animals," "rotten food") or unspecified materials (e.g., "muck," "cemicals [sic]"). When materials are mixed with water and the materials are no longer visible (e.g., salt dissolving in water), Level 2 students, like Level 1 students, may explain that the materials have disappeared. However, Level 2 students begin to provide novice explanations for tracing matter. Example responses to the Salt Dissolving Question include explaining that the substances stay separated, "The salt will go to the bottom," or explaining that you will see a visible change, "The water changes color." Level 2 students also describe human actors as using simple, macroscopic scale mechanisms to mix or unmix water and other substances. For example, one student responded to the Treatment Question by writing that a filter, "Takes the rocks and mud/dirt out of it." Level 2 students have difficulty tracing substances with water through invisible system boundaries. For example, some Level 2 students answered the Salty Rain Question by suggesting that salty water evaporates and turns into salty rain. Another student suggested that salty water does not turn into salty rain because the water is "filtered by the sky."

*Level 3: "School Science Narratives"*

Level 3 accounts can be characterized as the re-telling of stories about water that are learned in school. This level represents the beginning of model-based reasoning, because students are recognizing that water and substances in water are parts of connected systems and they can tell stories that use processes to move water and substances through systems. However, there are gaps in students' reasoning that suggests that students' stories are not connected into complete models that they use to explain and predict. Level 3 students do not consistently use principles to constrain processes. While they recognize that water and substances can exist at atomic-molecular scales, Level 3 students still provide accounts at the macroscopic-visible scale.

*Moving Water: Partially Connected Systems.* At Level 3, students trace water through multiple pathways in connected systems. However, the nature of the connections among systems is not always clear to students. For example, Level 3 responses to the Puddles Question included, "Yes. Water could seep down into the ground and slowly reach its way to your pipes, and it would leak in, and could be part of the water in your bathtub" and, "I think yes because of the fact where else would we get our water from? I know this because after it goes back into the water system it gets cleaned and then it goes to our wells and gets used in our bathtubs." The first student described water as leaking into underground pipes and the second left out essential steps in moving water from puddles into the engineered water system.

*Substances in Water: Substances Mixed with Water.* Students at Level 3 understand water quality in terms of identified substances mixed with water, and sometimes use common chemical names (e.g., identifying "chlorine" as a possible water treatment). They also conserve matter through changes in water quality, including invisible changes such as salt dissolving in water. Students' accounts demonstrate awareness of smaller than visible scales (e.g., they use the word "molecule"), but they do not describe structures and processes at the atomic-molecular scale. For example, one student answered the Salt Dissolving Question by writing, "The salt molecules spread out in the water." At this level, students' accounts trace water and substances across invisible boundaries, generally using macroscopic scale descriptions. For example, one student answered the Salty Rain Question, "No, because when water evaporates it only evaporated as water and leaves the salt behind."

*Level 4: Qualitative Model-Based Reasoning*

Level 4 students use scientific model-based accounts to explain and predict. Their explanations connect observations to patterns and models and use appropriate models and principles. Their predictions use data about particular situations along with principles to determine the movements of water and substances in water. Students who use scientific model-based thinking can trace water and substances in water along multiple pathways through connected systems and describe these pathways and movements at multiple scales (Gunckel, et al., 2009).

*Moving Water: Connected Systems at Multiple Scales.* At Level 4, students use scientific model-based thinking to qualitatively trace water through connected natural and engineered systems along multiple pathways and at multiple scales. For example, a Level 4 response to the

Puddles Question included, “Into the ground and into the air. The moleculs [sic] are soaked into the ground like a sponge. Then in evaporation the molecules are heated and forced to move more, and eventually become gas.” This response traces water through multiple connections and describes the process at the atomic-molecular scale.

*Substances in Water: Identified Substances Mixed with Water at Multiple Scales.* Students at Level 4 consistently provide chemical identities for substances and consider relative amounts of substances to reason about water quality. Furthermore, identified chemical substances are connected to an understanding of structure at atomic-molecular scale. For example, one student answered the Salt Dissolving Question by writing, “When salt is dissolved into water the salt breaks up into its ions of $NA^+$ and $CL^-$.” In the assessment data, there were some responses that reached Level 4 with respect to simple substances (e.g., salt). However, there were very few responses reaching Level 4 with respect to more complex substances (e.g., sewage). In addition, few students provided Level 4 accounts by tracing substances mixed with water across system boundaries (especially invisible boundaries) with atomic-molecular scale descriptions.

## Discussion

In this section we return to the defining questions for learning progressions.

### What Progresses?

Growth along a learning progression represents movement towards mastering a secondary Discourse. Students come to school relying on the practices and associated knowledge embedded in their primary Discourse(s). Students’ primary Discourse(s) shapes the way they view the world and the communities to which they have access. A central purpose of school is to support students in mastering secondary Discourses. Secondary Discourses provide new ways of looking at the world and provide new frameworks for participating in the practices of new or different communities. When looking at how students account for events, changes in Discourse are evident in the changes in the practices and knowledge students use while accounting for various phenomena.

In our research, we have seen that all students’ primary Discourses include elements of force-dynamic reasoning. Students’ initial accounts of water in environmental systems identify water as part of the background landscape, the setting for which other events happen. Students recognize water in streams, rivers, lakes, oceans, clouds, and rain, but do not connect the water in those locations to water in other places. They identify different types of water as discrete substances (e.g. dirty water and clean water). Students will also identify water as an actor with natural tendencies, such as running downhill or soaking into the ground. They often see water as useful for fulfilling the needs of other actors (e.g. people who need water to drink). Additionally, students invoke actors or agents who do things to water to change water, such as a machine that can turn dirty water into clean water.

As student learning progresses, students begin to develop model-based accounts of water in socio-ecological systems. Students begin to recognize that water is part of a connected system. They begin to recognize that water exists in invisible forms (e.g. water vapor) and in hidden places (e.g. underground). Students recognize that water quality is determined by the materials in suspension and solution in the water, and that specific process can add and remove substances to and from water according to certain scientific principles. Students begin to recognize that water does not disappear and reappear at random, but that all water and substances in water must be accounted for in all parts of a system. As students move from the lower end to the upper end of the learning progression, their responses to questions about water in environmental systems shows a shift from relying on the force-dynamic ways of looking at the world that are inherent in their primary Discourses to using a more principled, scientific, and model-based Discourse to trace matter through connected systems.

Recognizing that what is shifting is students' use of knowledge and practices embedded in different Discourses can help researchers, policy makers, curriculum and assessment developers, and teachers situate student learning in the larger, sociocultural context. Identifying student misconceptions and errors in thinking is important for identifying problems with student thinking. However, framing progress as a shift in Discourse casts errors and misconceptions not as problems located in individual students, but as indicators of the sociocultural contexts that are shaping student thinking. Such framing could help educators more carefully match instruction to students' needs and resources (Banks, et al., 2005; Gay, 2001; Ladson-Billings, 1995).

Usefulness of Levels

Learning progressions describe student progress in terms of levels. The word "level" is useful for marking significant shifts in students' views of the world as they account for their experiences. The notion of levels is also useful for indicating that students' accounts of the world become more sophisticated as they move along the learning progression. Students at Level 2 are limited to describing visible water at the macroscopic scale, whereas students at Level 4 can explain how water moves along various pathways in connected systems at multiple scales. Finally, the notion of levels is helpful in recognizing that there are ideas or concepts that are foundational for developing more sophisticated understandings. For example, in order to understand how groundwater moves through aquifers, students must be able to conceptualize that water exists in places they cannot see.

However, the notion of levels can also be problematic. Two problems are noted here. First, the word "levels" sometimes conjures up out-dated notions of rigid, Piagetian-type stages of development. Contrary to the notion of stages, levels in learning progressions are situated in and dependent upon instructional practices (National Research Council, 2007; Smith, et al., 2006). How students move through the levels, and in fact the form of the various intermediate levels between the lower and upper anchors of the learning progression, are shaped by the instruction in which students participate. Our eventual goal in developing the water learning progression is to develop instructional approaches that support students in moving up the levels of progression. Enactment of these instructional approaches will likely provide new pathways for students to reach higher levels of achievement than they currently do.

Second, the word "levels" suggests that as students move up the levels of achievement, they leave behind lower levels of thinking. However, the Discourse Practices Knowledge framework for learning progressions shows that as students develop the model-based reasoning of the secondary scientific Discourse, force-dynamic thinking does not disappear. Students at lower levels of achievement have only their primary Discourse to frame the way they view the world and participate in communities. As students gain mastery over secondary Discourses, they have more tools to use to account for their experiences and make sense of the world (Figure 4). The practices they engage in depend on the Discourse that shapes the community in which they are participating. Thus, students may be capable of providing a model-based account of water in environmental systems, but if they are not participating in a community where model-based accounts are a practice associated with that community, students may provide a more force-dynamic account of the system in question. In fact, force-dynamic accounts can often be sufficient for explaining phenomena. It is not always necessary to explain evaporation in terms of molecules and energy if one just needs to communicate that the puddle in the field is no longer there and the team can now play soccer (e.g., “The field dried up; let’s go play”). Stating that the puddle is gone is all that is necessary. However, if one is participating in a community that is trying to figure out why the soccer field is always soggy (i.e. it was built in a place where the water table is close to the surface) one needs to use a model-based account of a scientific secondary Discourse.

In reaching higher levels of achievement, students develop the tools that are necessary to participate in various communities, and the goal of school science should be to provide students with access to those communities that are vital for sustaining life and societies. Students who do not achieve higher levels do not have access to communities that rely on model-based reasoning, and are excluded from participating. Our evidence suggests that many students do not develop the higher levels of achievement that are necessary for participating in communities where scientific model-based reasoning is part of the Discourse.

From this perspective, “levels” are not individual steps in a staircase that one travels up in a one-way direction. Students can return to and participate in the Discourses of their home communities. The lower steps are more like foundational layers that support the higher steps and traveling up the steps provides access for participation in new and multiple communities.

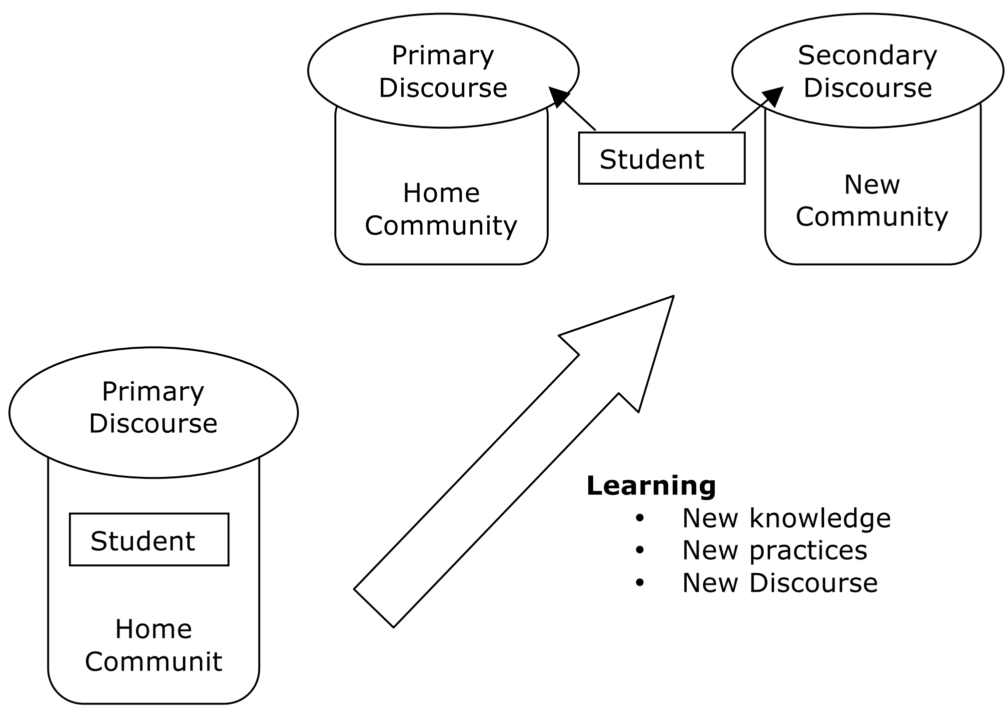


Figure 4: Learning as mastering a secondary Discourse and gaining access to a new community.

### Grain-Size

Learning progressions must be able to function at multiple grain sizes. Heritage (2008) notes that learning progressions should provide both the large-scale vision of how learning goals are connected and the small scale specificity to help guide instruction. Corcoran, Mosher, & Rogat (2009) suggest that learning progressions can be nested within each other, with learning progressions that describe student progress across a few weeks for a single unit of instruction nested within learning progressions that connect progress in related ideas across longer time spans.

Our work suggests that learning a secondary Discourse is not a rapid process, at least in the context of developing understanding of complex socio-ecological systems. The changes in Discourse noted in this learning progression occur across grades 2-12. However, claims about large grain-size changes in Discourse are grounded in small grain-size analyses of individual student performances. Because we are proposing that progress is not just about acquiring new knowledge, but rather about learning a new Discourse, we aim to create a consistent and coherent learning progressions framework through which student learning can be examined at multiple grain sizes, from small grain-size indicators in student performances to large grain-size descriptions of levels of achievement. Learning progressions that focus on changes across shorter time periods, on the scale of weeks or months, may miss the broader shifts in knowledge and practice that indicate that students are mastering new Discourses.

### Evaluation of Learning Progressions

The development and validation of learning progressions are iterative processes. We develop initial frameworks that reflect what we know from previous research and our experience, as well as our attempts to make the framework conceptually coherent. We use these frameworks to develop assessments and/or teaching experiments. We use the results of this empirical validation process to revise the frameworks. Then we start the process over again. With each new iteration we make progress toward meeting *standards for validation:* our list of qualities that learning progressions should have.

We seek to develop learning progressions that have three qualities:

- *Conceptual coherence:* a learning progression should "make sense," in that it tells a comprehensible and reasonable story of how initially naïve students can develop mastery in a domain.
- *Compatibility with current research:* a learning progression should build on findings or frameworks of the best current research about student learning. This research rarely provides precise guidance about what Learning Performances are appropriate for students at a particular grade level, but it does provide both domain-specific (i.e., focusing on specific subject matter) and domain-general (i.e., focusing on more general aspects of learning and reasoning) constraints on learning progressions.
- *Empirical validation:* The assertions we make about student learning should be grounded in empirical data from real students.

These criteria are applied to the key elements of the structure of learning progressions—Learning Performances, Levels of Achievement, and Progress Variables—in Table 2.

Table 2: Criteria for Validity of Learning Progressions (from Anderson, 2009)

| *Characteristic of Learning Progressions* | *Conceptual Coherence* | *Compatibility with Current Research* | *Empirical Validation* |
|---|---|---|---|
| *Individual cells: Learning performances* | • Learning performances are described in consistent ways, including (a) knowledge, (b) practice, and (c) context—real-world systems and phenomena. | • Learning performances are compatible with those described in the research literature. | • Learning performances describe actual observed performances by real students.<br>• Students are consistent across different questions or modes of assessment (e.g., written assessments and clinical interviews) that assess the same learning performance |
| *Rows: Levels of Achievement* | • Levels are conceptually coherent: Different Learning Performances reflect some underlying consistency in reasoning or outlook | • Levels reflect consideration (explicit or implicit) of strands of scientific literacy (see above). | • Levels have predictive power: Students should show similar Levels of Achievement for Learning Performances associated with different Progress Variable. |
| *Columns: Practices, principles, and processes* | • Definition of Progress Variable captures important aspects of Learning Performances at all Levels of Achievement | • Progress from one Level to the next is consistent with research on students' learning. | • Progress from one Level to the next can be achieved through teaching strategies that directly address the differences between Learning Performances |

## Conclusion

Many researchers are skeptical about learning progressions. They are skeptical about the nature of the claims about both the learning that is represented and the usefulness of learning progressions to policy makers, curriculum and assessment developers, and teachers. Many educators view learning progressions as offering nothing new to the myriad of curriculum documents and assessments already choking science education. To address these concerns we need to continue to seek clarity in defining what progresses along a learning progression, what levels of achievement and progress variables are, how learning progressions are validated, and what pathways or learning trajectories students take through the levels.

Defining and developing learning progressions are integrally connected. Each round of development and analysis leads to further clarity on the parameters of the project, the frameworks, and the methods for validating learning progressions. There are many additional important definitional issues to be addressed. For example, learning progression documents claim students can take multiple pathways through learning progressions (National Research Council, 2007). What do those trajectories look like and how do they help us understand what learning progressions are? The role of instruction in learning progressions is a key issue, and is related to the pathways that students take through learning progressions. Another issue is about how learning progressions can support classroom practice. How do teachers learn about and use learning progressions to understand their own students' thinking and to inform their instruction? Finally, this paper explored the way students' access to Discourses that are at play in their communities of practice influence how they see the world. Are there other aspects of students' primary Discourses that influence the pathway that they take through a learning progression? Are there other cultural influences that should be accounted for in describing how students' ideas change? As the field of learning progressions research moves forward, these are the types of defining questions that must be addressed if learning progressions are to fulfill their promise as powerful frameworks for policy, research, and teaching.

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