Using Virtual Worlds and Augmented Reality to Teach Causality Across Time and Distance in Ecosystems

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ABSTRACT

Reasoning about ecosystems includes consideration of causality over time and across spatial distances. This study examined the learning of fifth and sixth graders (n = 39) using the affordances of a virtual world called EcoMUVE and Mobile Broadband Device (MBDs) components designed to support learning and transfer of these causal features in ecosystems dynamics. Two conditions were contrasted; intermingling the MBD experience with the EcoMUVE program and using the MBD components following EcoMUVE. Findings suggest shifts towards greater recognition of the importance of change over time and distant drivers of change in ecosystem dynamics. Case study narratives developed from log-file data, video, and mappings of students movements within EcoMUVE illuminate changes in what students explored as their understanding developed. These narratives reveal more focused, hypothesis-driven exploration over time. Students who experienced the entire EcoMUVE experience prior to their MBD experience at the pond appear to have brought learning of terms and concepts to their pond explorations.

INTRODUCTION

Reasoning about ecosystems dynamics includes consideration of causality over time and across spatial distances. Research shows that students often frame systems concepts in reductive forms (Jacobson, 2001) that fall to capture complex dynamics (Grotzer & Basca, 2003; Hmelo-Silver & Pfeffer, 2004; Penner, 2000; Raia, 2008). How to help students learn to reason in more expert ways given the limitations of what is possible in the classroom has prompted researchers to explore how technology can create new instructional possibilities. For instance, researchers have developed virtual worlds (Dede, 2009), handheld devices (e.g. Klopfer & Yoon, 2005), and representational tools using hypermedia (e.g. Liu, Hmelo-Silver, & Marathe, 2007) to model complex dynamics. Such programs show promise in helping students learn ecosystems and complex systems concepts (e.g. Danish, Peppler, Phelps, & Washington, 2011; Grotzer, et al, 2013; Hmelo-Silver, Marathe & Liu, 2007; Metcalf et al, 2011).

Learning about underlying causal structure from experiences in virtual worlds that closely simulate the real world, is not without challenges. Learners may get caught up in surface features and dramatic or seductive details; the rich texture of these experiences can make discerning the underlying causal structure more difficult (e.g. Harp & Mayer, 1998; Ratterman & Gentner, 1998). Goldstone and Sakamoto (2003) found that real world similarity in technology simulations may advantage lower-achieving students in initial learning at the same time that it disadvantaged them for transfer of the concepts. As elaborated below, building affordances into simulated and real world learning experiences that abstract the causal patterns within a rich context may help all students achieve deep learning of the causal dynamics within that system, as well as transfer the learning to systems more broadly.

THEORETICAL FRAMEWORK

This study has its theoretical basis in the research on causal induction, which argues that humans discern causal patterns through a combination of noticing co-variation between causes and effects (Gopnik & Glymour, 2002; Gopnik & Schulz, 2007); relying upon knowledge of mechanisms (Atran, 1995; Keil,

1994), and considering trustworthy testimony (e.g. Harris, 2002). In learning to reason across time and distance, each of these modes of causal induction introduces different challenges that interact with the information available. For instance, noticing co-variation is challenging when causes and effects are separated by time and space. Mechanism knowledge and information from trusted sources can help in constructing the causal story. Helping students learn that causes can act across time and distance and to recognize such instances are important goals for instruction. Creating immersive representations and supports for these modes of induction to make these concepts more salient in the virtual world is a strategy employed in our research.

MUVES and MBDs May Work in Complementary Ways to Facilitate Deep Learning and Transfer of Causal Concepts. Multi-user virtual environments (MUVEs) are 3-D graphical worlds that enable simulated immersive experiences where users move through the world interacting with digital objects and tools and with computer-based agents. EcoMUVE is a virtual world (Metcalf et al., 2011) that harnesses the affordances of technology to accomplish ecosystem understanding goals that are otherwise difficult to achieve. It invites learners to realize how causes can act across time and distance by enabling them: 1) to view outcomes and then travel back in time to see how change occurred over time and; 2) to move across distances to realize co-variation relationships that otherwise would not be apparent. Mobile Broadband Devices (MBDs) can enable instructional experiences that take advantage of augmented and virtual reality in the context of the real world. Virtual characters from the past can be "transported" into the real environment providing information about change over time and learners can be offered tools enabling them to "see" beyond the confines of their location. MBDs enable learners to work on problems in authentic settings, thus potentially facilitating transfer (Dede, 2009). The MUVE and MBD interfaces are complementary, as each provides affordances that the other does not. These complementary affordances can be leveraged to help students learn to reason in more expert ways about the complex causal patterns in ecosystems—here specifically focused on causality across temporal and spatial gaps.

The research reported here investigated the impact of combining students' experience in a virtual world with affordances offered by augmented and virtual reality of handheld mobile devices in a real world environment that closely approximates that of the virtual environment. Given the exploratory nature of the research, the study was conducted as a case study contrasting the experience of two groups of students; one group who experienced the real world experience augmented by components on the mobile device (EcoMOBILE) intermingled with their experience in the virtual world (EcoMUVE) and the other who experienced the interventions sequentially. Rich data was collected in an effort to address the following research questions:

RESEARCH QUESTIONS

1. What does the evidence suggest about students' learning about changes over time and distance across and within the groups given the combined intervention of EcoMUVE and the EcoMOBILE (MBD) components?
2. What does the evidence suggest about whether students within each group transferred concepts between the EcoMUVE and the EcoMOBILE (MBD) components and vice versa?

METHODS

Design: A comparison case study was conducted contrasting two combined $5^{th}/6^{th}$ grade classes of approximately 20 students in each class (n = 39) from a school in Cambridge, MA. The students are middle to upper middle class with some ethnic diversity. The school was chosen for its location adjacent the pond that EcoMUVE was modeled upon. The students regularly visit the pond and most have taken three or more trips a year to the pond since Kindergarten. Two classes of the same science teacher participated in the following design: Students took pre-assessments about the importance of actions

related to investigating causality over time and distance to understanding an ecological issue. Then each class participated in a two-week exploration of EcoMUVE (Metcalf et al, 2011) with the following difference. In one class, after three days of exploration when the students discovered a fish-die off in the virtual world, they were then given an opportunity to visit the pond across from the school using MBDs with a program designed to support learning about causality across distance and time (EcoMOBILE). The other class completed its exploration of EcoMUVE and was then given an opportunity to visit the pond using the MBDs and program. This enabled comparison between the classes in how students approached the solution of EcoMUVE and whether the MBD experience may have impacted the approach of the first class to the virtual world and whether the completion of the learning in EcoMUVE may have impacted how the second class reasoned in the MBD augmented pond trip. When each class discovered the fish die-off, prior to investigating what happened, they took an assessment about what they thought happened to the fish. Rich data was collected to develop case studies for each group. Both classes finished with the post-assessments.

Intervention Components: The EcoMUVE Pond Module includes a virtual world representing a pond and its local and distal surroundings (See Figure 1.), including an adjacent golf course and more distant housing development. A calendar tool enables students to visit the pond on different days. They explore the environment, find organisms, talk to other characters, and collect data on the water, weather, and different populations. An eutrophication scenario is simulated in which a fish die-off occurs due to the proximal cause of low dissolved oxygen concentrations in the pond during a warm and windless night and the ultimate cause of eutrophication driven by excessive fertilizer runoff followed by algae growth and decomposition. To fully understand the fish die-off, students must attend to distant drivers of change, for instance, fertilizer that was applied in the watershed and made its way into the pond. Students collect data that is graphically represented over time enabling them to reason about the longer term patterns in the ecosystem.

Fig. 1: Screenshot of EcoMUVE Pond Module

The EcoMUVE pond module was used as follows. On the first day, the students were told that they would be visiting a pond in a simulated world and that they should explore it and see what they could learn about the pond. Students traveled around the world exploring the pond itself and its edges. They captured observations that they made in paper-based science notebooks. As they started to notice animals in the world, they were shown the camera tool which captures images in a virtual field guide and gives information about each organism (plants and animals, micro- and macro-organisms). On the second day, students were introduced to the submarine tool if they had not already discovered it and they began to add micro-organisms to their field guides. They were also introduced to a set of water quality measurement tools that offered information about phosphates, nitrates, dissolved oxygen, as well as a population tool that enabled them to collect information on the population levels of organisms in the pond. On the third day, they were introduced to the time traveling tool if they had not already discovered it. This enabled them to explore the virtual world over a number of calendar days in the summer and to start to collect data over time. At this point, a number of students discovered the fish die-off and were quite startled by it.

Students asked what happened to the fish and were inspired to explain the fish die-off as an event (Grotzer, Kamarainen, Tutwiler, Metcalf & Dede, 2013). At this point, the students took an assessment about what they thought was going on and one of the classes did the EcoMOBILE experience. The placement of EcoMOBILE after the fish die-off was to enable the researchers to qualitatively assess whether this class treated their further exploration in EcoMUVE differently than the class who did not have the EcoMOBILE experience infused at this point. The classes then continued with EcoMUVE. They collected data, filled out the data charts and studied the resulting graphs to help them think about change over time. Mapping between their observations in the simulated world and their data representations, they noticed patterns and relationships and documented how their thinking was changing in their science notebooks. While students could perceive patterns in the data, they did not understand what these patterns necessarily meant. In order to help them to test their various hypotheses, they were introduced to the learning quests. The Learning Quests are a series of brief on-line mini-modules designed to help students understand concepts related to photosynthesis, decay, phosphates, nitrates, the role of dissolved oxygen in the pond and other variables. Over the next week, students generated hypotheses about what might have been going on in the pond to result in the die-off of so many fish. They were asked to check their hypotheses against the available data, both observational and numerical, and to push beyond their first explanations to come up with the most compelling explanations based upon the evidence and the patterns in the data. They were asked to consider disconfirming evidence in addition to confirming evidence. Following the conclusion of EcoMUVE, the students in the second class participated in the EcoMOBILE experience. This offered the opportunity to compare how they approached their initial observations and the EcoMOBILE affordances in comparison to the first class.

EcoMUVE is a virtual simulation based on the ecology of Black's Nook in Cambridge, MA. Black's Nook sits beside Fresh Pond Reservoir which is the water source for the City of Cambridge. Presently, water from Black's Nook does not flow into Fresh Pond Reservoir, having been separated by dam in the 1930s. However, Black's Nook and Fresh Pond share water sources and so Black's Nook offers an accessible area of study and is not restricted in access as is Fresh Pond. The students at the school were regular visitors to Black's Nook and felt that they understood the pond well. Many had been at the school since preschool and took approximately three trips a year to the pond which is a five minute walk from their school.

The MBD or EcoMOBILE experience was designed to impact the kinds of observations students made about the pond and the kinds of questions they asked. Specifically, it sought to encourage them to embed their observations of the pond in a longer time frame to help them understand change over time and to realize that the pond is a part of a much larger watershed that includes a reservoir in the western suburbs known as the upper water shed or Hobbes Brook reservoir. The experience began by inviting students to make and record their open-ended observations of the pond and surroundings. These observations were unsupported by MBD affordances and enabled comparisons between the kinds of observations made by students who completed EcoMUVE first as opposed to having it intermingled. It then invited them to visit a number of hot-spots that enacted "Virtual Binoculars" that gave them the virtual ability to see twelve miles away to the water-monitoring stations at the upper reservoir and to gain information about what the water quality reports for the last few years indicated about the water flowing from that watershed. (See Appendix A.) The choice to focus on water flow as a mechanism was intentional. Previous research suggests that action at a distance is more easily understood when the mechanism is obvious than non-obvious (Grotzer & Solis, forthcoming). Water flow is an obvious mechanism and enables one to visualize how substances might be transported from one area to another.

The EcoMOBILE experience also invited students to virtually "Time Transport" a person from the past into the present to talk with them about changes at the pond over time. This person, who appears in period garb, told them of the attempts to fill in Black's Nook over time and the debris that was used to fill the pond to try to get rid of it along with many other nooks that existed in the 1930s. The text for the time

traveler can be found in Appendix A. This information is incongruous with what the students know about the pond. Presently, it looks like a nature preserve and is treated with great respect. A second virtual visitor from the current time period shared information about the time period following that of the visitor from the 1930s and speaks of the conservation efforts that brought the pond to its current state. In order to assess whether this information changes the ways that students think about the pond and its surroundings, the EcoMOBILE device then asks them to list questions that they have about the pond and what they now notice about it.

Data Sources: Rich data was collected including video and audiotape of student pairs; science journal notes; student interviews; teacher reflections; field observations; on-line data that students collected and log file data revealing how they moved through the virtual world. Students participated in two formal assessments from related work: 1) *The Action at a Distance and Change Over Time (ADCT) Assessment*- Students took an existing assessment designed to assess complex causal understanding developed in connection with the Causal Learning in the Classroom Project (CLIC). The assessment included four parts and a total of 22 questions. Eighteen questions use a four level Likert Scale to assess how important students consider the gathering of certain types of information to the possible solution of an ecological puzzle. Two questions involve the open-ended generation of hypotheses. A set of multiple choice questions juxtapose correct responses framed in local versus action at a distance framing to assess for the possibility that students reveal a preference for one type of explanation over the other regardless of their knowledge. (See Appendix A.) 2) *A Fish Die-Off Assessment* that asked for open-ended responses about what might have happened to the fish. It focused specifically on the causal structures of students' hypotheses about what happened in response to the fish die-off and was a slightly modified version of an assessment reported upon and used in earlier research (Grotzer et al., 2013). It offered three blank spaces for the students to provide open-ended responses about what might have happened. It also included a set of four questions on a Likert Scale to determine what investigations students believed were most important to undertake to figure out what happened and an additional space to explain any of their answers that they believed needed clarification.

Analysis: Data collection was completed in May 2013. Student responses on the Fish Die-Off Assessment were coded by two independent coders using a scheme developed in earlier work attaining reliability of .89 (Very Good) using Cohen's Kappa. Two coders who were not familiar with the differences between the two groups did a grounded analysis of the data; coding for emergent categories in each pair of students. Narratives of the experiences of four student teams (n= 8) were developed using the video, audio, log file data, and students' written notes. This includes mappings of students' movements within the EcoMUVE world and how they changed over time as students learned more about the environmental scenario. A third person then checked the narratives and points that were corroborated by both coders were used in the narratives of student performance. Students' explorations in specific zones were quantified to analyze whether those who used the MBD earlier ranged more distantly in their explorations than those who used it later. Overlapping themes were considered for possible transfer between the EcoMUVE and MBD components.

RESULTS

1. What does the evidence suggest about the students' learning about changes over time and distance across and within the groups given the combined intervention of EcoMUVE and the EcoMOBILE (MBD) components?

Our results suggest the following patterns. Student responses on the ADCT Assessment revealed that across the groups, students initially considered the most important actions those involving the immediate time frame and location at the pond. The post-tests showed subtle shifts in increased recognition of the

importance of considering a longer time span and more distant drivers of change. The ADCT pre- and post-assessments reveal subtle shifts towards realizing the importance of considering distant variables in

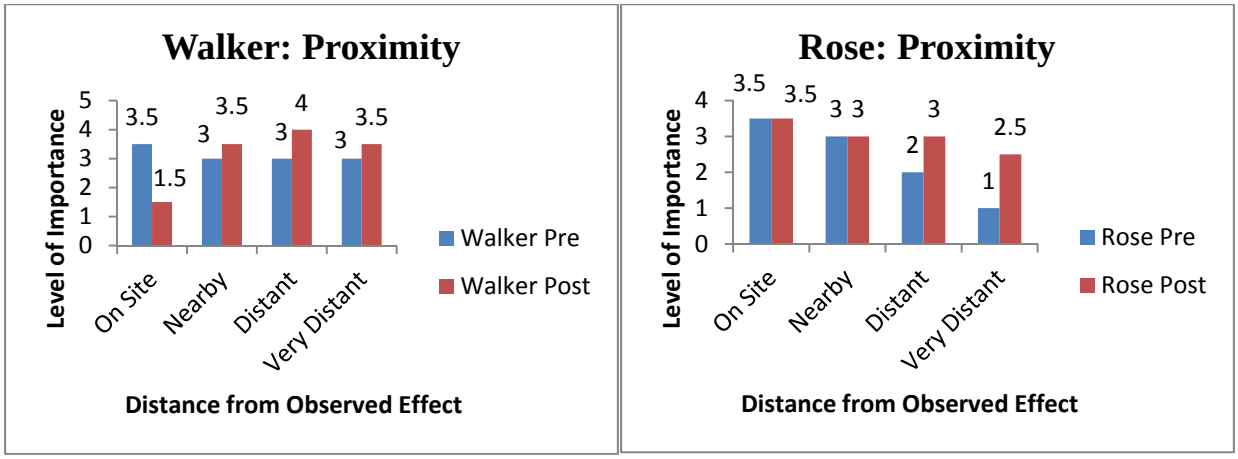

Fig.2. Shifts in Valuing of More Distant Variable Over Time Pre- to Post-Test: Sequential Intervention

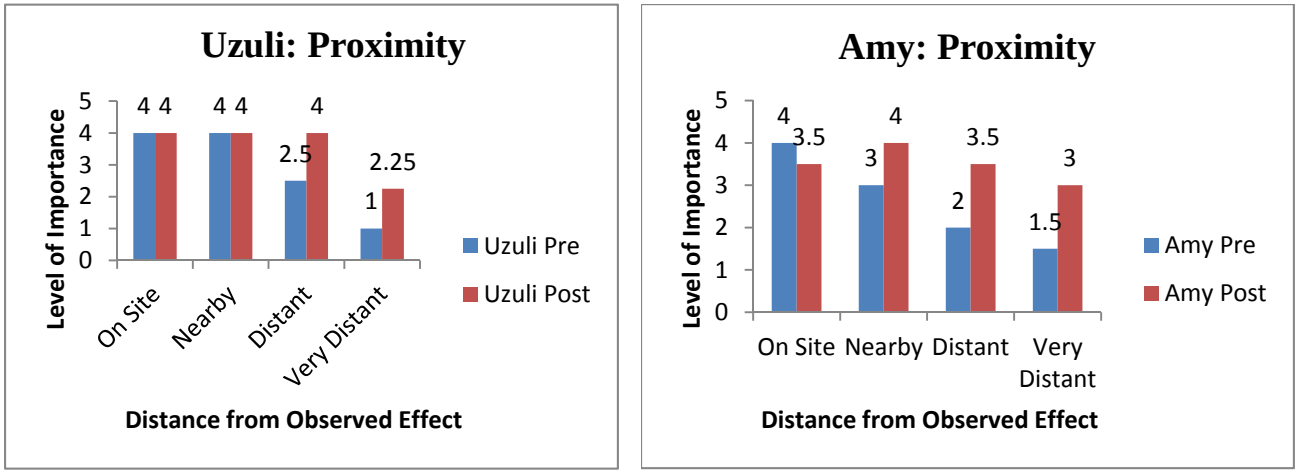

Fig.3. Shifts in Valuing of More Distant Variable Over Time Pre- to Post-Test: Intermingled Intervention

investigating environmental issues (See Figures 2 and 3.) Across both groups, students revealed changes in the assumptions that they made about whether it was important to investigate distant factors. It is not that they viewed exploring local factors as less important, rather that they realized that the causes of the environmental problems could exist quite far from the outcomes.

On the Fish-Die Off Assessment, across conditions, students showed a tendency towards more spatially local than distal responses on pretest (74 v. 34 respectively), and more balanced responses on the post-test (28 v 34 respectively). There were no discernable differences between conditions (Sequential Intervention Pre: 34 v 16; Post: 16 v 17); Intermingled Intervention Pre: 40 v. 18; Post: 12 v. 17).

The narratives of how each group investigated the EcoMUVE revealed a number of themes. As each pair of students begins to explore the EcoMUVE, their movement is sporadic and appears unintentional. The pairs find the various locations, including the edge of the MUVE, setting the boundaries within the

environment. They seem to get familiar with their virtual surroundings within the first or second visit to the MUVE, noted by the pairs revisiting the same locations multiple times or by stating, “We’ve already been here”. Two pairs find the “edge of the world” and the housing development in the first session. All of the pairs interact with animals, fish and humans beginning to use the field guides and camera functions. Within the first session, some students start to get a geographic sense of where things are. For example, Chloe said, “Go back to the pond, go back to Ranger Susan” and navigated back to that location directly from the housing development.

As the pairs learn about the fish die off through communication with classmates or their own observations within the MUVE, the more purposeful their movements seem to become. Once they know the exact date that the dead fish appear in the pond, they work before and after that date looking at the pond itself, take population counts for the fish that are still alive, and testing the water for different organisms and bacteria. They begin to develop strategies to seek out animals and humans in order to gather information and begin to discuss the data meaningfully, noticing trends of increase or decrease of specific organisms. Towards the end of their time with EcoMUVE, the pairs spend more time looking at data and graphs than moving around the environment.

The tools start as fun and become an integral part of solving the case. In the first 2-3 sessions, the pairs learn how to use the field guide, submarine and water tests but do not make any connections between them. Sean and Chloe begin to search for everything in the guide by going down the alphabetical list. They state, “We’re going to find everything on this list”. They continue this strategy through day 3. As the sessions progress and they discover the fish die off, they abandon that strategy and look purposefully for humans and evidence, such as the fertilizer bags. Amy and Uzuli focus on the tools more quickly and discover the fish die off in session 2. Walker and Rose discover the fish die off in session 2 (4/3), although it seems as though they have been talking to peers in the classroom because they did not discover it in session 1 (3/26). They utilize the population data immediately after discovering the fish die off.

Each pair formulates a hypothesis about the fish die off and attempt to build evidence to support it. Two pairs (Sean and Chloe, Walker and Rose) adjust their hypothesis based on additional collection of data and information.

Sean & Chloe –

Day 3: Make immediate assumption that sewage killed the fish. Sean says, “Yes, we know what caused it. The sewage.” Day 4: “I don’t think it was the sewage. I think it was the fertilizer.” –Chloe
After further exploration: “We figured it out.” – Chloe. “The day before it rained they were putting fertilizer on the golf course over here and on the instructions said not to put it on before it rains.” – Sean. “So it washed away, into the pond and killed the fish.” – Chloe

Walker & Rose –

Day 2: “It could be the fertilizer. Maybe that’s it.” –Walker. “Someone dropped it in…” – Rose
Day 3: “It just seems like it definitely happened.” –Walker. “But it only affected the big fish.”
Day 4: “It says not to do it before rain, and it got in the water…to prevent the loss of nutrients…” – Rose. “Oh so maybe the water could have taken the nutrients out and it went into the plants and the fish ate them”.
“We know one person probably made a mistake with fertilizer.”
“Our theory is that the oxygen—there’s not enough chlorophyll in the water and the plants died. The plants died because there was not enough sun.”

The mappings of student behavior shows that the students constrained their explorations to particular features in the world as they developed specific hypotheses about what might be happening.

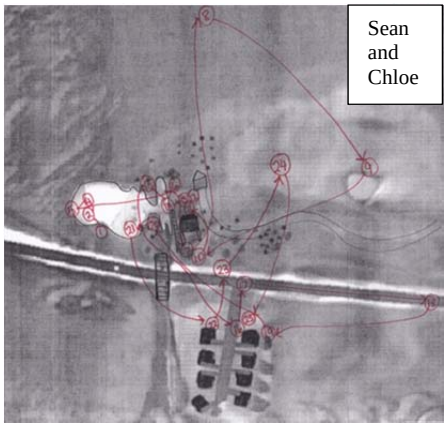

Fig. 4. Movement Patterns Time One

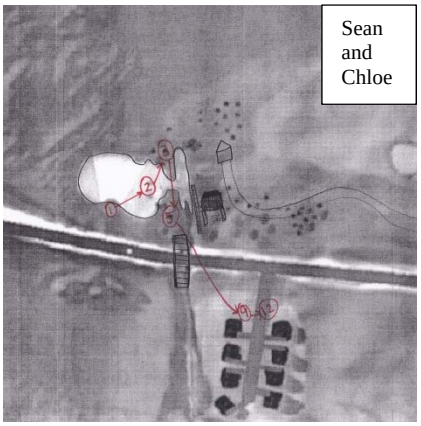

Fig. 5. Movement Patterns Time Two

2. What does the evidence suggest about whether students within each group transferred concepts between the EcoMUVE and the EcoMOBILE (MBD) components and vice versa?

Students' initial observations at the pond, prior to receiving support from the MBD and EcoMOBILE reveal what they brought to the experience, including a full EcoMUVE experience or just an initial exploration. Students who experienced all of EcoMUVE first appear to have transferred some aspects of their EcoMUVE experience. For instance, Chloe and Sean made mention of non-obvious variables from the outset of their visit to Black's Nook. In their observations of the pond, they made reference to variable that they learned in the EcoMUVE. For instance, they find a dead tadpole and use terminology learned in EcoMUVE as they consider what might have happened.

C: *Well, because it's the biggest tadpole we've ever seen, Uh, maybe it like- maybe it's not supposed to get that far out of the water, Because it looks like it's a little bit out of the water. And maybe they, like- maybe they, um, when they're little they still breathe the- the dissolved oxygen, I don't know.*
E: *Can you say more about that – about the dissolved oxygen?*
C: *Well, it's like oxygen, but it's in the water.*

S: *Alright. And, um, maybe , uh maybe look around and see –*
C: *Look and see if you can see things in unique places like look into the water and see if you can find any fish or like little tiny ecosystems inside the ecosystem.*
E: *Can you say more about that?*
C: *You know, like, I don't know there are just some things that are like small ecosystems inside ecosystems. Like, for instance, yeah bacteria and also like, I don't know, maybe like some animal eating another animal which is kind of like part of an ecosystem.*

They also paid attention to distant impacts:

S: *It's not right here but it seems kind of like it's having an effect.*
E: *Can you say more about that? It's not right here, but it's having an effect?*
C: *Like, didn't they say something about the swamps?*
S; *Like, it takes out the nasty things in the water and makes it good for drinking.*
C: *The swamp does?*
S: *No, the uh watershed.*
C: *The watershed. So do you think that, like, it's seeping into the water here?*
S: *Maybe.*
C: *And do you think that's having an effect on the animals?*
S: *Maybe.*

C: Because like maybe it's like bad for the animals, I don't know.

Their EcoMOBILE experience appears to extend their concern for distant impacts and things that they cannot see.

S: [Reading] Sodium concentrations increased. This may be due to the severity of recent winter sand the application of salt to the road surfaces. Compared to other stations, this tributary does not get as much highway runoff and so it has lower sodium amounts. That's interesting. Alright, Oh, virtual time transporter tool. Uh, fifty feet.
C: Are you going the right way? Did you find it?
S: Uh, another way to get to know an ecosystem is to think about what's happened there at different times.

S: Look around and see- dig up things, see if there are things there.
C: I mean also, you can kind of – you can see like how some of the things sunk in so that- like that happened.
S: You could ask people.
C: Yeah, you could ask people.
E: Hm, like you might- do you have any ideas who you might ask?
C: Like someone who's lived in Cambridge for a long time.
E: Okay.
S: And lives near here.
E: Why do you think that's important to ask someone who's lived around here for a long time?
S: Cause they know how it's been.
C: Because it was before- because we haven't been around here a long time to tell, you know? [Reading] What do you know about Black's Nook now that you did not know before you started observing today? Well, I didn't know what they tried to fill it in.
C: I didn't know, either- and I didn't know that it was basically a trash hole.
S: I didn't know it was a military place, either.
C: I did not know that. I didn't know it was a military place. I did know a lot of the history of Black's nook, and-
S: I didn't.
C: Yeah, me neither. I thought it was always like a healthy, thriving place.
S: I know, right?
C: Right? But actually, people have put a lot of effort into that. I might- I just- I'm thankful to that.
S: Yeah.
C: Yeah, cause like, we wouldn't have this beautiful place to go like running and stuff, right?

C: Well I learned a lot about the history of the pond. You know, before I thought it was a thriving, you know, ecosystem but it turns out that the gardening club have been doing a lot of work to help out- keep this ecosystem running because there are lot of things that have stopped the ecosystem from working and things- plants have died. But, you know, over the past 60 years they've made an effort to kind of help the ecosystem thrive. And also I did not know anything about the history – like I didn't know that they used this pond as a trash hole. I also didn't know that there was a cabin here. And I didn't know they used it for military. I mean, that's just really interesting to me.

The second group who experienced the interventions sequentially are aware of the impacts of the city on the pond. They are immediately concerned with pollution. They are much less talkative than the first pair and seem shy around each other making it difficult to discern their thinking as well. Walker finds a wrapper and takes it out of the pond. He focuses on the pond and considers the pollution.

W: I don't know- a lot of pollution. Dogs and… yeah.
E: Hm. Influence of pollution and people and yeah. Do you want to sit and talk with Rose about what you've noticed?
W: Sure.
E: You want to sit right here? It's kind of shady and nice. Wan to?
R: Can we?

E: *Yeah.*
W: *So I'm noticing like a lot of bugs. Especially like right around the water.*
R: *Every once in a while there are like some ripples or something comes out of the water.*
E: *Uh-huh. So you're noticing patterns in the water?*
R: *I guess.*
W: *I definitely see some like plants. Very sprawled out and…*
W: *It's so close to the city. It's like-*
E: *Yup, yup.*
W: *Fifty yards away.*

Following their experience with EcoMOBILE, they comment on how surprising the history is and that the pond is still there.

R: *It's pretty cool how like they actually wanted like to fill it in. Didn't- yeah and it's pretty cool how like it's still here-*

Both groups who were experiencing EcoMOBILE intermingled within their EcoMUVE begin their explorations focused deeply on the pond and the visible animals that they can find. Both pairs focused their initial EcoMOBILE observations primarily on the pond. For instance, Amy and Uzuli focus on what is in the water. They are very observant and notice a frog that is well camouflaged on the bottom of the pond.

U: *He um he has, since he's in the water, he has webbed feet so that he can swim. He's kind of grayish and his eyes are kind of yellow with like a black pupil. Kind of like snakes.*
E: *Those are really nice observations about his appearance. Do you notice anything about his behavior?*
U: *He's just staying still.*
E: *Can you think of any reasons why that might be so.*
U: *Um, maybe he's sick, sleeping, or…*
E: *Sleeping, uh huh.*
A: *But his eyes are open.*
E: *Uh huh. Do you think he would sleep with his eyes not open? So what do you think he's uh…Can you think of any reasons why it might be nice for him to stay very still?*
U: *So that we can't see him, and then he can camouflage.*
A: *Maybe he's like, maybe the water's a little colder, and so sometimes if you like if you go like this, and if you kind of go like that (covers face with jacket), you stay a little warm.*

Later:

A: *So we found a frog at Black's Nook, so we have seen nine ducks and females and males.*

While they are initially focused on what they can see, the affordances in the EcoMOBILE experience invite them to look beyond what they initially see:

U: *I learned about um I think there's like a water system that pours into like Fresh Pond.*
E: *Yeah.*
A: *Which is like go into Black?*
E: *It pours into…Well it comes into this whole area. Mostly Fresh Pond. Some here too. So what does it tell you about it? What does it…What are some things that it might bring?*
A: *It might bring like bad stuff, and it might…*
U: *Like harmful things.*
A: *Yeah.*
E: *Uhmm. How does that change the way this place feels to you? Because here you are sitting in this very beautiful place.*
A: *But the water is a little dirty mucky.*
U: *It's in the city, and it's not*
A: *Like cars.*

U: *Yeah, cars and like exhaust would be like poisons to some animals.*

The second pair also focuses primarily on the animals in the pond.

[Focused on the geese…]
V: *What are they eating?*
T: *Okay, so.*
V: *They're eating leaves.*
T: *They're diving.*
V: *No, but they were eating leaves. I think it was kelp – I love their- oh, look they're eating kelp.*
T: *We find that the Canadian geese are eating kelpie things.*
V: *What's that white thing? Just trash?*
T: *Mm, yeah.*
V: *That's sad.*
T: *I guess it's too cold for frogs.*
V: *I love those geese.*
V: *Oh, oh there's mal- there were a few ducks over there and there's mallards. There's a male mallard duck.*
T: *There's a biplane going over.*

Their observations suggest that they are aware of location and what is around them.

V: *Oh, and there's a wind blowing towards us and –*
T: *There's a wind blowing towards us from that- east-ish.*
V: *Yeah.*
T: *And, uh, east. Wait, does the sun rise in the east?*
V: *I don't know.*
T: *So then that means that the east is there. Oh, and west is there.*
V: *The wind is blowing.*
T: *So the wind is blowing from the, uh, from about the north.*
V: *North-ish.*
T: *North-ish.*
V: *And there's like a wooden walk. And, um, but there's like ground that is squishy here. Lot of sticks and like dead grass and plants. And then along the bank, there's moss growing. And in the shallow parts, there's lots of like mud and sticks and algae things.*

Discussing a frog that they found…

T: *It probably got uncovered by mud. It's probably just enjoying the heat.*
T: *Cause the pond is probably pretty cold.*
E: *Well, why wouldn't it just go where the heat is right there?*
V: *Well, hopefully, he's okay. That's so cool, we found a frog, Theo. Ooh, get him get him get him, get a picture. It's not a mallard duck, it's a Canadian geese. Goose. Canadian goose. The duck's are over there.*

T: *Okay, so- did that. Did that. WE have found a frog at Black's Nook and we also have seen mallard ducks and Canadian geese and-*
V: *Females and males.*
T: *And also we found things that are pretty fluffy and like-*
V: *And cattail-like.*
T: *Yeah, they almost look like cattail stuff.*
V: *Let's see what it writes.*
X: *Want to see a picture of a frog?*
T: *We already- we were the one who found the frog.*

E: *Okay. Yeah, so the prompt is basically "is there anything you wish you could take a picture of but couldn't?" For any reason, maybe because you can't-*
A: *If there's like a fish or anything like below the pond.*
E: *Cool, that's one.*

T: *Alright, um, we wish that we could have recorded more of the ducks and what?*
V: *Under the water like the turtles.*
T: *Oh, yeah what's happening under the water like the turtles, catfish, and frog. And the tadpoles, well they're probably-*
X: *And the newts.*
T: *And the newts.*

Following the EcoMOBILE Experience, both students express surprise at what they are learning about the water in Cambridge:

T: *[Reading] …Water that flows… eventually flows into the watershed nearby and eventually becomes drinking water for the city of Cambridge. Click done to see a map of the location.*
V: *Thank god I don't live in Cambridge.*

V: *Well it changes what we know because it's out there where we can't see.*
T: *Showing us what out naked eye can't.*

E: *So you didn't know what?*
T: *We didn't know that- I didn't know that there were like three different places that Cambridge gets its water supply.*
E: *And how does it change how you look at this ecosystem?*
T: *It means that I's almost like…*
E: *What?*
T: *It's almost like more important. That it's almost more important in like the context of the pond. And if it was like destroyed or changed or people walk in front of it.*
V: *Conservation.*

T: *Okay, so what did you not know about the history of black's nook before today?*
V: *Well, that like it was… um. Well, I didn't know about the whole like the whole 1800s thing about it being filled up and stuff.*
T: *Yeah, I didn't know about the surrounding nooks either.*
A: *I didn't know stuff was planted here, I thought it just grew wild.*
V: *And I didn't know there were odd objects like cars and stuff.*
U: *Yeah, trucks…. That'd be interesting to find out if that's true. Are you done?*
A: *Yup.*
T: *Well, like, there's not a lot of stuff that's here from back then, but like yeah that's a beech tree and that's a beech tree.*
V: *Yeah, and you can tell that the trees have been here for like a while.*
T: *Yeah, like definitely. So many of them are like huge. Like that one that fell over and that one. And that one.*

DISCUSSION

This work suggests that both groups of students made subtle shifts towards realizing the importance of distant possible causes in addition to local ones. Their exploration within the EcoMUVE became more focused and hypothesis-driven as they collected more information and refined their ideas about what might be happening. Some of these hypotheses led them further from the pond and they shifted their efforts to focus there. There were no discernible differences in exploration within the EcoMUVE for students who experienced the EcoMOBILE components intermingled within the EcoMUVE experience. It may be that they had not progressed far enough into the EcoMUVE to recognize that what they were learning at the pond held relevance. One set of students who experienced the entire EcoMUVE and then investigated the pond made unscaffolded observations that connected directly to their EcoMUVE experience. They also seemed better positioned to benefit from the EcoMOBILE components. The second team made some connections though less clearly so. This is a small focused study with many sources of

corroborating data. These tentative findings from a close look at four pairs of students will be further vetted against a larger data set to see if the narratives of their experiences hold in other pairs of students. These preliminary findings suggest that digital tools can offer complementary affordances and can encourage transfer of concepts in the real world. Further findings should have important lessons for developing effective technology-based interventions for teaching the complex causal dynamics of ecosystems.

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APPENDIX A.

Students are given information on three water monitoring stations. They are the three tributaries into Hobbes Brook Upper Reservoir.

This is the Hobbs Brook Water Monitoring Station at Mill Street in Lincoln, MA (4405)

This is the largest of three tributaries that bring water to the upper basin of Hobbs Brook Reservoir. The sub-basin has a large proportion of wetland and forested cover. Compared to the other stations, it exhibited lower estimated amounts of manganese, phosphorus, nitrogen, and sodium. Overall manganese, sodium, and fecal coliform bacteria concentrations however, were slightly higher than three years ago. Dissolved oxygen concentrations were shown to have slightly decreased, but still remains above the State standard. Sodium concentrations increased. This might be due to the severity of recent winters and the application of de-icing compounds to the road surfaces. Compared to other stations, this station is not a major recipient of highway runoff, thus it yielded relatively low sodium concentrations.

Can you find it on the map?

This is the Salt Depot Brook Water Monitoring Station in Lexington, MA (4410)

This tributary by far had the highest amounts of manganese and the second highest amounts of fecal coliform of any of the tributary stations. It also had one of the highest sodium amounts. Nitrogen and phosphorus yields were relatively low compared to the other stations. Fecal coliform, nitrogen, phosphorus, sodium, and manganese amounts were all higher than three years ago. High sodium yields at this station are consistent with upstream historical land uses of open salt storage piles associated with road de-icing operations. Over the years, salt from these piles may have slowly migrated into the ground water re-surfacing in the wetland that feeds this tributary. Relatively high amounts of fecal coliform bacteria may also be attributed to the wetland that contributes to this sampling station as wetlands typically provide habitat for an abundance of wildlife.

Can you find it on the map?

This is the Lexington Brook Water Monitoring Station in Lexington, MA (Tributary 2), (Parallel to Rt. 128) (4415)

This station drains the second largest area in the Hobbes Brook sub-basin and is fed by groundwater and direct discharges from highway and road surfaces. An automated gauging station continuously records temperature, stage, and specific conductance, showed the highest conductance values and sodium concentrations in the entire water area and higher than three years ago. Nitrogen and phosphorus were less than in the other two tributaries in this sub-basin. Nitrate went down from three years ago but was still the third highest in the area. Fecal coliform concentrations are the lowest of the three tributaries but increased recently. It is likely that much of the sodium contamination is related to highway runoff. More than 13 percent of the drainage area for this tributary is covered by roads, the highest coverage of any drainage area in the source watershed. The tributary's drainage area includes a major highway interchange connecting State routes 2A and 128 and a salt storage area managed by the Mass Highway Department. State highways cover twice as much area in this sub-basin as any other and are in close proximity to the sampling station, the tributary, and the reservoir. Inclusion of this station in a water-quality monitoring program is essential because of the serious potential for increased contributions of sodium and other contaminants to the water supply.

Time Traveler Explanation and Text:

In this narrative, the time traveling tool allows the students to pull a character out the past into their time. The reason is because having them traveling back in time makes it so that what is around them should look different which it won't. If they pull a character forward, then he can say "This doesn't seem like 1939" announcing the year and can be startled that Black's Nook still exists and how different it is. It also gets around issues of knowing what is

relevant without mixing up his knowledge because he will be in the new timeframe and can compare to the past. The character is about 50 years old. He talks about things that he remembers from his childhood at Black's Nook and recall significant events from the late 1890s but also knows about the later filling in of the nook that happened in the late 1930s.

"Hey, what am I doing here? Who are you kids? You aren't from my time are you? You don't look like kids do in the 1930s. Why have you summoned me here?

Wow, look at this place! This really is a survivor pond. Why would I call it a survivor pond? Well, let me tell you what happened around here in my day….

When I was younger than you, in the 1880s, there were lots of nooks here—Eames Nook, Boathouse Nook, Bright's Nook, but they're all gone now. You see, those guys at the Water Department got all worried that all those lovely marshes would let "inferior water" into the big pond—you know, the one that they call Fresh Pond, where we get drinking water here in Cambridge. So they went around and started filling 'em in. But not this one, this is the nook that wouldn't go away. The official story says that in 1889, they filled the nook right up to the level of the land. The water superintendent said that he did not ever expect to refer to the existence of Black's Nook again. But then two years later, it was back and they had to keep filling it. Every day, they added 700 cubic yards of fill….That would fill 70 of those contraptions that you call dump trucks, but in my day, they had to haul the dirt with horses and wagons." And do you know what happened to all that fill? It just sunk! One hot summer night, a great big section of the fill sank 17 feet and a hundred feet away, the ground bulged up as tall as a three story building—35 feet in the air. Scary! They finally gave up trying to fill Black's Nook in 1895.

Of course, that's the official story. Rumor has it that they are still trying to fill it in. We just had a hurricane last year in 1938. People say that they dumped trees from the storm, the roof of a building, fencing and parts of the road in there. I've hears that they even put old cars, hot pavement, bricks, gravel, cement, locomotives, you name it, into the nook. But it just sunk in.
But probably they felt like they could put all those things in Black's Nook because after the first attempt to fill it in, they built a wall between Black's Nook and Fresh Pond. They wanted to keep the "foul water" away from the reservoir. Looking at it now, it seems crazy to do that to such a beautiful place."

STOP HERE for Section 1.

"Did you ever wonder why this place is called Black's Nook? The other nooks are not the only things that are gone. When I was just three, the Water Board bought the ice house that was here. It belonged to Mary Black and she sold ice from it to make a living for many years. When the Water Board bought the land, they demolished the Black's ice house.

Other things happened right around here. In 1917, a military training group at Harvard called ROTC, was given permission to dig lots of trenches all around Fresh Pond to conduct mock combat drills. The trenches were five to six feet high. In 1918, the trenches were filled back in, but some said that even afterwards you could walk around and feel soft spots in the soil. Do you notice any indentations in the landscapes when you walk around Fresh Pond?

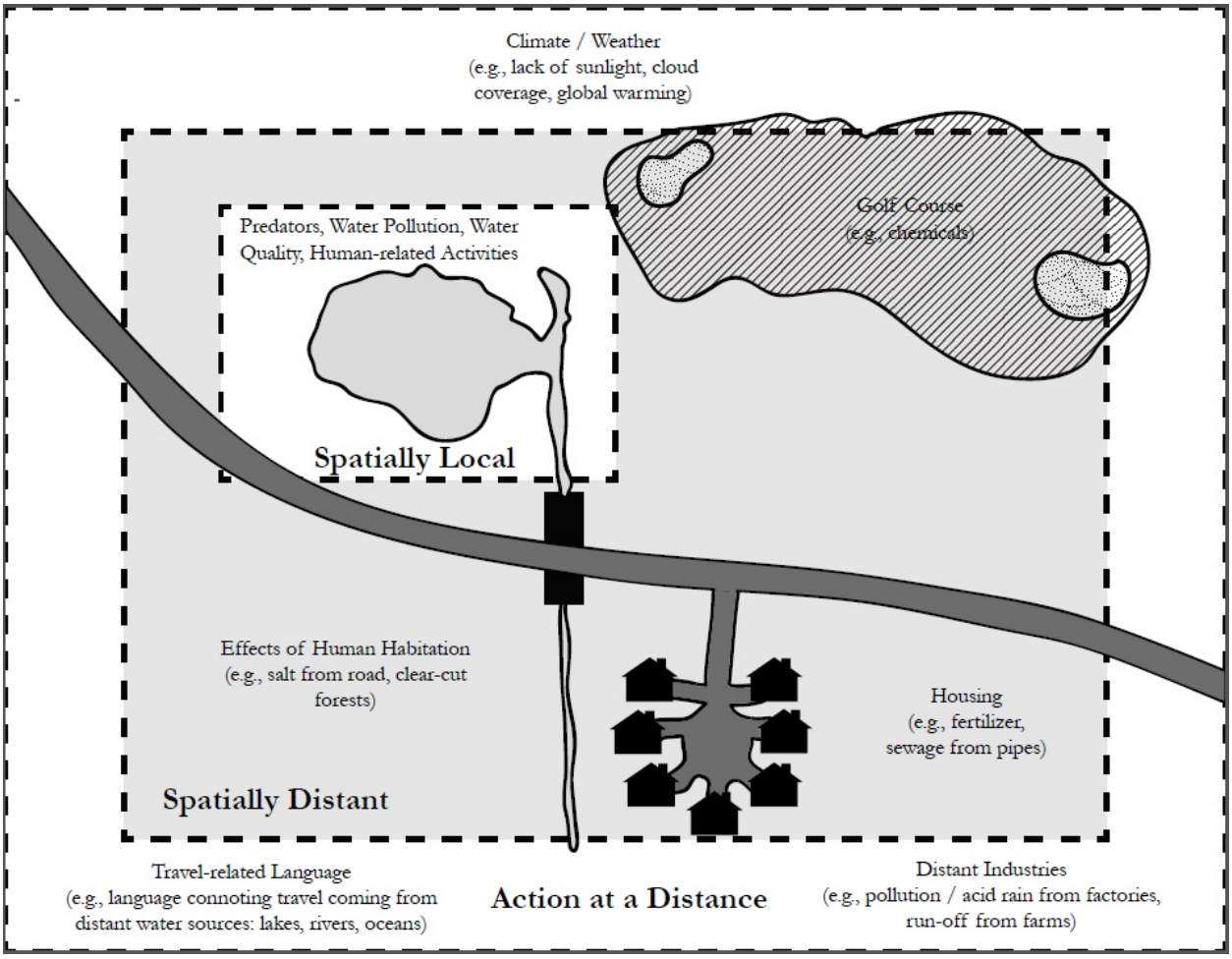
That golf course is still here, I see. Amazing! They just finished building it recently. The designer wanted it to be twice as big—18 holes--and to take up all the land on both sides of Black's Nook. But they only made it 9 holes instead.

Did Lily Pond survive, too? Do you know of a pond called Lily Pond?

Well, I better be getting back to my time. Wow, it makes me feel so happy to see that this nook has been a survivor. I hope that you take really good care of it so that it survives many more years."

Scoring the Causal Features of Students' Responses to the Pond Question

Action-at-a-Distance



Spatially Local vs. Action at a Distance		
Concept	**Explanation**	**Examples**

Spatially local (SL)	Within the same attentional set as the effect. Here, this refers to in the pond and along the banks of the pond. In other words, "*in the pond*."	• References "in the pond/water"
		• Bacteria/disease spread in the pond
		• People polluting
		  o Pollution in the water
		  o Throwing trash in the pond
		  o Dumping
		  o Oil spill in pond/ toxic water from an oil spill
		• Various Compounds *in the pond*
		  o Chemicals
		  o Toxins
		  o Poison

		• Water-related issues
		  o Dissolved oxygen in water (if student does not mention a more distant precipitating cause)
		  o Water was too warm/cold
		• Miscellaneous
		  o "Something in the water"
		  o Electricity killed the fish
		• Fisherman fishing
		• Any type of predator
		  o Bigger fish ate all the food in the pond

Spatially distant (SD)	Outside the attentional set of the effect. Here, this refers to beyond the banks of the pond. In other words, "*land around pond*."	• Effects of human habitation
		  o Salt from the road leached in
		  o People cut down trees
		  o Chlorine from a pool/waterslide
		  o Human/animal waste
		• Housing development
		  o Runoff/sewage, pipe/drainage
		  o Fertilizer
		• Hazardous materials traveling from golf course
		• Some travel-related language
		  o Clearly connotes materials' traveling from outside the pond to inside the pond *without being directly dumped or thrown*, such as "draining in, rolling in, blowing in"
		  o Phosphates leached into the water from the development

Action at a considerable distance (AD)	Causes that result from action at a considerable distance. Here this is defined as beyond what can be seen when standing at the pond. In other words, "*far away from land/pond*."	• Climate/Weather related
		  o Global warming
		  o Tsunami
		  o Sunlight/lack of sunlight
		  o Wind
		  o Thunderstorms, lightening,
		• Impacts of distant factories/causes
		  o Acid rain from a factory, cars, pollution, etc.
		  o Nearby factories, farms
		  o Runoff from farms
		  o Pollution from companies
		• Some travel-related language
		  o Travel coming from distant water sources: rivers, lakes, oceans
		  o Something flowed into the river, which flowed into the pond

Ambiguous origins (AO)	Some causes have ambiguous origins (AO). The answers might imply distributed action at a distance, such as "acid rain." However, if the student doesn't talk about their cause as distributed and distant (e.g., "people all over the world contribute to acid rain	• One-word answers without reference to origin/point of impact
		  o "Acid rain"
		  o "Toxins"
		  o "Oil spill"
		  o "Sediments"
		  o "Pollution"
		  o "Salt"
		  o "Natural disaster" (unless focus is on the

	that falls into the pond") then score it as having ambiguous origins. Take care not to project your interpretation of the cause but rather to try to see it as the student perceived of it.	pond) • Anything that "killed" the fish but doesn't mention that it was in the pond • Mother Nature • Food chain/web • Old Age • Weather is too hot or too cold