EXPLORING STUDENT ENGAGEMENT AND TRANSFER IN TECHNOLOGY MEDIATED ENVIRONMENTS

By

SUPARNA SINHA

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ABSTRACT OF THE DISSERTATION

Exploring student engagement and transfer of mechanistic reasoning skills

in computer-supported learning environments

by SUPARNA SINHA

Dissertation Director: Cindy Hmelo-Silver

Computer-supported environments designed on learning science principles aim to provide a rich learning experience for students. Students are given opportunities to collaborate, model their understanding, have access to real-time data and engage in hypotheses testing to solve authentic problems. That is to say that affordances of technologies make it possible for students to engage in mechanistic reasoning, a complex inquiry-oriented practice (Machamer, Craver & Darden, 2000; Russ et al., 2008). However, we have limited understanding of the quality of engagement fostered in these contexts. This calls for close observations of the activity systems that the students participate in. The situative perspective focuses on analyzing interactions of individuals (students) with other people, tools and materials within activity systems (Greeno, 2006). Importantly, as the central goal of education is to provide learning experiences that are useful beyond the specific conditions of initial learning, analysis of such interactions sheds light on key experiences that lead to transfer of mechanistic reasoning skills. This is made possible, as computer-supported contexts are activity systems that bring forth trends in students' engagement. From a curriculum design perspective, observing student engagement can be a useful tool to identify features of interactions (with technological tools, peers, curriculum materials) that lead to successful learning. Therefore, the purpose of the present studies is to explore the extent to which technological affordances influence students' engagement and subsequent transfer of reasoning skills. Specifically, the goal of this research is

to address the following research questions: *How do learners generalize understanding of mechanistic reasoning in computer-supported learning environments?, What kinds of engagement with technological tools are needed to facilitate high quality conceptual understanding of the problem?,* and *How does engagement with technological affordances influence transfer of mechanistic reasoning skills?*

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

1.1 Statement of the Problem

The National Science Education Standards (National Research Council, 1996) recommends that students develop abilities for scientific inquiry. Russ, Scherr, Hammer & Mikeska (2008) second this notion by emphasizing that the focus of science curriculums should be to refine students' inquiry skills by giving them opportunities to engage in scientific reasoning. Mechanistic reasoning (MR) encourages inquiry-based practices as it promotes predicting and explaining behavior of components within the context of physical systems (Machamer, Darden & Craver, 2000; Nersessian, 2008). Designing technology rich science curriculums appear to be feasible for achieving this goal. This is because computer-supported technologies afford opportunities for engaging in inquiry-based practices that mirror practices of scientists (Krajcik et al., 2000; Novak & Krajcik, 2004; Metcalf- Jackson et al., 2000). However research on influence of students' engagement (in such learning environments) on their uptake of opportunities to engage in MR and use of this line of reasoning to make sense of new problems has not been documented. This dissertation aims to address research questions that look closely at students' engagement with computer-supported technologies, their uptake of MR practices and consequent usage of MR skills to solve novel problems.

Findings from this work shed light on three prominent areas of research. First, given that computer-supported inquiry environments have the potential to encourage scientific practices (Krajcik et al., 2000; Novak & Krajcik, 2004; Metcalf- Jackson et al., 2000), it becomes imperative to understand the extent to which students engage with technologies. As learning scientists we assume that computer-supported inquiry learning environments are engaging and provide affordances for high quality participation. Krejins et al (2002) caution that purposeful interactions may not necessarily occur even though they are afforded by available technologies. This implies that there are differences in the ways students participate in inquiry-based practices in such contexts. This research seeks to use engagement as an indicator of students' uptake of opportunities to engage in inquiry-based practices afforded by media-rich learning environments.

Second, findings from this study sheds light on MR. MR are typically used to explain "how a phenomena comes about or how some significant process works" (Machamer et al., 2000). Scientific reasoning prepares students to think about specific mechanisms that are part of processes that bring about an effect (Koslowski, 1996; Schauble, 1996). This dissertation explores the numerous ways by which students make sense of components-mechansims-phenomena (CMP), adapted from Structure-Behavior-Function theory (Goel et al., 1996; Hmelo-Silver et al., 2007), as a framework that encourages MR in biological sciences. Phenomena refer to the problem or outcome under investigation. Components are the entities that display specific behaviors or mechanisms based on their properties. Mechanisms are characterized as causal explanations of how phenomena occur. They are typically used to explain how a phenomena comes about or how some significant process works.

Research suggests that instruction designed to support inquiry focuses primarily on assessing accuracy (Marx et al, 2004). However, Russ et al. (2009) argue for a shift of assessments from textbook correctness to designing curriculums that encourage MR and pay close attention to student discourse to evaluate the quality of their thinking. As a result, the third contribution of this dissertation is to explore novel ways to trace and assess quality of students' MR in computer-supported environments. Actor-oriented transfer (AOT; Lobato et al., 2003) served as a theoretical lens that illuminated aspects of MR that groups focused on and were eventually transferred by individual group members. Lobato (2012) gives importance to multiple factors such as classroom interactions, curricular resources and individual cognition as influences on transfer from the student (actor's) perspective. This implies that the sociocultural perspective is consistent with the AOT lens as it helps to identify the sources and factors that may possibly influence learning and transfer (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011).

However there is a gap in the literature that explores the influence of the sociocultural environment on the development of reasoning skills and subsequent transfer of such skills to make sense of new problems. This dissertation attempts to fill this gap and add to this body of literature by unpacking the relevance of students' collaborative engagement with technological affordances as an additional factor that may influence development of MR skills and transfer. Thus it becomes pertinent to understand engagement from a sociocultural or situative perspective and uncover influences of technological affordances on student engagement.

1.1.1 Understanding engagement from a situative perspective.

The term engagement typically describes the ways that individuals relate to ongoing interactions with people and objects (Nolen et al., 2011). The situative or sociocultural perspective regards engagement as a specific aspect of participation that is a result of interactions with the learning environment (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011). As a result, engagement is viewed as meaningful participation within communities of practice where knowledge-to-be learned is used and valued

(Wenger, 1989). It is primarily a result of meaningful participation with the environment. This distributes the burden for motivating engagement between the context and the individual (Hickey & McCaslin, 2001). Greeno et al. (1996) propose that if learning environments a) provide practice in formulating and solving realistic problems, b) foster participation in social practices of inquiry and learning, c) provide support for positive epistemic identity, and d) develop disciplinary practice of discourse and representation, they are likely to be engaging for students.

Computer-supported inquiry environments incorporate design elements that are intended to foster meaningful participation. This may occur because students have the opportunity to collaborate on authentic problems situated in media-rich environments. However, we have limited understanding of the quality of engagement fostered in these contexts. The situative perspective is a useful lens to observe engagement as it focuses on analyzing interactions of individuals (students) with other people, tools and materials within activity systems (Greeno, 2006). This is critical for identifying features of the interactions that lead to successful learning.

1.1.2 Engagement with technological affordances and inquiry learning

An important goal of science educators and researchers is to support students' inquiry as they learn about the big ideas in the discipline of science (Duschl, Schweingruber & Shouse, 2007). Computer-supported technologies afford opportunities for students to engage in inquiry-based practices that mirror practices of scientists (Krajcik et al., 2000; Novak & Krajcik, 2004; Metcalf- Jackson et al., 2000). Affordances such as analyzing and interpreting data, planning, building and testing models are valuable experiences for students as they make thinking visible (Edelson & Reiser, 2006;

Lehrer & Schauble, 2006). For instance, software technologies such as Planetary Forecaster (Edelson et al., 2006) and Struggle for Survival (Reiser et al., 2001) designed on a project-based science approach contextualize learning through driving questions (Krajcik & Blumenfeld, 2006). That is students are given access to data sets and tools for analyzing real life problems. Specifically such software "reduce complexity by scaffolding three different authentic practices: selecting data to investigate, constructing data representation, and interpreting data representations" (Edelson & Reiser, 2006; p. 340).

The National Research Council (2011) promotes the integration of simulation technology in science curriculums. This is because simulations afford opportunities for learners to engage in hypothesis testing by formulating questions and receiving dynamic feedback that reflects their actions (Harper et al., 2000). Learners are positioned to take on active roles that support inquiry practices such as predicting outcomes, experimenting with variables, in addition to observing and interpreting simulation outputs. This is beneficial for two reasons. First, repeated interaction with simulations has the potential to strengthen students' conceptual understanding (de Jong, 2009; Quellmalz, Timms, and Schneider, 2009). This is possible if students are successful at interpreting the simulation's underlying conceptual model (de Jong & van Joolingen, 1998). As a result simulations can be powerful tools in inquiry-based classrooms as they encourage learning by doing as opposed to relying on practices of reading, seeing or listening to engage in knowledge construction (Akpan, 2001). Second, working with simulations affords opportunities for collaborative sense making. Students draw from multiple perspectives to determine strategies for manipulating variables and interpreting outcomes.

Besides simulations, student collaboration with modeling tools supports classroom experiences to mimic a scientific research community in several ways. First, collaboration supports intersubjective learning (Suthers, 2006). That is, there is scope to jointly create interpretations in addition to opinions formed by individual participants prior to group discussions. This reiterates the point that the cognitive activities that lead to learning are distributed across individuals, the learning environment and creation of artifacts (Hollan, Hutchins, & Kirsch, 2002). Second, as students develop models by working in small research teams, they identify relevant questions that need to be asked, focus on ways to answer them, ensure claims are supported by justifiable evidence and develop efficient ways to communicate thinking (Lehrer & Schauble, 2006). Finally, such inquiry-based practices are valuable as students are given a chance to make their thinking visible and in the process engage in collective sense making by considering multiple perspectives. Having to present their group model to other classmates, defend it against any criticisms that are offered and make revisions based on feedback prepares students to strengthen their reasoning skills.

Russ & Hutchison (2006) propose that MR is central to scientific inquiry. A primary goal of this dissertation is to explore students' engagement with technological affordances in the development and transfer of this key aspect of scientific inquiry i.e. MR skills.

1.1.3 Engagement and transfer of reasoning skills.

There are several educational software programs that support students' inquiry-based practices. For instance, research indicates that simulations make it possible for students to reason mechanistically and strengthen their understanding about concepts in physics such as force, work, potential energy, mechanical advantage and force-distance tradeoff (Carmichael, Chini, Rebello, Puntambekar, 2010). Simulations have also been useful to engage in scientific inquiry in the field of genetics (Gelbart et al., 2009; Gelbart & Yarden, 2006). Multimedia tools such as GenScope, BioLogica (Buckley, Gobert, Mansfield, & Horwitz, 2006; Hickey, Kindfield, Horwitz, & Christie, 1999; Tsui & Treagust, 2007) and Genetics Construction Kit (Cartier & Stewart, 2000) make it possible for students to increase conceptual understanding of genetics by making sense of genetic phenomena and experimenting with multiple variables to test for their influence. Duncan, Rogat & Yarden (2008) discuss that existing technologies promote genetic understanding at the secondary school level. They stress the need to extend research on genetic literacy at the elementary and middle school level. This dissertation studies students' use of simulations and a modeling tool to make sense of phenomena in another area of biological sciences i.e. aquatic ecosystems.

Assessment of MR in classrooms is another area of research that is still in its infancy. Russ et al. (2009) suggest a shift of assessments from textbook correctness to designing curriculums that encourage MR and pay close attention to student discourse to evaluate the quality of their thinking. Bolger et al. (2012) propose that responding to interview questions is likely to provide opportunities for students to predict, describe, explain and compare mechanistic behavior. Conlin, Gupta, Scherr & Hammer (2007) couple Russ' (2006) discourse analysis framework with Scherr's (2006) observation of student behaviors to explore students' MR in collaborative physics tutorials. There exists limited literature that explores assessment of MR. As a result, there is a need to expand on strategies that bring forth students' reasoning about mechanisms, especially in the context of computer-supported learning environment.

This dissertation explores actor-oriented transfer (AOT; Lobato, 2003) as a theoretical lens for assessing students' MR in technology rich contexts. AOT has the potential to help understand how students' earlier experiences with MR affect later MR practices. For instance, if using CMP as a tool to engage in MR, the AOT lens will focus on specific aspects of CMP that students transfer to make sense of novel problems - even if it results in non-normative or incorrect use of CMP. I anticipate that AOT will help highlight aspects of CMP that students notice as a result of social and technological interactions that are a part of their learning environment. Lobato, Rhodamel & Hohensee (2012) propose that *noticing* is a transfer mechanism that prompts students to generalize their learning. As a result the AOT perspective adds to the MR literature as it allows us to focus on *what* content is transferred on the basis of influencing experiences. It sheds light on interactions of prior learning experiences, affordances, discursive interplay with others, and personal goals as setting the stage to solve new problems (Lobato, 2012). Another significant advantage of the AOT perspective is that it highlights specific aspects of the learning environment that the student (actor) pays attention to. It is likely that observing students' engagement will be helpful in tracing their reasoning strategies. This is so as engagement has the potential to " link the antecedents and consequences of how students behave, how they feel, and how they think, especially in the context of new pedagogical and technology-based learning environments" (Jarvela et al., 2008; p. 299).

Studies in this dissertation conceptualize that collaborative engagement has a bearing on MR and subsequent individual transfer of CMP (Figure 1.1). Research indicates that the skill of reasoning about causes and effects emerges very early during the course of human development (Gopnik, Sobel, Schulz, & Glymour, 2001; Nazzi & Gopnik, 2003). As a result, each group member has a prior understanding of mechanisms as causal explanations of how phenomena occur. It is possible that their knowledge of CMP may be challenged or enhanced as a result of collaborative engagement with the learning environment. Importantly, interactions with the learning environment may direct the group to pay attention to specific aspects of CMP. It is anticipated that this has a bearing on individual students' understanding and generalization of CMP.

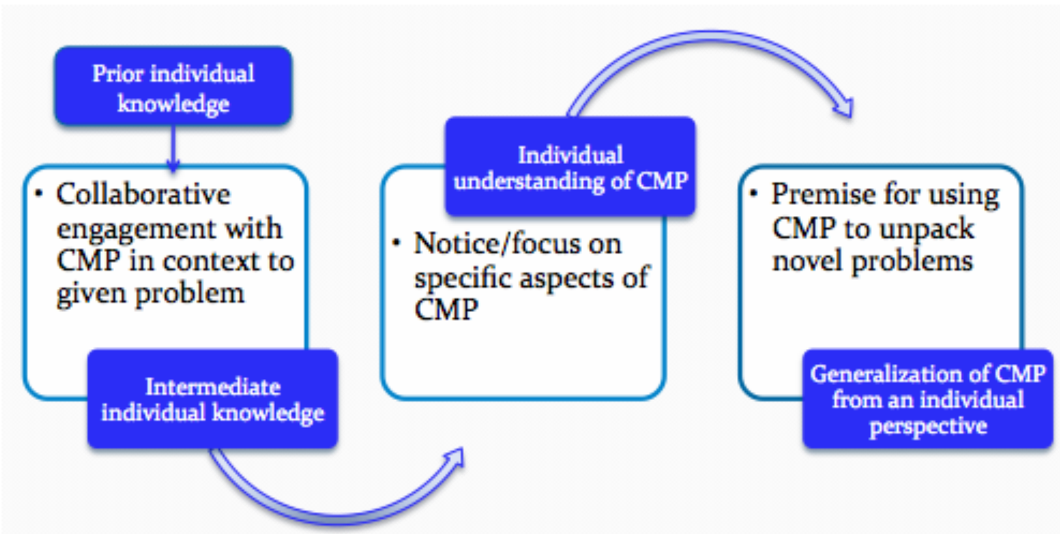


Figure 1. Developing and transferring mechanistic reasoning

Current research calls for developing tools that assess MR in science education (Russ et al., 2009). This aligns with the need to extend literature in AOT to other domains as current research in that area has focused on observing transfer in the field of math education (Hannula & Lehtinen, 2004, 2005; Lehtinen & Hannula, 2006; Lobato, 2003, 2012; Thompson, 2011), physics (Cui, 2006; Cui, Rebello & Bennett, 2006; Rebello et al., 2007) and professional development of teachers (Sinha et al., in press).

1.1.4 Overview of the three studies.

The following three studies take different approaches to address the questions: *How do learners generalize understanding of mechanistic reasoning in computer-supported learning environments?, How do learners take up opportunities to engage in inquiry-based practices in computer-supported environments?* and *How does engagement with technological affordances influence transfer of mechanistic reasoning skills?* These questions serve to examine collaborative engagement with technologies that support mechanistic reasoning and subsequent generalization and transfer of reasoning skills to solve new problems. Findings from these studies contribute to the literature by demonstrating the relevance of the socio-cultural environment on development of inquiry-based practices and transfer.

In the first study (Chapter 2), I observed a middle school science teacher's generalization of SBF as a tool to represent complex systems, such as the human body systems. Use of qualitative research methods served a dual purpose. First, it helped to trace development and refinement of the teacher's understanding of SBF over a period of time. And secondly it highlighted ways by which the teacher generalized her understanding and prepared her to use the knowledge to make sense of another complex system, that was beyond the scope of our research. Findings demonstrated that SBF was a lens through which the teacher could see the relationship between systems and prepare her to learn about new systems. Her learning trajectory included an initial superficial engagement with SBF that she deepened and refined over several years. During the interview she reflected on her journey as a learner. From a preparation for future learning perspective (Bransford & Schwartz, 1999), the results shed light on specific processes and challenges that the teacher had to overcome. Overall the findings suggest the possibilities of extending research on alternative approaches to transfer by productively integrating different theoretical frameworks.

In the first study, I examined a single case study. However, because of the importance of the social interactions and feedback that the teacher received from teaching her students, it set the stage to explore influence of the sociocultural perspective on classroom practices. In my second study (Chapter 3), I focused on investigating the influence of collaborative engagement on uptake of opportunities to engage in inquiry-based practices. Ten groups of students (n= 36) participated in the study. I relied upon a mix of quantitative and qualitative data analysis strategies. Quantitative data analysis indicated that social coordination had a bearing on the ways by which groups took up opportunities to engage with technological affordances. Importantly it helped in classifying groups on the basis of level of engagement they demonstrated. Qualitative data analysis in the form of in depth video-analysis (of groups of students as they engaged with affordances of two computer supported technologies) confirmed that quality of engagement determined uptake of opportunities. Findings suggested that highly engaged groups ensured that opinions from all its members were integrated in discussions, considered numerous possibilities in terms of hypotheses testing and focused on understanding connections between components in context to the assigned problems. In contrast, moderate-to-low quality engagement led groups to pay attention to superficial features of the task.

This finer grained approach to analyzing students' collaborative engagement, led to the final study that tested my conjecture that group engagement with technologies have a bearing on individual transfer of reasoning skills. The final study (Chapter 4) sought to explore how students' collaborative engagement drives the group to pay attention to specific aspects of mechanistic reasoning. Participants of the study were the same who were part of the second study on collaborative engagement (n=36). For the purpose of this study, I focused my attention on four case studies. Two case studies were members of groups that demonstrated high quality engagement with the computer-supported technologies. To observe possible variations in terms of individual transfer, the remaining two case studies were from groups that displayed low-quality engagement. Specifically I focused on analyzing influence of engagement on developing an understanding of MR and subsequent usage of this reasoning skill to solve new problems. Mixed methods data analysis strategies highlighted group engagement and individual transfer. Findings from this study demonstrated that individual transfer was not entirely dependent on group engagement. It reflected the importance of individual cognitive level, interaction with peers, tools and artifacts as key factors that determined the extent to which individuals engaged in mechanistic reasoning and used it to make sense of novel problems.

Findings from all three studies have the potential to guide decisions about design of curriculum and technologies that encourage learners to engage in inquiry-based practices. By identifying aspects of the learning environment that draw the learners' attention to notice aspects of mechanistic reasoning and sustain high quality participatory practices can inform educational researchers and practitioners about student learning and transfer. Although this dissertation focuses primarily on engaging in MR in the context of aquatic ecosystems, the broader implications of this work are applicable to other areas of science education.

Chapter 2:

Conceptual Representations for Transfer:

A Case Study Tracing Back and Looking Forward

Abstract

A primary goal of instruction is to prepare learners to transfer their knowledge and skills to new contexts, but how far this transfer goes is an open question. In the research reported here, we seek to explain a case of transfer through examining the processes by which a conceptual representation used to reason about complex systems was transferred from one natural system (an aquarium ecosystem) to another natural system (human cells and body systems). In this case study, a teacher was motivated to generalize her understanding of the Structure, Behaviour, and Function (SBF) conceptual representation and modify her classroom instruction and teaching materials for another system. This case of transfer was unexpected and required that we trace back through the video and artefacts collected over several years of this teacher enacting a technology-rich classroom unit organized around this conceptual representation. We provide evidence of transfer using three data sources: (1) artefacts that the teacher created (2) in-depth semi-structured interview data with the teacher about how her understanding of the representation changed over time and (3) video data over multiple years, covering units on the aquatic ecosystem and the new system that the teacher applied the SBF representation to, the cell and body. Borrowing from interactive ethnography, we traced backward from where the teacher showed transfer to understand how she got there. The use of the actor-oriented transfer and preparation for future learning perspectives provided lenses for understanding transfer. Results of this study suggest that identifying similarities under the lens of SBF and using it as a conceptual tool are some primary factors that may have supported transfer.

2.1 Introduction

The aim of transfer research is to identify instructional conditions that prepare learners to apply what they have learned to new contexts. As designers of learning environments, we seek to create tools to facilitate transfer. We argue that one such tool is the use of conceptual representations to organize instruction by allowing students to develop a means to think about conceptual elements in a more generalised way (Liu & Hmelo-Silver 2009). In addition, our prior research suggests that use of certain conceptual representations can promote understanding complex systems.

Helping students and their teachers develop an understanding of complex systems is a difficult yet important component of scientific literacy (Sabelli 2006). Given the ubiquity of complex systems in the natural world, transferring ideas about complex system learning in one context to another is critical for the development of scientific thought. In many cases the behaviour of system components can affect its overall function, through emergent processes and localized interactions (Jacobson & Wilensky 2006). These interactions are often dynamic and invisible which make them difficult for learners to understand and present instructional challenges for teachers (Feltovich et al. 2001; Hmelo-Silver et al. 2007).

Here, we define systems thinking as being able to understand how bounded phenomena arise through considering the interactions and relationships among these interdependent structures, behaviours, and functions. There is evidence to suggest that students find it especially challenging to think about: (1) the interactions between visible and invisible structures, (2) the effect of their dynamic behaviours on overall functions, and (3) being able to extend their thinking beyond direct causality of complex systems (Grotzer & Bell-Basca 2003; Hogan 2000; Hogan & Fisherkeller 1996; Jacobson & Wilensky, 2006; Leach et al. 1996; Reiner & Eilam

2001).

In the research presented here, we investigate an unexpected case of transfer in a teacher--as the learner—who had been involved in a long-term classroom research project and appropriated the conceptual representation from the researcher-developed units to develop new instruction. This is particularly notable because teaching about complex systems is often difficult for teachers (Hmelo-Silver et al., 2007).

Although our research focused on the use of conceptual representations as a tool for learners, it also appears that it can be a tool for teachers to deepen their own understanding of complex systems (Liu & Hmelo-Silver 2009; Goel et al., 1996). Specifically we discuss how Structure-Behaviour-Function (SBF) served as a conceptual representation that promoted transfer across different complex system (Goel et al., 1996). Structures are defined as the components of a system, behaviours as the mechanisms or processes that occur within a system and functions as system outcomes (Goel et al., 1996; Machamer et al., 2000). We developed technological tools using the SBF representation that make these features of complex systems salient (Hmelo-Silver et al., 2007; Liu & Hmelo-Silver 2009; Vattam et al. 2011). Our study draws attention to a teacher's journey of understanding SBF as a conceptual tool, using it in the context of a technology-intensive science curriculum and her initiative to appropriate SBF as a conceptual representation beyond what we designed it for and use it meet her local curricular needs.

2.1.1 Research Goals

This study focuses on two main research questions:

1. How does a middle school science teacher develop her understanding of SBF as a representational tool?

2. How does generalization of SBF prepare her to make sense of a new complex system?

Specifically the focus of this study is to understand the means by which the teacher takes up opportunities to generalize her understanding of SBF as a representational tool to view similarities between two systems; one provided by researchers and one designated by the teacher. To understand the conditions that facilitated transfer, we need to view it through a lens that magnifies this teacher's learning trajectory. To focus on the dynamic nature of transfer, we did not see a traditional model of transfer as a productive lens. Traditional transfer researchers consider decontextualized expert knowledge, independent of how learners construe meaning in situations (Cobb & Bowers, 1999; Greeno, 1997). Because our objective was to highlight the processes the teacher used to understand and transfer a conceptual representation, we needed to consider alternative transfer models. Such models should illuminate the interactions that were meaningful and engaging for the teacher and subsequently, lead her to generalize her learning experience.

2.2 Literature Review

We consider transfer from both an actor oriented approach (Lobato 2004, 2006) and a preparation for future learning perspective (Bransford & Schwartz 1999) to investigate a teacher as a learner applying knowledge in a new curricular unit. Lobato (2003, 2006) proposes that shifting from the observer's (expert's) perspective to considering how the actor (learner) perceives similarities between the new problem scenarios to prior experiences is a useful tool to understand transfer. Evidence for transfer from this perspective is found by scrutinizing a given activity for any indication of influence from previous activities.

Moreover, we investigate how a greater understanding of SBF representations might have contributed to transfer from a preparation for future learning (PFL; Bransford & Schwartz, 1999) perspective. The PFL perspective focuses on the strategies used by learners in knowledge rich environments and their ability "to learn a second program as a function of their previous experiences" (Bransford & Schwartz, 1999, p. 69). This provides a framework for evaluating the quality of particular kinds of learning experiences and the feedback they provide. Feedback is a powerful factor in preparing students to make sense of instructional materials, help them in knowledge construction and as a result facilitate transfer of skills needed to unpack novel problems (Moreno, 2004; Tan & Biswas, 2006). Like other alternative perspectives on transfer (Konkola, Tuomi-Grohn, Lambert, & Ludvigsen, 2007), the classroom context and activity is an important factor in promoting transfer).

We add to the transfer literature by exploring the use of the SBF as conceptual tool for abstracting systems thinking. That is, the conceptual tool can be used to make sense of complex systems by thinking about macro and micro level connections either independently or at multiple levels of intersections. We make the conjecture that SBF as a conceptual tool can serve as a focusing phenomenon, which makes it suitable for integrating the AOT and PFL lenses of transfer as we describe in the next section. In this study, we investigate how the experiences that lead to successful generalization of SBF as a conceptual tool prepared the teacher to keep refining her systems thinking.

2.2.1 Supporting Transfer through Focusing Phenomena

Lobato et al (2003) propose that *focusing phenomena* support transfer by prompting students to generalize their learning. As a concept they define focusing phenomena as "observable features of the classroom environment that regularly direct attention to certain mathematical properties or patterns." (p.2) They attribute a combination of factors such as curriculum materials, artefacts, teacher's instructions as important for directing and focusing students' attention towards the intended content. In the context of this study, we extend the notion of focusing phenomena to science.

We propose that SBF serves as *focusing phenomena* (see Figure 2.1) to advance systems thinking. It helps the teacher focus her attention on understanding connections between multiple structures, their functional roles within the complex system and the behaviours they exhibit. Here, we consider the importance of generalizing SBF as a tool for transfer.

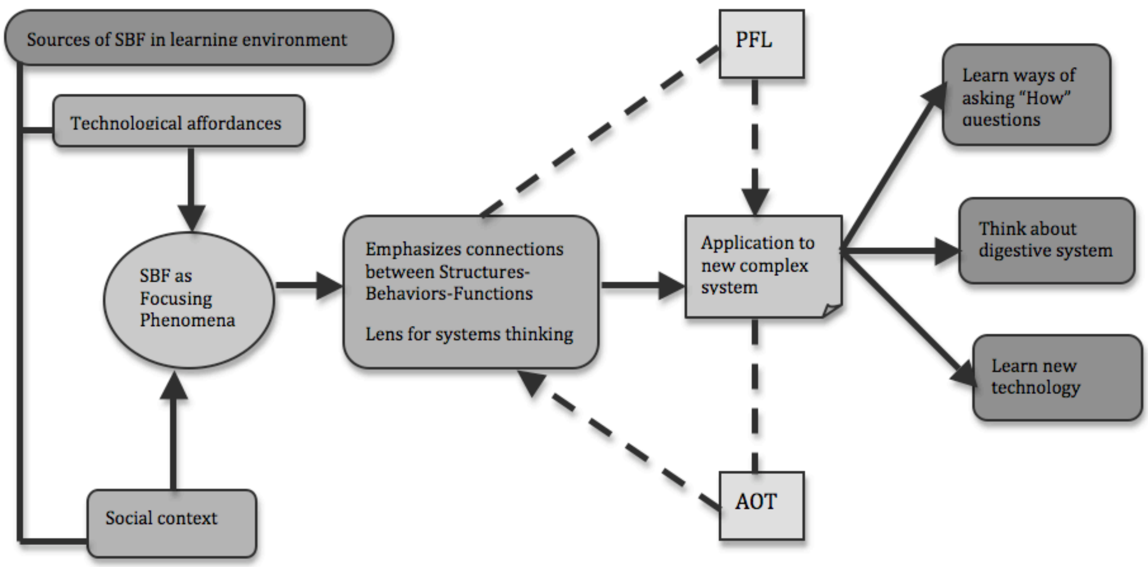


Figure 2.1 SBF as Focusing Phenomena

From an AOT perspective, SBF as a *focusing phenomena* highlights what is similar between two complex systems i.e. the aquatic ecosystem (introduced by the researcher) and human digestive system (introduced by the teacher). It helps concretize the idea that biological systems are similar to ecosystems in terms of interacting at multiple levels. Using this framework affords the teacher opportunities to focus on the connections that exist between various organs of the digestive system. Specifically, it directs the teacher's attention to the ways that "structure and function in biological systems are causally related through behavioural mechanisms" (Hmelo-Silver et al., 2007; p. 308). The teacher's understanding of SBF in the classroom mirrors her understanding of systems thinking. This is important for us, as researchers, as it lets us trace the teacher's learning trajectory. From a PFL perspective, thinking in terms of SBF prepares learners to understand that behaviours are mechanisms and processes that enable structures to achieve their functions in biological systems (Bechtel & Abrahamson, 2005; Machamer, Darden, & Craver, 2000). In the remainder of the paper, we present a case study that considers how several aspects of the learning environment influenced the teacher's generalization of SBF as a conceptual tool.

2.2.2 A Case of Transfer: The Instructional Context

This study is part of a larger research program, which is a technology-intensive curriculum unit centred on an aquarium based aquatic ecosystem. The curriculum provides multiple opportunities for learners to develop and deepen their understanding of SBF as a conceptual tool. First, technological tools such as the RepTools toolkit (Hmelo-Silver et al., 2011) and the Aquarium Construction Toolkit (ACT; Vattam et al., 2011) were designed: (1) to help learners think about aquatic ecosystems in terms of structures, the functions they perform within the system and the behaviours they exhibit to perform the functions (2) teach about the aquarium ecosystems using SBF as a conceptual tool for a period of 4 years, and (3) engage in active discussions about the concept and ways to teach it with the research team present daily in the classroom and at the annual professional development workshops.

SBF Tools

The RepTools toolkit includes a function-oriented hypermedia (Hmelo-Silver et al., 2007; 2009; Liu & Hmelo-Silver, 2009) organized in terms of SBF representation and Net Logo computer simulations (Wilensky & Reisman, 2006). The hypermedia (Figure 2.2) introduces the aquarium system with a focus on functions and provides linkages between structural, behavioural and functional levels of aquariums. It is organized around what, how, and why questions which correspond to structures, behaviors, and functions.

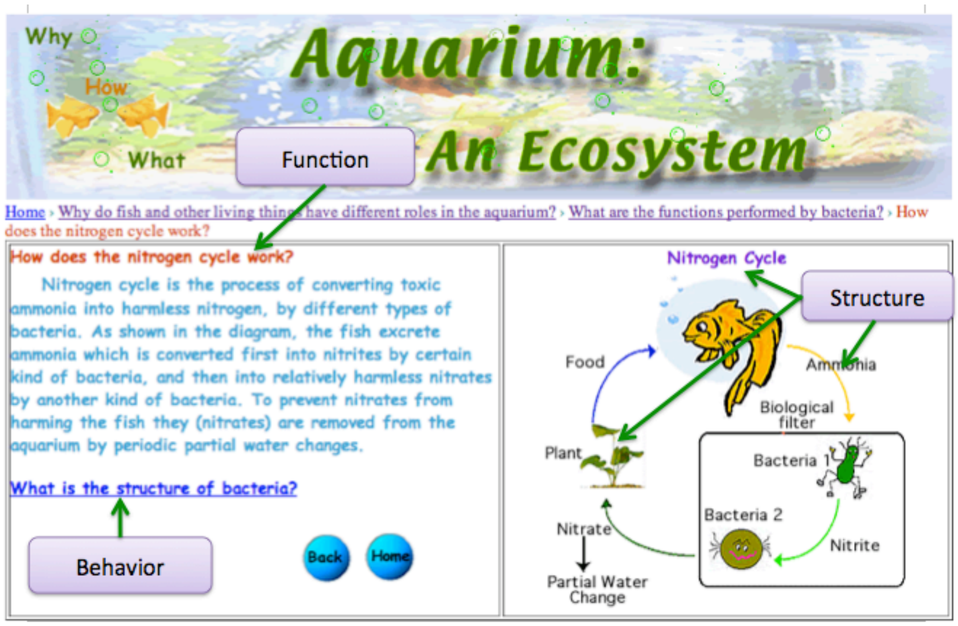


Figure 2.2 Aquarium Hypermedia

Two NetLogo simulations allow learners to explore macroscopic processes of fish reproduction (i.e., the *fishspawn* simulation, Figure 2.3 a) as well as microscopic processes (the *nitrification* simulation, Figure 2.3 b) that represent the chemical and biological processes in the aquarium. The simulations provide a context for learners' investigation of the aquatic ecosystem. They afford opportunities for designing experiments, manipulating variables, making predictions, and discussing conflicts between predictions and results. Each simulation allows learners to explore key features that are relevant to the process of fish spawn or nitrification cycle.

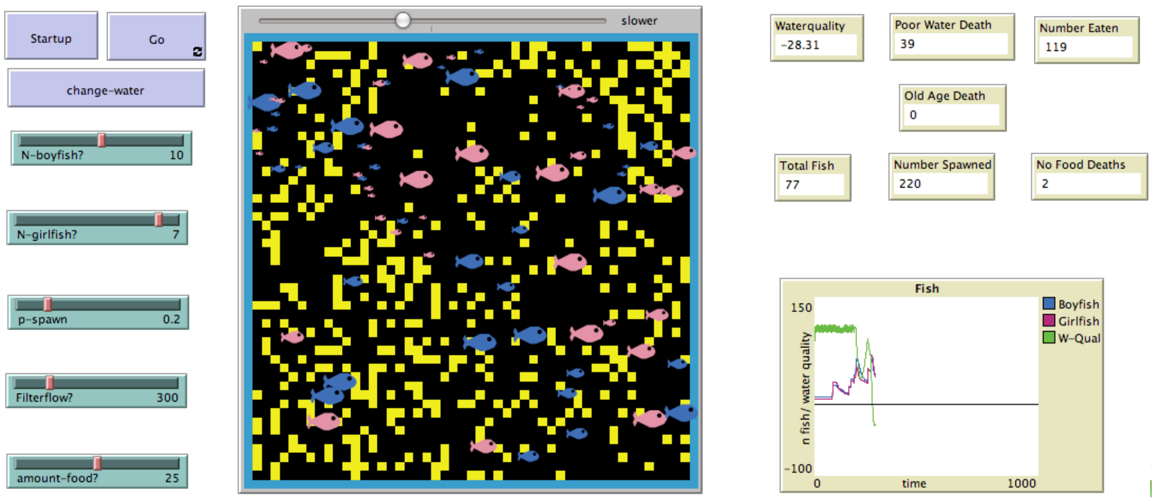


Figure 2.3a Macro level- Fish spawn simulation

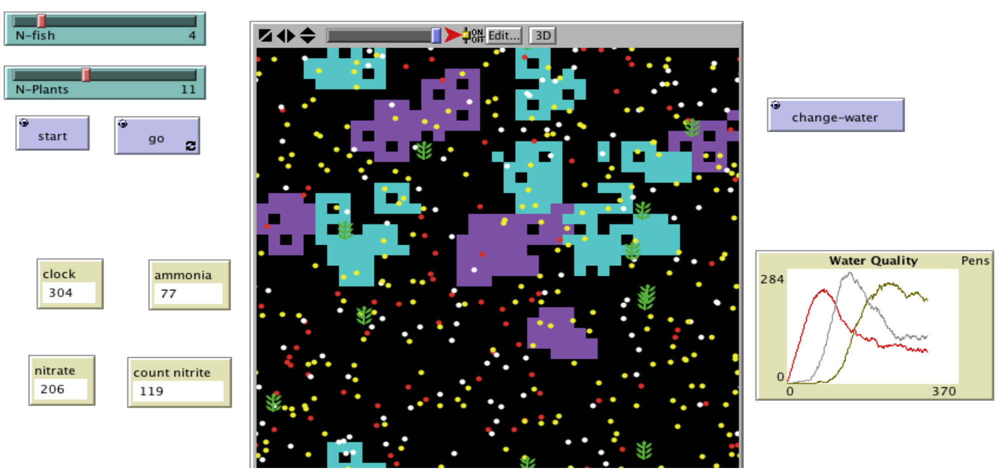
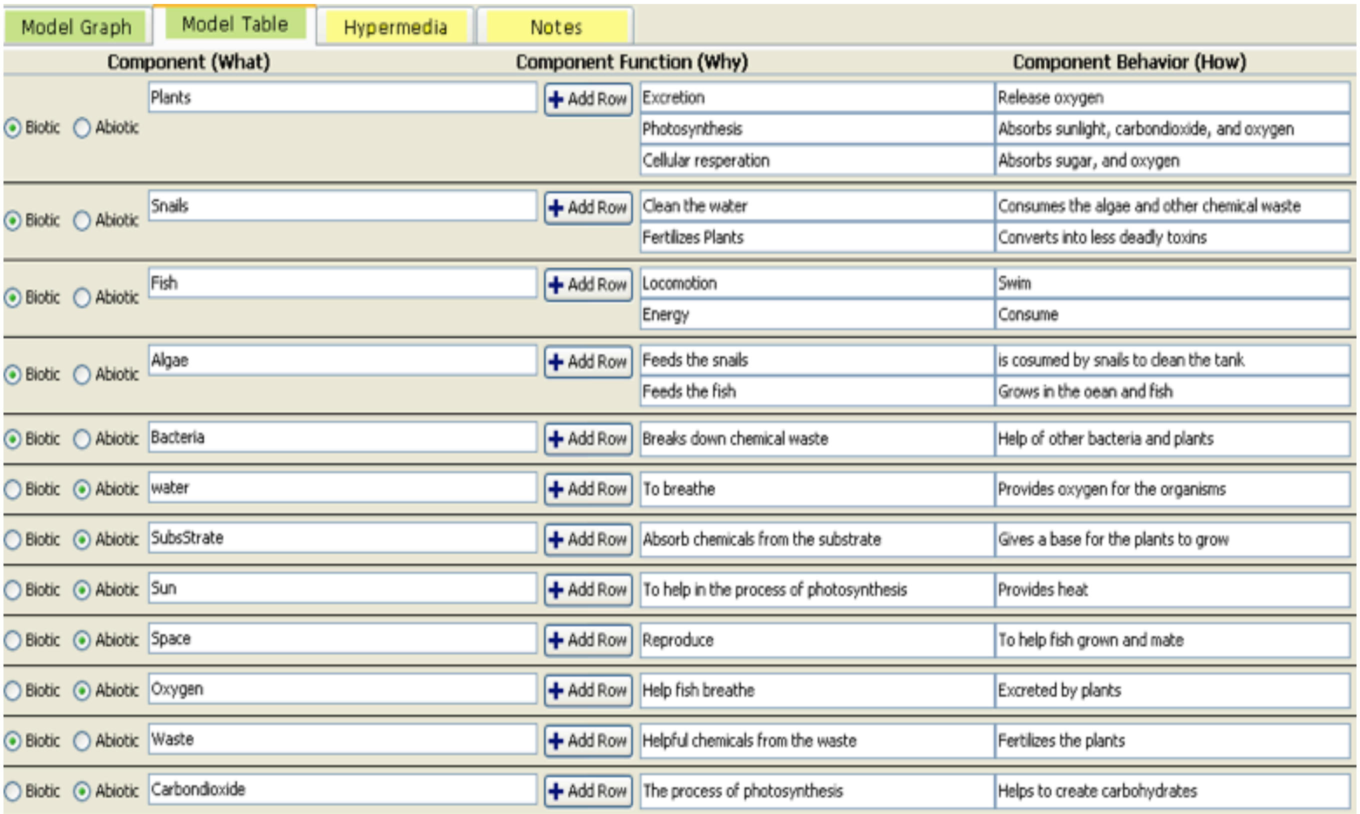


Figure 2.3b Micro level – Nitrification simulation

The second component to the learning environment, ACT is designed to promote construction of SBF models (Vattam et al., 2011). Models can be constructed either in a table (Figure 2.4 a) or graph (Figure 2.4 b) format. The model table focuses learners' attention on thinking about various structures in an ecosystem. The three column table affords the opportunity for learners to think about the structural components and their multiple behaviours and functions.

This is valuable because learners get an opportunity to understand both individual mechanisms in the system and the meta-level concepts related to complex systems.



Model Graph | Model Table | Hypermedia | Notes

Biotic / Abiotic	Component (What)	Component Function (Why)	Component Behavior (How)
Biotic	Plants	Excretion	Release oxygen
		Photosynthesis	Absorbs sunlight, carbondioxide, and oxygen
		Cellular resperation	Absorbs sugar, and oxygen
Biotic	Snails	Clean the water	Consumes the algae and other chemical waste
		Fertilizes Plants	Converts into less deadly toxins
Biotic	Fish	Locomotion	Swim
		Energy	Consume
Biotic	Algae	Feeds the snails	is cosumed by snails to clean the tank
		Feeds the fish	Grows in the oean and fish
Biotic	Bacteria	Breaks down chemical waste	Help of other bacteria and plants
Abiotic	water	To breathe	Provides oxygen for the organisms
Abiotic	SubsStrate	Absorb chemicals from the substrate	Gives a base for the plants to grow
Abiotic	Sun	To help in the process of photosynthesis	Provides heat
Abiotic	Space	Reproduce	To help fish grown and mate
Abiotic	Oxygen	Help fish breathe	Excreted by plants
Biotic	Waste	Helpful chemicals from the waste	Fertilizes the plants
Abiotic	Carbondioxide	The process of photosynthesis	Helps to create carbohydrates

Figure 2.4a Sample ACT Model Table

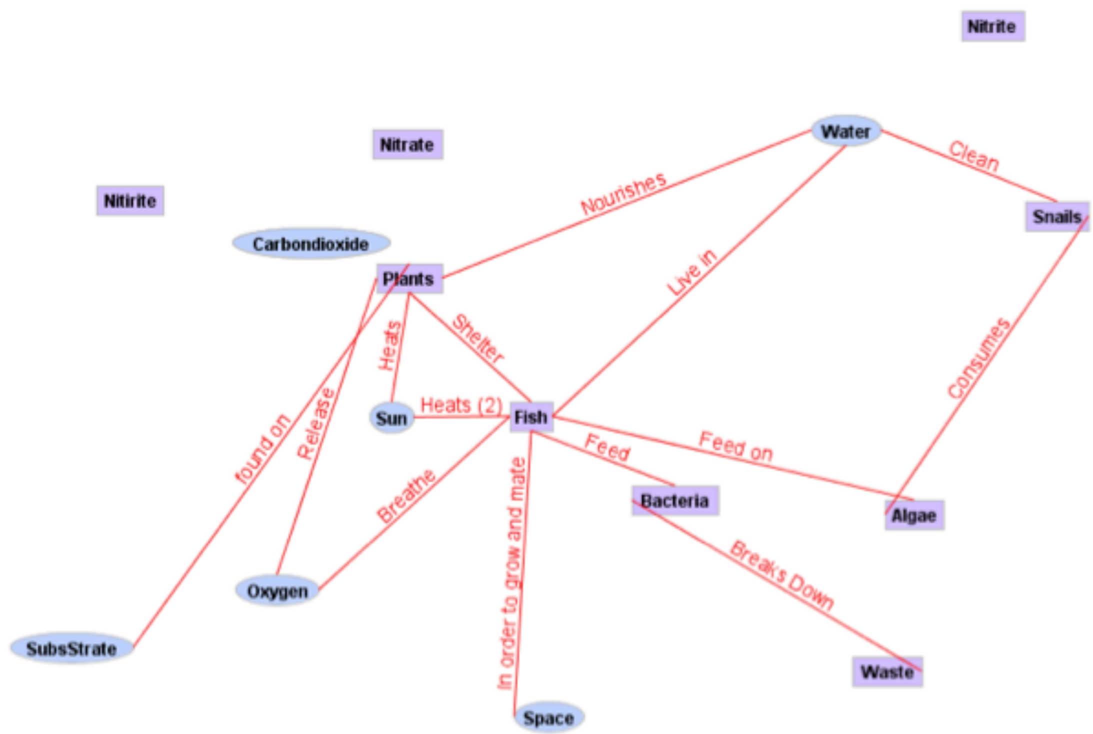


Figure 2.4b Sample ACT Model Graph

The ACT model graph is a platform for learners to create models of their evolving understanding of ecosystem processes in terms of SBF. As students read through the hypermedia, generate and test their hypotheses with the simulations, they integrate the critical structures with their behaviours and functions in ACT models.

2.3 Methods

We used a case study approach to characterize how a science teacher, Ms. Y, appropriated her understanding of SBF as a representational tool and applied it to make sense of a new complex system. Case study methodology allowed us to use multiple data sources to study this complex phenomenon in context (e.g., Stake, 1998; Yin, 2009). Borrowing from interactional ethnography (Castanheira, Green, & Yeager, 2009) we began at the end—the SBF hypermedia that Ms. Y constructed. The unit of analysis for this case is the individual teacher in her classroom context over several years. Through this approach, we used multiple sources of data to trace the social and cognitive events that occurred over time and led Ms. Y to see SBF as a tool she could appropriate for her teaching practice. Although this was not an ethnography, we borrowed the logic of this inquiry approach to understand how the disciplinary content that an individual within a social context constructed particular knowledge over time (Bridges, Botelho, Green, & Chau, 2012).

2.3.1 Context

Ms. Y taught seventh grade science at a public middle school in North East United States. She had been teaching science for 26 years and had a Bachelor's degree in Elementary Education. This study was part of a larger 4-year study focused on teaching middle school science students about aquatic ecosystems. Ms. Y participated in annual professional development (PD) workshops. The PD focused on concepts related to aquatic ecosystem and analysis in terms of SBF as well as the technological tools that she would need to use in her classroom. During the PD, Ms. Y. had the chance to share her pedagogical challenges and experiences, such as difficulties in using the software or teaching about SBF as a conceptual tool.

Ms. Y had been using the RepTools and ACT in an aquarium curriculum for four years when she informed us that she wanted to develop her own instructional tools using the SBF representation to teach about cell and human body systems. This prompted her to collaborate with her colleague, another science teacher, Ms. T. Together they used Microsoft Power Point to create a human body system presentation, modelled after the function-centred aquatic hypermedia. We refer to it as the *teacher created hypermedia*. Given their limitations in terms of technical knowledge in designing a hypermedia similar to the one we had created, the teachers hyperlinked key words in their power point presentation and follow up questions to point to relevant slides.

Ms. T also taught seventh grade science in the same school. She was a new teacher with one year of teaching experience. Ms. T had a science education background. While she collaborated with Ms. Y, she also attended the annual PD and implemented the same technology intensive curriculum on aquatic ecosystem in her classroom.

Each teacher taught four diverse seventh grade classes with approximately twenty-five students in each section. During the curriculum implementation the students were grouped together in small heterogeneous groups.

2.3.2 Data sources

We had three primary sources of data. First was the artefact that the teacher created (this indeed was the impetus for our research). Second, we conducted a semi-structured interview with the two teachers, Ms. Y & Ms. T. Finally, we used video data of classroom interactions. These videos were drawn from classroom data from a long-term (i.e., four year) research project. These helped us to understand: (1) why the teacher transferred her generalizations of SBF representations to new instructional domains and (2) how she transferred these understandings. We interviewed Ms. Y & Ms T approximately two months after Ms. Y completed teaching about both systems. The primary focus of the interview was to understand how she conceived the idea of extending the computer-based representational tools beyond what was expected from her, the influence of her prior knowledge during this process, and her attempts to prepare herself to solve new challenges.

Following Powell, Francisco and Maher's (2003) recommendations for video analysis, we searched video to identify critical events. In an attempt to trace and track the nature of Ms.

Y's generalizations of SBF we selected representative clips of critical events from her classroom that demonstrated evidence of her developing understanding and generalization of SBF representations as a tool to teach about another complex system. These video clips included whole class discussions that Ms. Y had with her students while: (1) introducing the SBF representation for the aquatic ecosystem in Year 3 (i.e., the year before she created the digestive system unit), (2) introducing the SBF representation for the aquatic ecosystem in Year 4 i.e. the year she employed the digestive system unit, and (3) explanation of SBF representations and modelling of the digestive system unit. We viewed a total of nine clips that consisted of three classroom interactions for each of the three kinds of whole class discussions.

2.3.3 Data analysis

We examined classroom interactions that highlight Ms. Y's learning trajectory with SBF as a representational tool. The video data were analysed using Interaction Analysis (IA; Jordan & Henderson 1995), which involved collaborative viewing of video clips by six members of the interdisciplinary research team. We successively conducted nine IA sessions to collaboratively review the selected video clips, describe observations, and generate hypotheses. Any differences in opinions were resolved by discussions. This helped ensure the trustworthiness of our interpretations through the initial independent interpretations of the IA session participants and the subsequent discussions.

During the IA sessions we focused our attention on two specific aspects of Ms Y's practice. First, we paid attention to patterns and variations in the ways that she introduced the SBF as a conceptual tool in relation to the aquatic ecosystem across the four years. Specifically, we examined her explanation of the concept, the analogies she presented and whether or not she sought help from any external resources, such as researchers in the classroom or Ms T.

Second, we focused on how she introduced SBF as a conceptual tool in the context of the human body unit. At this time we made comparisons between the ways the topic was introduced in the aquatic ecosystem with the human body system. We also looked for similarities in terms of analogies. In particular, we wanted to understand if and how her prior knowledge of SBF prepared her to discuss this particular complex system with ease and confidence.

To gain a holistic perspective of the teacher's journey we also examined the interview transcript. We looked for themes related to the mechanisms by which transfer occurred in the ways in which the teacher constructed similarities between aquarium and digestive systems. This allowed us to triangulate the teacher's perspective with the IA and artefact analysis.

2.4 Findings

Based on our analysis of the interview and video data we identified themes related to AOT or PFL perspectives. These findings helped strengthen our understanding of the processes Ms. Y used to generalize SBF as a representational tool and observe how it prepared her for the transfer. The AOT perspective provided a framework to trace Ms. Y's evolving understanding of using the SBF lens as a tool to make sense of aquatic ecosystem. The PFL perspective demonstrated how Ms. Y transferred and used her knowledge of SBF to make sense of a complex system that was outside the scope of our research.

Tracing and Tracking Ms Y's Understanding of SBF from an AOT lens

Orientation to the SBF representation led by the teacher. Ms Y's journey began with using the ACT tool. The ACT technology enabled construction of SBF representations using the Model Table (Figure 2.4a). The tool introduced the students and Ms. Y to the language of SBF representations. Initial data analysis of the whole class video revealed that the teacher's introduction of the SBF representation played a critical role in students' conceptual understanding of the complex system. She presented the idea that the SBF representations captured interconnected entities within a complex system while completing ACT table:

1. Ms. Y: Alright, so the first thing yours say is fish right? So, lets go back and tell me what is the behaviour of the fish?
2. Student: Releases waste.
3. Ms Y. OK. So the fish releases waste. Right? Alright, so it, it releases what kind of waste?
4. Students (in unison): Ammonia.
5. Ms. Y: Right, so you have that in there right? Now. What is the function?
6. Students (in unison)*:* Remove toxins from the body.
7. Ms. Y: Okay. So we want to get these things out of the fishes' body. Now next, the next one is what?
8. Students: Ammonia.
9. Ms. Y: Ammonia. So, put, put ammonia here. Alright, so now, what is, what is the behaviour of the ammonia? What's it do if you look at it in the tank?
10. Student: Water?
11. Ms. Y: Yeah, it's just floating around right? What's its function do? It's food for bacteria. So it has its purpose right? So the next one on our list which is blank on yours will be what?

In this excerpt, Ms. Y drew the students' attention to the functions and behaviours of various structures present in the aquarium. The students identified structures such as fish (turn 1) and ammonia (turn 8). Next she prompted them to think about their behaviours and functions. In turn 2, the students respond that the behaviour of the fish is to release waste. She pushed them to think in detail about the kind of waste (turn 3) and the function or overall purpose of this behaviour (turn 5). In turn 11, she clearly articulated that structures have a function within complex systems. Although this is a somewhat mechanical application, it also allowed her to begin to see how the SBF lens might serve as a tool for understanding systems.

We speculate that this discussion prepared both the students and Ms Y. to use the SBF conceptual representation to understand the interconnectivity between various structures within complex systems. This initial understanding of SBF as a representation may have prepared Ms. Y to appropriate SBF as tool when she collaborated with her colleague to create a new learning tool i.e. the teacher-created hypermedia.

Teacher-created hypermedia. Just as the orientation to SBF was the starting point, the case study was bounded by the artefact that Ms. Y created at the other end. Ms Y., in collaboration with her colleague Ms. T, created new hypermedia in the form of an interactive PowerPoint of the cell and body systems mirroring the aquarium hypermedia developed by the research team (Figures 5a and 5b). The teachers' hypermedia outlined the different structures in the system along with orienting *why* and *how* questions. The *how* questions were directed towards behaviours of system components and the *why* questions focused on functions. The teachers created this hypermedia as a learning resource to help students connect cell systems to larger body systems. The research team did not plan either the body system hypermedia or the use of modelling these systems using the ACT software; the teachers did this of their own volition.

The development of the cell hypermedia demonstrated multiple ways by which Ms. Y generalized and transferred her understanding of SBF as a conceptual tool. First, understanding the SBF of the aquatic ecosystem prepared her to teach it better in successive years and second, she was able to modify the learning environment (i.e., by changing them physically–from an aquarium hypermedia to a cell hypermedia and by seeking resources) into something that was more compatible with her current goals.

Identifying similarities through SBF representations. Ms. Y's initiative to extend and appropriate our research and develop additional classroom instruction suggested that the SBF representation was becoming a tool for her to see similarities across complex systems. Adopting an AOT perspective helped us understand how she constructed similarities between what she had been teaching for several years (the aquatic ecosystem) to the current unit she developed (cell and body systems). This perspective helped us recognize which connections she made, on what basis, and how and why those connections were productive (Lobato, 2004). For example, consider Ms. Y's response when asked about the utility of their hypermedia during the interview session:

> Right, and it's a hard concept to get. So, what we were thinking about is like the kids actually think when they eat food it breaks down and then leaves the body. They don't get that the food has to go to the cells and the cell actually works and creates energy from this food and then there's a waste and it sends that back to the body for it to be excreted. So we're trying to give them not only the names of the parts and what each part does individually but how it needs to work-...And we're doing the behaviour not only of the cell itself but behaviour of all the systems and then the behaviour of the whole body. And the cells are all part of that whole body.

This highlights that Ms. Y understood that the cells were an integral part of the body systems and could not be taught in isolation. Earlier, she noted that systems in the body are not disconnected and have complex mechanisms that allows for higher order operation. This provided evidence that she now understood how structures within a system perform multiple behaviours in order for it to function effectively. The IA results showed how Ms. Y introduced the SBF representation and refined her thinking over multiple years.

Refining the SBF representation as a conceptual tool. From an AOT perspective we needed to track Ms. Y's transition from her initial naïve ideas about SBF representations to a more expert conception. The results from the IA indicated that Ms. Y's understanding of the SBF representation as a conceptual tool changed. She used several distinct strategies to introduce the topic of complex systems ranging from discrete (i.e., in Years 1, 2 and 3), to acknowledging complexity (in Year 4), and finally providing a systems perspective with her new cell/body unit. In the first three years, she introduced to the SBF representation to her students by mentioning the new terminology being used to understand the aquatic system. However, she introduced structures, behaviours, and functions as discrete constructs. In Year 4, she espoused a coherent view of SBF representation as a conceptual unit. Later that year, while introducing SBF in the context of the unit on cells and body she explained SBF as a system, complete with nested and interconnected subsystems.

Year 3: SBF representations. Ms. Y's early introduction to SBF representation suggested a focus on linear connections. This was shown by the way in which she filled out the ACT SBF table (Figure 2.4 a) in front of the classroom. As a way to connect ideas about SBF she drew clear conceptual lines between one structure at a time and all the behaviours exhibited by that structure as the following example shows:

> We just named them all yesterday. The heater, the fish, the plants. Those things are called the 'structure'. The next word we're gonna use is 'behaviour'. The

> behaviour is what the fish do. What do the things do in the tank? And the next word we're gonna use is 'function' okay? So what I want to do today is to start with structure and behaviour. So, I made a chart and the first column is the structure, or the parts. So everyone write down one of the things in the fish tank is fish and the second column I wrote was behaviour, and the third column I wrote was function. We're going to start with this second column that is behaviour. When I ask you the behaviour of something, I want to know is what does it do? "What do fish do?" Swims, eats, breathes, and poops. Okay, all fish swim. That is their behaviour okay. They swim. What else do fish do?

Here Ms. Y. described the meaning of the term "behaviour" somewhat superficially as "what fish do" rather than the more expert mechanistic view. She established linear connections between the structure (fish) and the multiple behaviours (swims, eats, breathes, poops) that this structure exhibits. After promoting an understanding of the behaviour exhibited by the structure (fish), she then drew another relationship between each individual behaviour in the last column to indicate the behaviour's function.

Year 4: SBF representations are interconnected. Over time, Ms Y's introduction to the SBF representation became richer and more complex. In the excerpt below taken from a whole class discussion in year 4 she described structures, behaviours and functions as interconnected entities within a system, rather than discrete elements on a worksheet:

1. Ms. Y: Okay, now, let's do the filter. I'm gonna do the filter with you and then you're gonna do one on your own. All right, so what does the filter do? What does the filter do? Jim what does the filter do?
2. Jim: Um, cleans out the tank

3. Ms. Y: Cleans the tank. Or cleans the “what part of the tank?”
4. Jim: The water in the tank?
5. Ms. Y: All right, so the filter will clean the water. Okay? Now, why does it clean the water?
6. Jim: So it can put more oxygen into the water?
7. Ms. Y: No. That's another thing that it does. It actually, because it's spinning around, because it's spinning like this, it's actually, one of the things it does…is it adds oxygen to the water. Now, this part here, why does it do it? First of all, I want to stop right here. The filter is this big grey thing here. Right? Now, first of all, how does it work? What's this big tube doing? *[Points to picture of filter on the screen.]*
8. Pat: Sucking up the water
9. Ms. Y: Sucking up the water. Then the water comes up here, right? And it gets sucked up and it goes back here and it pours back down. When it flushes back over that's when the oxygen from the air can get pulled back into the water. Okay, so how- you said it cleans the water- how does it do this?
10. Pat: Well, it has the filter. The filter has like chemicals and stuff.
11. Ms. Y: What do you think is in this bag?
12. Pat: Bad stuff
13. Ms. Y: Well, eventually the bad stuff is going to get in here, but actually there's charcoal in here, gravel in here. And then when the water flows through it, can it catch all the big chunks? Maybe the fish faeces and stuff like that? So, and then see how it spins back down here? Water splashes and it's pulling in the oxygen. So now, all right so now, why does it clean the water? What is the point of cleaning the water?

After turn13, the class went on to discuss the fish and the plants, how the filter aerates the tank and how it affects the whole system. In turns 3 and 5 when Ms. Y discussed the behaviours (the mechanism that cleans water in tank) and function of the filter (by collecting faeces from fish) she was guiding students' answers to structure, behaviour, and function simultaneously and filling in the chart appropriately, stressing relationships rather than focusing on any one aspect in isolation. Turns 6- 12 show that Ms. Y used student response to generate more questions that linked what and why questions throughout her classroom discussion, highlighting the system complexity.

Year 4: SBF representations at multiple levels of complex systems. Later in the same year, when introducing her unit on the cells to the class, Ms Y emphasized that SBF works as a whole across multiple levels of complex systems. As the next excerpt shows, she did so not directly, but more subtly through leading questions:

1. Ms. Y: Eventually what we want [the researchers] to do for us is allow us to model systems within systems. What happens if I can click on the cell and zoom in on that and put the cell parts in there? Because they don't have the ability to zoom right in on that one part, are there any ideas on how to connect the cell through modelling to the other body systems? Because you also want to go and look at the function. What do you think?
2. Lucia: Umm, what about if you like umm put a picture of the cell.
3. Ms Y: Yeah but I want to drive everything to the cell because that's, you know, the whole body operates to get things to the cell you know that right? But then I also want to show what the cell does inside once you send the food there. So how can I show that part…on this graph? Okay. You know how this is a system. The body parts

> and the cell is its own little mini system, how can I show the stuff inside the cell? Should I circle all the mitochondria right around the cell? Or should I pull the cell out and make that part separate? …

These demonstrate how Ms. Y refined her thinking about SBF as a conceptual tool. Whereas earlier, her focus was primarily in working with the aquatic ecosystem, she later introduced a new level of complexity by introducing the idea that there exists multiple 'mini systems' within the human body system. She still focused largely on structures but she also made connections to behaviours and functions. In addition, she helped students understand that one structure may have multiple behaviours and functions (in turns 1 and 3).

Comparing her SBF representation of the cell system here to that of the aquatic ecosystem in the earlier unit, she presented it to the class as a coherent system rather than discrete SBFs. In addition, when applying the SBF representation to the cell, Ms. Y introduced a meta-perspective by explicitly explaining that the task was to represent their ideas through modelling (in turn 1). Moving away from the isolated task provided in earlier (i.e., filling out the table by first listing structure followed by behaviour, and then function), Ms. Y explained that the students were organizing their knowledge in model graph. By placing emphasis on the modelling tool and providing students with the starting point of the structure, the cell, Ms. Y explained that the task was to develop a representation of their ideas about the human body system, using the table to organize their ideas and providing the students with leading questions that she had provided earlier when talking about the SBF representation in the aquarium unit.

This transition suggested that Ms. Y was an active learner herself. She frequently asked questions to the research team and Ms. T, to refine her understanding. This practice of asking questions had two effects. First, it helped Ms. Y identify and address the gaps in her understanding, which prepared her for future learning. Second, it shed light on the processes that she as an actor (learner) used to construct similarities between the aquatic ecosystem and cell system.

Experiences to Promote Transfer from a PFL Perspective

Recognition of teacher as a learner. In the interview, Ms. Y indicated that since the beginning of her involvement in the project, her knowledge continually developed. She explained that she was the primary source by which information was passed from the research team to the students and that over time she felt that she became more competent in this role. In the interview, she acknowledged her lack of mastery over the content and was aware that she refined her ideas of the SBF representation and the aquarium unit which lead to development of the new unit:

> Okay, my knowledge of this still develops every year because it's knowledge that [research team leader] had and it- you know- was her angle on something and then I had to try to understand what was going on in her head. So it's taken me many years of practice and talking to [research team leader], talking to [researchers in the room], to kind of get this. And I still do not feel like I'm really solid on it, but I get it more and more each year.

These statements demonstrated that Ms. Y saw herself as a learner in her classroom as she was looking critically at her current knowledge and beliefs. This experience prepared her to deepen her understanding of the content, and revise her ideas as she gathered new information.

Collaboration facilitates generalization. The collaboration aspect was beneficial during the inception, design, and construction of the teacher created hypermedia. Together they went beyond our research agenda by using SBF as a conceptual tool to create a power point presentation of human body systems. It afforded opportunities for sense making and focus on critical aspects of complex systems while working with the tools (Figure 2.5).

As Ms. Y talked about the creation of the cell hypermedia, she revealed that she was highly motivated to do so because of the potential for feedback and interaction with Ms. T. For example, when asked how the idea came about and the variables that affected the development of the new tool, Ms. Y responded:

> So then I kind of realized that what I needed to do was give her [Ms. T.] my idea and then hear from her what she would add to that and in turn that would- I would take what she added into my lesson, so one of us throws out like a main idea and then the other one builds upon that main idea and then we get a better idea. And that's how I think that the Hypermedia came along. Because this whole concept has been in my head for a long time, about how kids don't understand the whole body and the cells connection to the body. So I talked about it with Ms. T and then she started talking about making a Hypermedia and then we went back and forth on how we we're going to do it.

From a PFL perspective, people seeking multiple viewpoints about issues may be one of the most important ways to prepare them for future learning (Bransford & Schwartz, 1999). It is clear from this excerpt that Ms. Y. felt it useful that she could exchange her ideas and collaborate in the creation of the new hypermedia with Ms. T.

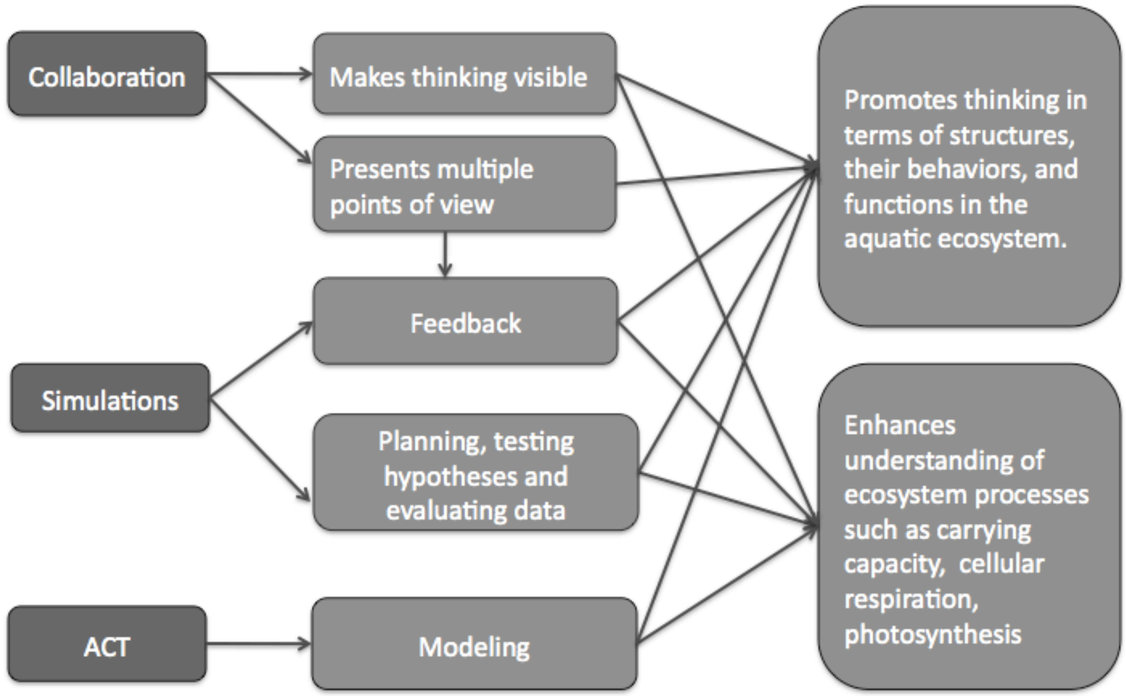
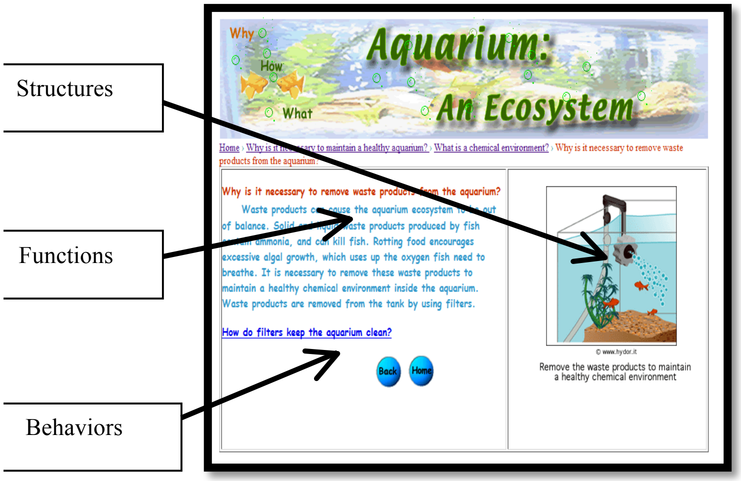


Figure 2.5 Affordances of the learning environment that promote SBF thinking

This finding suggests that Ms. Y. was able to see the possibilities for transferring her understanding of the SBF representation. However, this transfer was dependent on the idea of using hypermedia itself as a way to organize complex content in addition to the SBF representations. Our next set of results focus on elaborating how she used the aquatic hypermedia to guide her thinking about designing for another complex system.

Appropriating salient features of the aquarium hypermedia. When asked about what parts of the hypermedia she found useful in her own development, Ms. Y felt that working with the same Aquarium Hypermedia (Figure 2.6 a) for four years allowed her to incorporate some of the key features in the hypermedia she created (Figure 2.6 b). Although her hypermedia does not possess the technological and conceptual sophistication of the aquarium hypermedia, it prepared her for refining her model along a trajectory of increasing expertise.



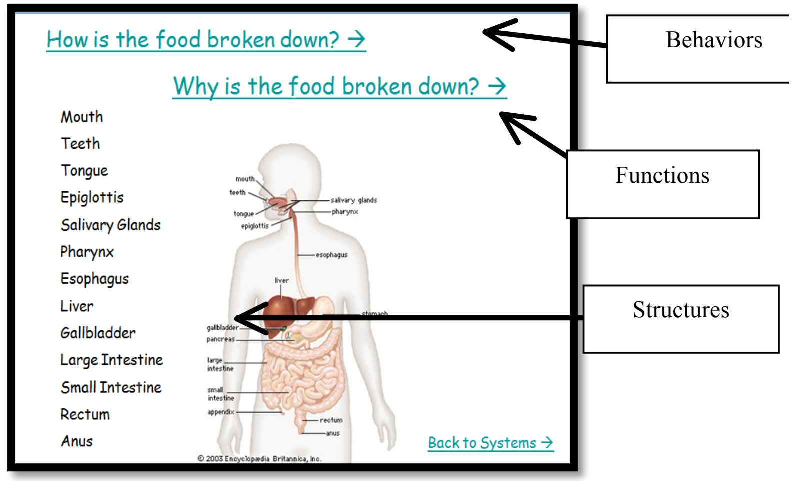


Figure 2.6a Researcher-developed hypermedia *Figure 2.6b* Teacher-developed Hypermedia

This process was important from an AOT perspective as it enabled her to see the connections between two situations by identifying the salient features from the earlier hypermedia environment (Lobato, 2004). It is notable that she transferred other features of the hypermedia structure beyond SBF, including the use of guiding questions as well as the use of short pieces of text accompanied by simple and relevant graphics:

> I would say that I definitely liked how each question lead to another question because that's how we modelled ours was every question gave an answer but then lead to another question and another question and another question…. We also used just short pieces of information because I think the kids get bored if you put too much it's overwhelming. We used pictures and then we also had it not only lead to different the next one and the next one but it bounced back sometimes a design in the hypermedia too.

From the interview it is clear that Ms. Y drew upon relevant features of the aquarium hypermedia. Although her rationale for keeping a short text is different from what we had in mind while designing the aquarium hypermedia, this process of experimentation is also helping her clarify her own thinking about the concepts that she is placing within the new hypermedia contexts (Bransford et al., 1990).

Appropriating ACT to model a new system. In addition to appropriating aspects of the Aquarium Hypermedia, Ms. Y also appropriated the ACT tool so that students could model body systems in the same fashion as they had for the aquarium system (see Figures 2.7 a and 2.7 b).

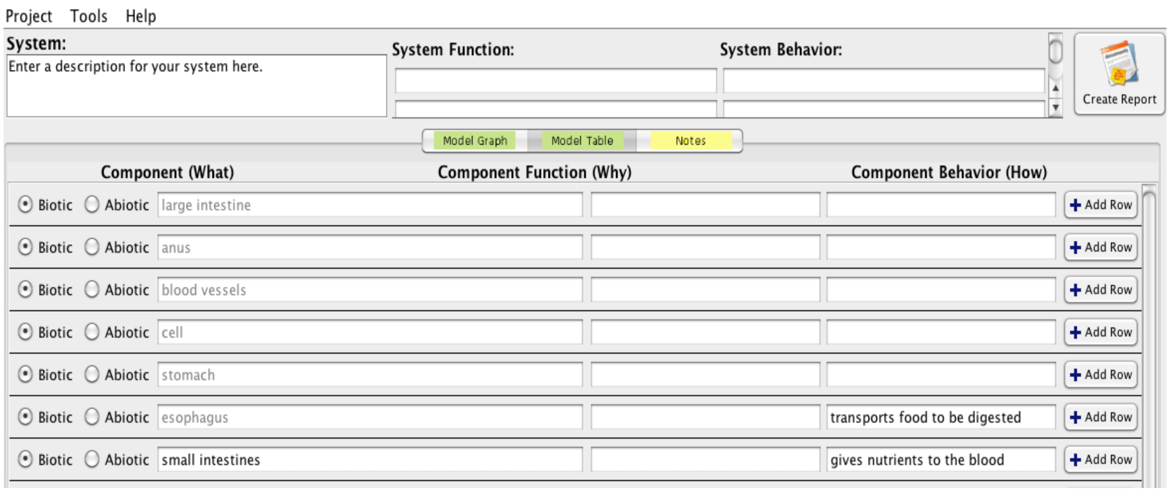


Figure 2.7 a. Digestive system ACT Table view

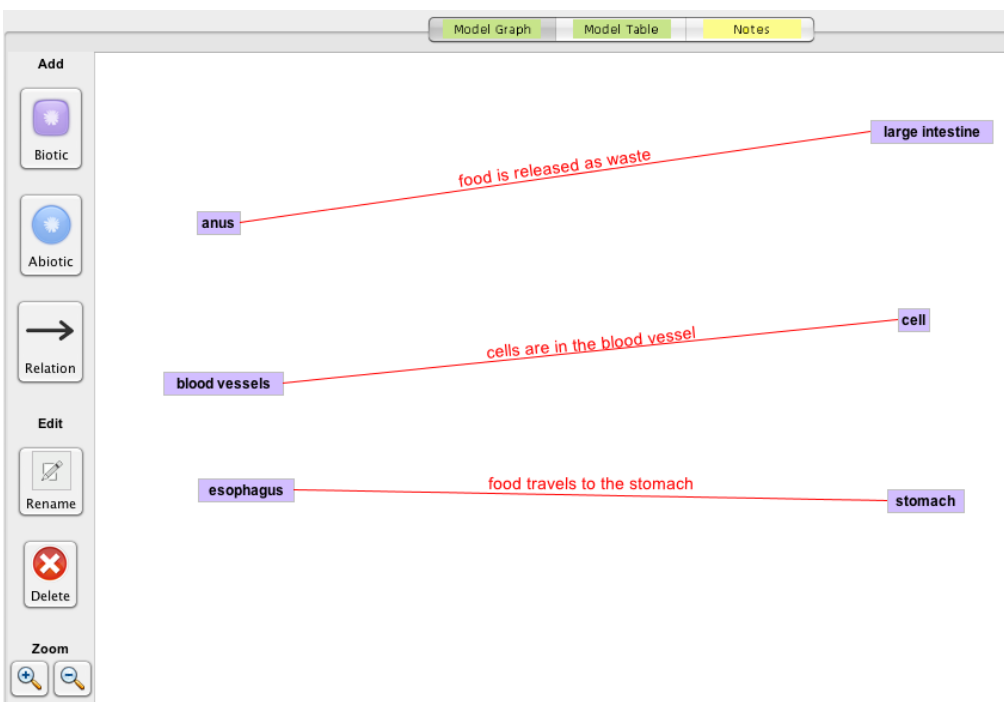


Figure 2.7 b. Digestive System ACT graph view

The following excerpt highlights Ms.Y's journey of trying to understand how to use SBF as a conceptual tool and the ACT technology itself and feel comfortable using it to teach by herself:

> At first she (research team leader) came and she was just testing the kids' knowledge and that I was not really involved. And then … we originally started talking about the cell and the body as that was an area she worked in, and then she got the idea of the respiratory system because that slowly developed into … the NetLogo and the Hypermedia. Back then structure, function and behaviour I think for me was all just disjointed. All the pieces were here and I was just trying to keep up with her. And then … the ACT program helped a lot because it sort of put everything together for me in the end, like okay, here's all the knowledge that the kids have been getting along the way, here is proof that they got it. And for me it was just a slow process of absorbing everything and you know kind of understanding it until I could you know turnkey it and then we could turn around and together make another Hypermedia with it.

This exemplifies the importance of the ACT software as a capstone to allow for students' and Ms. Y's understanding of the new system be made explicit. In the interview Ms. Y recalled that in the beginning of the research program (i.e., Years 1 and 2), her understanding of the framework was "disjointed". She attributed the ACT modelling toolkit to prepare her to create the human body system hypermedia. It appeared to help her think about interconnections between structures, their functions and visible behaviours. This example from the interview, and the classroom task of modelling body systems in ACT, indicates that Ms. Y possessed the confidence to organize the new ideas generated by her hypermedia into SBF terms using the tool and the importance. Additionally it also highlights her ability to appropriate the ACT tool as the final classroom task to evaluate knowledge generated by the hypermedia as a way to organize student ideas about complex systems.

Preparing to ask SBF oriented questions. A critical aspect of transfer of the SBF framework involved being able to make sense the new complex system in terms of "what", "how" and "why" questions. The ACT modelling table (see Figure 2.4 a) prepared learners to think about the aquatic ecosystem in terms of SBF by answering questions related to "what", "how" and "why." As is evident, questions related to "what" pertain to visible and invisible structures that determine key variables of the aquatic ecosystem. Because the learner had to only identify relevant components in the first column, it involved an important but superficial level of system understanding, unless it led the learner to consider why and how it performs specific actions in context to the aquatic ecosystem.

Video analysis in Year 1 revealed that although Ms. Y discussed the role of functions and behaviours, she was more comfortable labelling the aquatic ecosystem in terms of its relevant components. This was apparent, as she would begin the class with "what" questions. If the students gave her the expected answer she would make an attempt to elaborate on it. But when the students gave incorrect answers, she just ignored the response. As a result the students were not encouraged to share their confusion with the class in terms of why they think so and how they came to the conclusion. During the year we observed that Ms. Y consistently asked more "what" questions. This prompted the students to give single word responses. The students also noticed that the teacher expected them to give short answers that did not call for detailed explanations. This indicated that Ms. Y was hesitant to open the discussion for an in-depth systems thinking conversation that focused on SBF relations. It was likely that at that stage her idea about complex systems was focused on identifying relevant structures.

We observed a slightly different trend in Year 2. Although the "what" questions dominated the whole class discussions, students were also asked to think about possible interactions or connections between structures. As the students identified such relationships, Ms. Y led the discussion on “how” questions by writing down behaviours that connected structures.

Video analysis indicated that in years 3 and 4, Ms. Y appeared to be confident in discussing the aquatic ecosystem in terms of a complex system, interconnected by visible and invisible components as this next example shows:

1. Ms. Y: Yes, anybody have something else, let’s put another living thing in there. What do you have?
2. Jaden: Microorganisms.
3. Ms. Y: Okay. So what are microorganisms?
4. Jaden: They clean up the waste.
5. Ms. Y: What do you mean they clean up waste?
6. Jaden: They eat.
7. Ms. Y: Ok, the next problem is function. These particular structures do a particular behaviour and that behaviour fits in a little bit more into the whole picture. Think why does it need to do this behaviour for it, why do the fish need to swim?

This excerpt shows that Ms. Y opened the discussion by asking the class to identify structures connected to the aquatic ecosystem. Next she drew their attention to thinking about their behaviors. As soon as the class discussed some behaviors, she asked them to think about behaviours in context to their functional role in the aquarium based aquatic ecosystem. Ms. Y was able to build upon her prior understanding of SBF as a conceptual tool.

2.5 Discussion

As we seek to understand transfer, we must address questions related to the "what" and "how" of transfer. That is, we need to articulate the exact nature of the content or "what" is being transferred. Equally important is identifying the mechanisms or the "how" that is responsible for this transfer to occur. We suggest that we can accomplish these goals through the integration of AOT and PFL perspectives on transfer. We used AOT to reach backwards and see how the similarities were constructed, whereas PFL allowed a look forward at how applying SBF prepared Ms. Y for her future learning and practice. The case study findings showcase how different perspectives on transfer allowed us to understand how participation in a research project driven by principles of learning empowered a teacher to appropriate these tools in her own practice, going beyond the research project context.

This case study suggests that SBF as a conceptual tool has potential for making sense of complex systems. We propose that using SBF as a *focusing phenomena* (Lobato et al., 2003) is a mechanism that facilitates transfer. SBF was a lens through which Ms. Y could see the relationship between systems and prepare her to learn about new systems. Our findings demonstrated the processes adopted by the teacher to generalize her understanding of SBF. This included an initial superficial engagement with SBF that she deepened and refined over several years and her own reflectiveness in seeing herself as a learner. In addition we discussed the influence of the social environment and technological affordances that appear to prepare her for transfer. The additional viewpoints of Ms. T. and the conversations with the research team suggest that collaboration is important in preparing for transfer. Having a general-purpose tool that she could re-purpose to use for a new unit was instrumental in this process. Finally, she was able to use the hypermedia that the research team had created as a worked example that allowed her to explore the content and how SBF could be applied to a new domain.

From a PFL perspective, these results shed light on specific processes and challenges that Ms. Y had to overcome. Specifically we were keen to understand what it takes for a teacher to acquire mastery over using a conceptual tool in one context and be prepared to use it to solve a problem in a different context. The findings indicate that SBF representation focused the teachers' attention on the behavioural connections and functional roles of components within complex systems. It prepared them to think about the actions or "how" components behave within a complex system in relation to their overall functions. Both teachers reported that this was useful when they started working on creating the hypermedia on digestive system.

Although the teacher-constructed hypermedia lacked the technical sophistication of the researcher created hypermedia, the teachers made productive use of a technology they were familiar with, a power point presentation. The teachers also successfully incorporated key features of the aquarium hypermedia such as leading questions, short descriptions and use of images. Their interview responses indicated that their prior experience with the aquarium hypermedia drew their attention to these features. This prepared them to be efficient and effective with their own hypermedia design. Both these processes (i.e., creation of the new hypermedia and thinking in terms of behaviours, in addition to structures and functions) were vital as Ms. Y was able to revise her knowledge and beliefs, which set the stage for her to analyse and appreciate critical features of the new information presented to her (Bransford et al. 1990; Moore & Schwartz, 1998). This process of analysing her beliefs and strategies also highlights the active nature of transfer, which is an important part of PFL. The initiative she took in applying her SBF representation understanding to teaching a new unit demonstrates her ability to revise and rethink the current situation to suit her current goals. From a PFL perspective this is valuable as it reveals the importance of activities and practices that are beneficial for "extended learning" rather than on one-shot task performances (Bransford & Schwartz, 1999).

Our study also extends the transfer literature by proposing new ways for understanding teacher learning trajectories. As we observed Ms. Y's transition over multiple years, our focus was on the processes she followed during this transition rather than assessing mastery over content knowledge. In terms of learning trajectories, our results highlight the fact that Ms. Y was looking critically at her knowledge and gradually developed a deeper understanding in that content area. Data analysis from earlier years revealed a limited understanding of the SBF representation as a conceptual tool. However, she actively sought resources (fellow colleague, Ms. T and researchers present in the classroom) to help her understand the interconnections between multiple structures, their functions in the system and visible and invisible behaviours. Her increasing confidence in the content area, coupled with collaboration, resulted in her being highly motivated to extend the research tools to other areas of her classroom practice.

This case study provides an existence proof that AOT and PFL can be used to explain a single case of transfer. It is important however to consider the limitations from a single case (Yin, 2009). Although we cannot rule out all possible rival explanations, we triangulated data from multiple data sources and included researchers with a range of disciplinary backgrounds and experience in the interaction analysis. Other members of the research team who were not involved in the IA sessions reviewed the examples and interpretations that were presented here. We acknowledge that further research in complex classroom environments is needed in order to generalize these findings. Because of the importance of the social interactions and feedback that

Ms. Y received from teaching her students (e.g., Okita & Schwartz, in press), it is unlikely that a purely cognitive explanation could account for these results.

2.6 Future Research

The analysis presented in this study suggests the possibilities of extending research on alternative approaches to transfer (Lobato, 2006; Bransford & Schwartz, 1999; aVan Oers, 1998). These new approaches to transfer suggest a much more complex and dynamic process than traditional cognitive accounts. Our results also suggest that different theoretical frameworks can be productive integrated in providing accounts of transfer. In our case, teacher adoption and appropriation of a learning framework was an exciting by-product of scholarly research because it provides evidence that classroom innovations can be appropriated and sustained.

Chapter 3:

Engagement in a Computer-Supported Learning Environment:

Abstract

Computer-supported learning environments provide opportunities for students to collaborate and participate in inquiry-based practices to solve authentic problems. However, we have limited understanding of the quality of engagement fostered in these contexts. Facilitating high quality engagement is critical given benefits of engagement for learning outcomes. Our research agenda explores students' engagement trends in such contexts. Specifically we aim to understand influences of on task behavior, group dynamics and plans made by the group to use available digital resources to accomplish intended curricular goals. Our findings indicate that groups that exhibit high quality engagement take advantage of knowledge building communities. In contrast, groups that engage in low quality engagement, display low levels of group cohesion and use available technologies to focus on superficial aspects of the task appear to have a restricted understanding of aquatic ecosystems.

Keywords: engagement, computer-supported learning, social interactions, technological affordances

3.1 Introduction

Computer-supported inquiry learning has the potential to foster productive cognitive engagement as well as to enhance learner motivation (Blumenfeld et al., 1991; Hakkarainen et al., 2002; Järvela & Salovaara, 2004; Renninger & Shumar, 2002, 2004; Veermans & Järvela, 2004). Multimedia technologies, such as simulations and modeling tools, afford opportunities for learners to engage in inquiry-based practices by exploring their own understanding and work collaboratively on solving problems. High quality social interactions in such online environments have the potential to foster deep levels of learning (Harasim, 1993; Kreijns et al., 2002). This is because computer-supported technologies position students to negotiate meaning and engage in the construction and maintenance of shared understanding and task goals (Arvaja et al., 2007; Stahl et al., 2006).

As learning scientists, we assume that computer-supported inquiry learning environments are engaging and provide affordances for high quality participation. But is this necessarily so? Krejins et al (2002) caution us that purposeful interactions may not necessarily occur even though they are afforded by available technologies. This implies that there are differences in the ways students participate in inquiry-based practices in such contexts. In this research we will examine how engagement influences students' uptake of opportunities to participate in inquiry-based practices in a technology-rich context. In the sections that follow, we will briefly review research on computer-supported inquiry based learning and engagement.

3.2 Literature Review

We view engagement as meaningful participation within communities of practice where knowledge-to-be learned is used and valued (Wenger, 1998). As a result, we conceptualize engagement in inquiry-based environments as taking part in the practices of scientific communities. That is, “active participation in social communities is primary to learning” (Wenger, 1998, p.10)

3.2.1 Conceptualizing Engagement in Computer-Supported Inquiry Learning Environments

Greeno et al. (1996) propose that it is possible for learning environments to sustain engaged participation by a) providing practice in formulating and solving realistic problems, b) fostering participation in social practices of inquiry and learning, c) providing support for positive epistemic identity, and d) developing disciplinary practice of discourse and representation. Prior research highlights that computer-supported inquiry environments incorporate design elements that are intended to foster meaningful participation (Edelson & Reiser, 2006; Lehrer & Schauble, 2006). While we suspect that technologies (such as multimedia tools) sustain behavioral engagement, there is a gap in the literature that investigates the roles played by individual engagement towards the negotiation of meaning. To fully understand learning through inquiry in computer-supported learning environments, a more comprehensive conceptualization of engagement is needed.

We propose to conceptualize student engagement on the basis of specific technological affordances (Figure 3.1). For instance, technologies such as simulations and clickers afford dynamic feedback in response to learner activity. This should sustain students’ on task behavioral engagement. As a result, the choice of technology used in the classroom may have a bearing on learning effectiveness and satisfaction that influences students' learning engagement (Hu & Hui, 2012). We envision that being engaged with the tool behaviorally may act as a precursor for students to use it to make sense of assigned problems.

In the past twenty years various kinds of multimedia technologies have found their way in classrooms. Despite this change there has been little research that studies the extent to which students take up opportunities afforded by the tools to engage with curricular tasks designed to support student learning. Lee and Brophy (1996) define task engagement in terms of strategies or procedures that students use to achieve required classroom goals. In our work, we extend this definition to include the sociocultural context (Vygotsky, 1978, 1986). We conceptualize task engagement (TE) as attempts to support meaning-making by solving the problem at hand, monitor the execution of a plan of action, and move beyond focusing on superficial features of technologies used in the classroom context. For students to stay engaged with a task they need to anticipate and strategize efficient use of the technology. TE may be an indicator that students are being thoughtful and deliberate in taking up the affordances offered by the learning environment. Planning is deeper when it moves toward the task's solution and problem solving and more superficial when it focuses on features such as spelling, color and presentation from an aesthetic point of view.

We envision that high levels of TE may set the stage for students to strengthen their conceptual understanding by engaging in the practice of sense making. Gresalfi et al, (2009) argue that, "conceptual engagement captures the work of sense making" (p. 22). Research has shown that engaging in practices such as conducting experiments (diSessa & Minstrell, 1998), constructing explanations of anomalous data (Chan et al., 1997) and generating self-explanations (Chi, 2000) have been successful in encouraging students to make sense of problems and as a result lead to high quality conceptual engagement. Similarly, there research supports the project-based science curriculums benefit from technology integration and directs students to make sense of problems and as a result, learn key scientific concepts (Hug, Krajcik & Marx, 2005). Given that computer-supported technologies afford opportunities where students can take up such inquiry-based practices it is anticipated that inclusion of such kinds of learning experiences may prepare students to use knowledge to solve new problems.

Using knowledge as a tool for problem solving resonates with Gresalfi et al's (2009) notion of consequential engagement. Gresalfi et al. (2009) note that consequential engagement captures students intentional application of specific tools based on the situation. They suggest that if students can make sense of the tool's underlying conceptual framework, they are in a position to use it to solve new problems. This implies that students' conceptual and consequential engagement is interrelated and may perhaps be a continuum of this dimension of engagement. We anticipate that productive use of technology will enhance students' conceptual engagement and prepare them to use the tool to solve new problems outside the context in which it was learned. As a result, we define conceptual-to-consequential engagement (C-C) as attempts at content connections on a continuum that range from simple knowledge telling (low engagement; Chernobilsky, DaCosta, & Hmelo-Silver, 2004; Bereiter & Scardamalia 1996), to content connections (moderate engagement), to connections to prior knowledge, everyday experiences or the larger problem (i.e., consequential engagement; Gresalfi et al., 2009).

C-C engagement positions students to discuss and share ideas that highlight content connections at varying levels of intensity. This is especially relevant when working with computer-supported technologies. Primarily this is because such technologies encourage collaboration by establishing a point of shared reference for students to discuss and make sense of assigned problems (Crook, 1994; Roschelle & Teasley, 1995).

Building upon Rogat & Linnenbrink-Garcia's (2011) work, we consider collaboration in terms of a group's social coordination (SC; Adams et al., 2012). SC is relevant for learning and engagement when it involves active participation in communities of practice. Our primary focus is on addressing the role of access to opportunities for participation. Adams et al. (2012) define SC as the overall coordination and flow of interactions between group members, with a specific focus on respectful interactions and equality of opportunities for participation. High social coordination is evidenced by mutual respect, group member responsiveness toward one another, high group cohesion, incorporation of other members' ideas, and equal access to tools. Low coordination, on the other hand, is characterized by disrespectful interactions, failure to integrate each other's ideas, unresponsiveness toward group members, lack of cohesion, and monopolization of access to tools. Given that computer-supported environments facilitate specific affordances, we anticipate that differences in SC will influence a group's uptake of opportunities afforded by the technologies.

Type of Engagement	Technological Affordance
Behavioral (Fredricks et al., 2004)	Dynamic feedback
Task (Lee & Brophy, 1996)	Planning, building and testing models
Conceptual (Gresalfi et al., 2009)	Collaboration, planning, building and testing models
Conceptual-to-Consequential (Gresalfi et al., 2009)	Collaboration, Dynamic feedback
Social Coordination (Adams et al., 2012)	Collaboration

Figure 3.1 Conceptualizing engagement in computer-supported environments

Currently there is a gap in the literature that looks closely at the ways by which collaborative task and behavioral engagement in conjunction with social coordination has a bearing on conceptual-to-consequential engagement in computer-supported learning environments. To that effect our research aims to bridge this gap by addressing the following research question:

What kinds of engagement (behavioral, task, social coordination) are needed to facilitate high quality collaborative conceptual-to-consequential engagement in a computer-supported learning environment?

3.3 Methods

As our goal was to observe characteristics of group engagement on uptake of opportunities afforded by technologies, we relied on a case study approach (Stake, 1995; Yin, 1994). Case studies were utilized to examine the processes that members undergo in addition to the outcomes (Merriam, 1988). Stake's (1995) collective case study approach helped us to consider a number of cases to observe variations in groups' engagement.

3.3.1 Instructional Context

The study was part of a technology-intensive curricular unit designed to support 7th-grade students' learning about aquatic ecosystems (Hmelo-Silver et al., 2011). The curricular unit was six to seven weeks long spread over the academic school year. The curriculum was divided into three units focusing on aquariums, ponds and marine ecology. Each unit had a driving question in the form of a problem. For the purpose of this study we focus our attention to the pond unit where students were asked to investigate the cause for sudden death of fish in a local pond.

Students collaborated in small groups to investigate possible causes of problems in each case. They had access to the same curricular materials and computer tools in all classrooms. Classroom instruction was a mix of whole class and small group activities organized around components-mechanisms-phenomena (CMP). CMP is a conceptual representation adapted from Structure-Behavior-Function theory (Goel et al., 1996; Hmelo-Silver et al., 2007). In brief, phenomena are the problems or patterns to be explained. Components are the individual entities in the system and mechanisms are characterized as causal explanations of how phenomena occur or how significant processes work. The curriculum materials and technologies were designed to help students use CMP as a tool for systems thinking.

3.3.2 Description of technologies

Simulations, modeling tools and hypermedia were an integral part of the curriculum that promoted the usage of CMP as a conceptual tool to make sense of problems in the aquatic ecosystem. For instance, simulations provided opportunities for students to engage with mechanism and phenomena. Modeling tools provided occasions for students to integrate their CMP understanding and hypermedia provided background knowledge that was organized around functions of components in aquatic ecosystems. We describe each of these in more detail.

NetLogo simulations (Wilensky & Reisman, 2006) were used to explore macro and micro biogeochemical processes thus giving students opportunities to engage with mechanisms and the phenemona to be explained. Simulations designed for the pond unit were intended to help students make sense of the problem or phenomena of sudden death of fish. Students used simulations to explore the mechanistic process of eutrophication that led to depletion in the oxygen levels causing the fish to die. As students ran the simulations they were afforded opportunities to receive dynamic feedback that enabled them to display, identify and repair their understandings of the process. The macro level simulation (see Figure 3.2 a) positioned students to use the tool to establish a connection with the given problem. This was possible as the simulation afforded opportunities to explore the relationship between visible structures such as sunlight and algae and invisible structures such as nutrients and amount of oxygen and carbon dioxide present in the water. The micro level (see Figure 3.2 b) simulation was designed to build upon knowledge acquired from the macro level simulation. It was intended for students to understand the influence of nutrient run-off on the quality of water and subsequent dip in levels of dissolved oxygen leading to sudden death of fish.

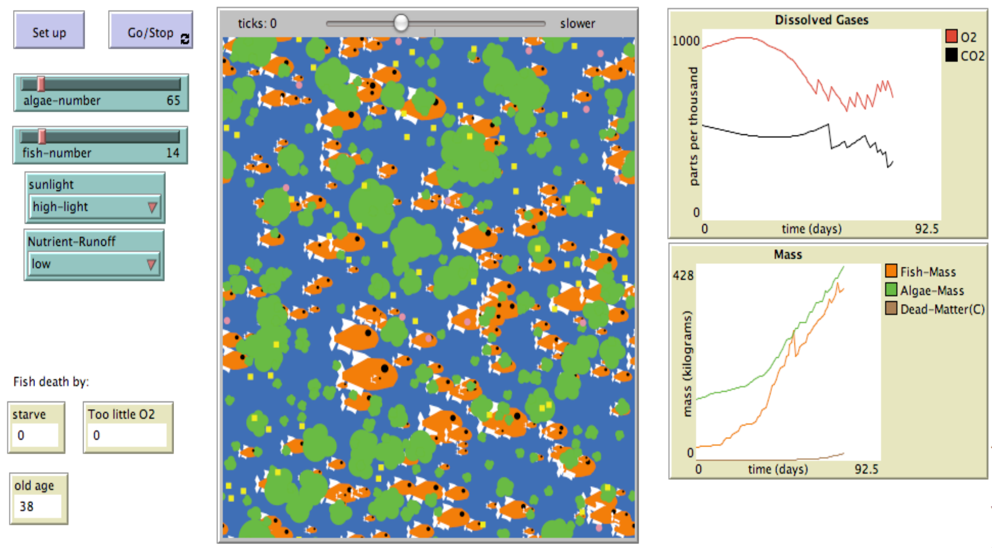


Figure 3.2a Pond macro simulation

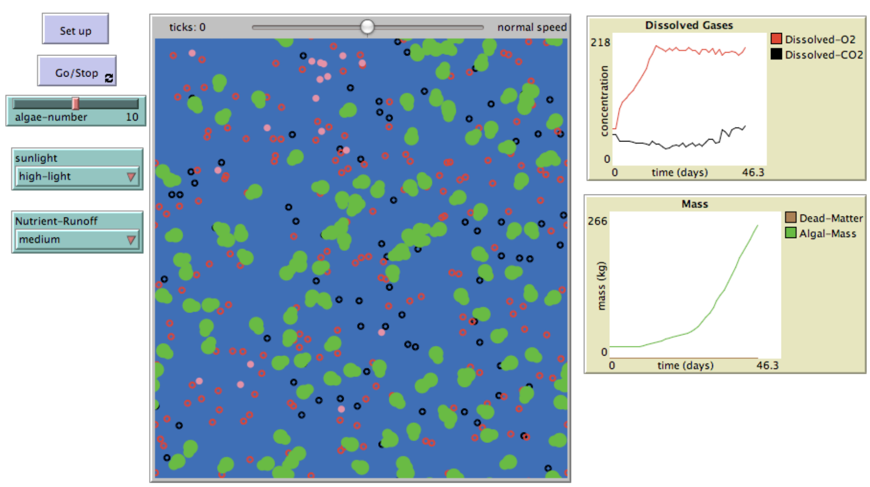


Figure 3.2b Pond micro simulation

The pond hypermedia (Figure 3.3) provided background knowledge about components or structures that are important to pond-based ecosystems, their functional roles and the behaviors they exhibited. While working with simulations, groups were expected to draw upon information gathered from hypermedia. It was intended to influence implementation of practices such as hypotheses testing along with observing and interpreting outcomes.

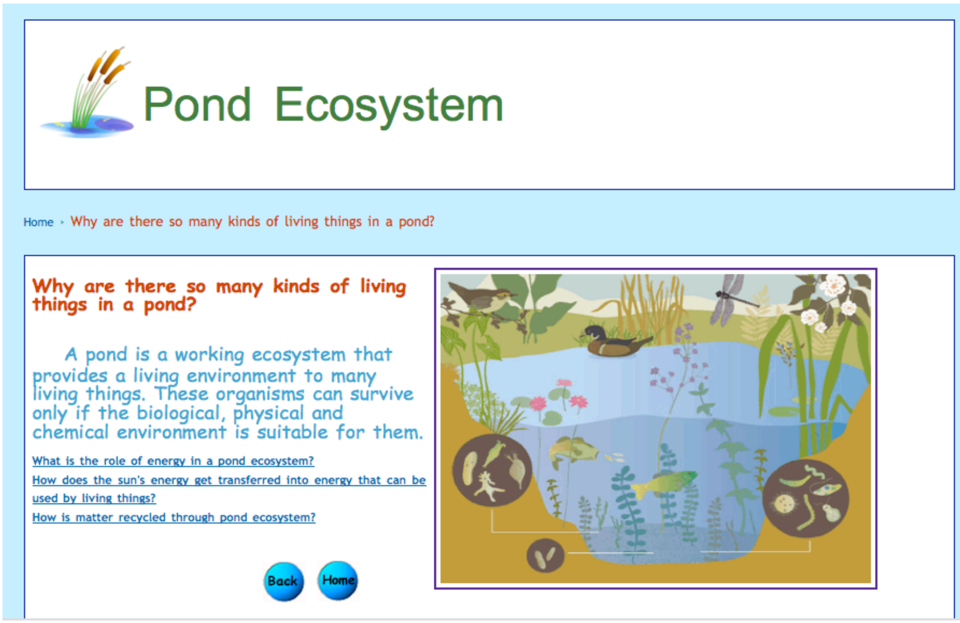


Figure 3.3 Pond Hypermedia

As part of our design principles, students participated in modeling activities, both on paper and with modeling software, the Ecological Modeling Toolkit (EMT; Vattam et al., 2011). EMT models provided the basis for social negotiation around the shared artifact. Importantly it afforded opportunities to construct explanations that would be consistent with the groups' C-C engagement. From a TE perspective it encouraged groups to integrate information collected from multiple sources (such as simulations, hypermedia, curriculum materials and whole class discussions) and incorporate them while editing their model (see Figure 3.4). This helped them to understand both individual mechanisms and the meta-level concepts related to complex systems (Goel et al, 2009). Group members worked together to create a single group model for the given problem in each of the three units.

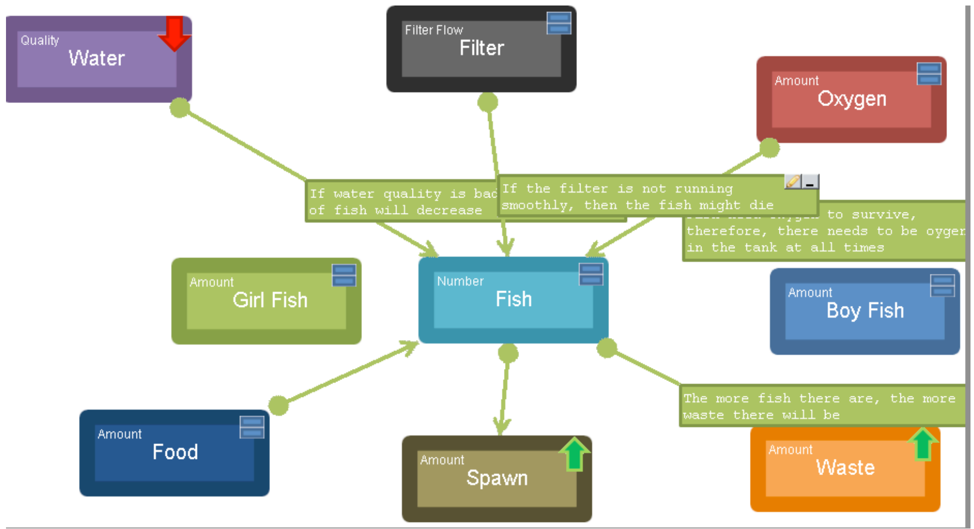


Figure 3.4 Sample EMT model

3.3.3 Participants

From a total of 109 students who participated in a larger study, 36 students were randomly assigned to ten groups as focus groups for videotaping. Overall there were 19 male and 17 female participants. Students were grouped heterogeneously to represent mixed gender and ability. Each group comprised of three to four students.

3.3.4 Data Sources

Keeping with the case study approach, we relied on multiple data sources. Data were recorded electronically in two modes: videotapes of group interactions with the technologies and group models created using the EMT software. Student worksheets while working with simulations were an additional source of data.

Ten forty-minute lesson observations or events (see Table 3.1) per group were selected for analysis; as students created initial models of their understanding of problems in each of the three units with EMT, engaged in hypothesis testing with simulations and then followed it up with revision of their initial EMT models. For the purpose of our study we focused our attention to groups' revisions of their EMT models during the pond unit.

Table 3.1

Data collection events

Event #	Event	Technology used	Curriculum Unit
1	Aquarium Model creation	EMT	Aquarium ecosystem
2	Fish Spawn	Simulation	Aquarium ecosystem
3	Aquarium Model revision	EMT	Aquarium ecosystem
4	Pond Model creation	EMT	Pond ecosystem
5	Pond Macro	Simulation	Pond ecosystem
6	Pond Micro	Simulation	Pond ecosystem
7	Pond Model revision	EMT	Pond ecosystem
8	Marine Model creation	EMT	Ocean ecosystem
9	Carbon Cycle	Simulation	Ocean ecosystem
10	Marine Model revision	EMT	Ocean ecosystem

3.3.5 Data Analysis

In total we analyzed ninety-eight video clips accounting for all the ten groups. Videos were segmented at five-minute intervals. As we were primarily interested in observing groups' engagement with the available technologies, we only coded segments where students were using the technologies. Each segment was coded as low, medium, or high quality engagement (on a scale of 1 to 3, with 1 being low, 2 moderate and 3 high) for each of the four engagement categories (see Tables 3.2, 3.3, 3.4 and 3.5). All codes were accompanied with justifications.

The first author coded all ninety-eight videos. A research assistant coded 20% of the videos from this pool. An 86% inter-rater reliability was achieved between the two independent coders.

Table 3.2

Coding behavioral engagement: This refers to the degree of the group's on-task behavior.

Low (1)	Moderate (2)	High (3)
Significant off-task talk dominate group interactions and substantially derails group's participation; This may be evident in portions of the task remaining incomplete or rushed due to loss of time; group does not work with the tool at all; disengaged group members are successful in promoting whole group off-task behavior.	Moderate on-task behavior; some group members (1/2) participate in discussion; Some intermittent off-task behavior.	All or majority of group (3/4) is on-task, members participate in discussion. This can be evident by the group continuing a task until it is complete or time given has elapsed; group pursues revisions or further discussion if extra time is available after completing the task; or group pursues task even in the face of distractions

Table 3.3

Coding social coordination: This refers to overall coordination and flow of interactions between group members.

Low (1)	Moderate (2)	High (3)
Ignore or lack of integration of group member's ideas. Taking away the task from another team member. Task is conceptualized as an individual rather than a group task (e.g. low group cohesion). Examples: Tools are used by individuals, responses to teacher reflect "I".	Contributions from all group members are acknowledged, but not always discussed or further incorporated; Attempts made to clarify comments, but may be somewhat misunderstood by group; One or two group members are dominant, and do not fully include or account for other's perspectives ; do not resolve tensions or competing ideas. Some evidence of less group cohesion.	Contributions from all group members are acknowledged and incorporated; successful attempts to clarify comments and connections are made; tools, materials and tasks are used collaboratively.

Table 3.4

Coding task engagement: This refers to focus of engagement on efficient planning and what steps to take next to accomplish the task.

Low (1)	Moderate (2)	High (3)
Planning focuses on superficial aspects of the task (for e.g. spelling, neatness, who does what, which handout, placement of components within the model) rather than planning for task solution. Planning is inefficient, time consuming and does not clearly result in a group plan. Group seems to lack a specific plan all together for engaging with the technology, and is simply "playing" or tweaking	Group discuses a plan of action. Group may not follow a plan. Planning may be somewhat inefficient and time consuming but a plan is ultimately set by the group. Task plan or tool use may be more haphazard rather than thoroughly thought out (e.g., multiple variables are modified).	Planning is efficient and the group ensures that the plan is followed (monitoring) or appropriately modified through by the group. Focus primarily on moving toward the task solution and problem solving, rather than only on superficial task elements. Group plans to solve the task with a thoughtful and purposeful discussion: regarding which variables to manipulate, interpreting data gathered from graph

elements of the tool without reflection or rationale.		and data boxes (within simulations) and addition/deletion of components and relations (within EMT).

Table 3.5

Coding conceptual-to-consequential engagement: Conceptual engagement is considered a continuum that ranges from content connections that are focused on the key question or task problem or relating to the real world/experiences to simple knowledge telling.

Low (1)	Moderate (2)	High (3)
Group task work is only grounded in low-level declarative knowledge; facts, no connections.	Group discussions and task work aim to build content connections and build conceptual understanding, but do not necessarily reflect or take a step back to solve the central question or relate to the real world.	Group attempts to connect to other sources of knowledge and experiences; Connections to the larger question or problem of the task is sustained and group reflects/takes a step back to the larger question or problem (e.g. why do fish die). Evidence of transfer

attempts present.

To highlight characteristics of group engagement on uptake of opportunities to engage in inquiry based practices afforded by the technologies, we relied on quantitative and qualitative data analysis strategies. For instance, we were interested to see if groups that appeared to demonstrate high levels of TE, by carefully setting up parameters for hypotheses testing were successful in reasoning about processes in context to the problem and establish connections with multiple data sources, thereby displaying high quality C-C engagement. In addition, we anticipated that groups that were behavioraly engaged were more likely to listen and integrate everyone's suggestions and opinion while using the tools to make sense of the given problem. In order to determine if different kinds of engagement may have had a bearing on each other, we ran correlations (see Table 3.6).

We created a table of cumulative C-C, TE, SC and BE score for each group (Table 3.7). This helped us get a visual representation of engagement patterns in each group. Importantly, it facilitated comparisons between high and low engagement groups and select examples for cases studies. We calculated the engagement scores for each group at all ten data collection points. That meant we totaled the scores for each the engagement categories- C-C, TE, BE and SC. Next, we noted the number of segments that were coded at that data point for that group. There were variations in the number of segments coded for each group at each data point. This was because in some classes time spent in whole class discussions was longer than others. In order to accommodate for differences in overall time spent with the technologies we divided each of the cumulative scores by the number of segments that were coded. This was important as it helped us to make a fair comparison between different groups.

Qualitatively, we triangulated the data by looking at it from multiple data sources i.e. video recordings of the groups during curriculum implementation, their group models created with EMT and handouts that students used for hypothesis testing while working with simulations. Going back to the video data, we observed the ways by which the groups engaged with available technologies. That is, we looked closely at their group interactions, efforts made towards planning for tasks and discussions on developing an understanding of scientific processes related to aquatic ecosystems. Next we looked at the final EMT models created by each group at the end of the three curricular units on aquariums, pond and ocean ecology. Our intention for doing so was to determine the extent to which group engagement had a bearing on their uptake of specific affordances with the modelling tool. The third source of data for triangulation purposes, were the handouts accompanying the simulations. We paid attention to the hypothesis testing strategies used by the group as an indicator of their TE and C-C engagement.

To examine the ways by which group's social coordination, task and behavioral engagement influenced their conceptual-to-consequential engagement we selected two-groups- A and B from our pool of ten participant groups. Groups A had the lowest overall engagement score, while Group B had the highest. Names of all participants in groups are pseudonyms.

3.4 Findings

Quantitative Data Analysis

Quantitative data analysis provided a broad overview of group engagement patterns. It drew our attention to specific aspects of the data, such as possible influence of task engagement on conceptual-to-consequential engagement. We also noted trends such as, variability in overall engagement with the tools between groups.

Correlation Analysis. C-C engagement and TE had high correlation with SC, *r*=.64, *p* (one-tailed) < 0.05 and *r*=. 81, *p* (one-tailed) < 0.01, respectively. This indicated that there was a strong association between the way students planned for the task, the kinds of conceptual connections they made and overall group coordination that facilitated this interaction with the tool (Table 3.6).

Table 3.6

Correlations between engagement types

	C-C	TE	SC	BE
C-C	-	-	-	-
TE	.57*	-	-	-
SC	.65*	.81**	-	-
BE	.48	.87**	.76**	-

Note: *. Correlation is significant at the 0.05 level (1-tailed)

**. Correlation is significant at the 0.01 level (1-tailed)

TE and C-C engagement were highly correlated. This indicated time and effort spent in planning (on how to use the technologies) were closely associated with the extent to which such discussions promote conceptual and content connections to the larger problem. In addition, it was interesting to note that task engagement had the highest correlation with behavioral engagement (r= .87). This implied that the extent to which the groups stayed on task had a bearing on the plans they made to use the tools to help them make sense of the problem.

The most notable finding from this analysis were that BE and C-C were not highly correlated. This implied that being behaviorally engaged might be insufficient to sustain C-C engagement. That is, the technologies may have afforded multiple opportunities for groups to stay on task but did not necessarily engage them to use the given tool to make sense of conceptual connections.

Variability in engagement. Visual representation of patterns of TE, SC, BE and C-C engagement at a group level illuminated the differences in the ways groups took advantage of the technological affordances (see Table 3.7). That is, some groups appeared to demonstrate overall higher levels of engagement than others.

Table 3.7

Groups' overall engagement scores

Group #	Engagement types				
	BE	SC	TE	C-C	Total engagement score
1	1.4	2.1	2.3	2.1	7.9
2	1.7	2.1	2.4	2.1	8.3
3	1.9	2	2	1.8	7.7
4	1.5	1.5	2.1	1.9	7
5	1.5	1.7	2	1.9	7.1
6	***1.1***	***1.4***	***1.8***	***1.5***	***5.8***
7	2.1	1.7	2.0	2.1	7.9
8	1.8	2.1	2.0	2.3	8.2

9	1.6	1.8	2.1	2	7.5
10	***2***	***2.1***	***2.5***	***2.3***	***8.9***

This was intriguing as all groups had access to the same set of technologies. This prompted us to take a closer look at interactions that highlighted the plans made by group members, the conceptual connections that were established and overall group coordination that facilitated such experiences. This variability provided an opportunity to examine how these engagement patterns related to how groups made use of the technologies.

Qualitative Data Analysis

Review of the models indicated a range in terms of how the groups made sense of the problem using the given resources. We were interested to understand the extent to which different forms of engagement (behavioral, social coordination, task) led the groups to model their evolving understanding of the problem. As a result we focused our attention on two groups that reported diversity in terms of overall engagement scores (Table 3.7): A (lowest i.e. Group 6) and B (highest i.e. Group 10) to take a closer look at their engagement trends while revising their model with EMT.

Group A's engagement patterns. Low group cohesion in addition to lack of responsiveness to team members ideas were trademark traits of Group A. The limited coordination evidenced by Group A seemed to relate to the group's superficial use of the modeling tool. Conceptual connections were restricted to reporting information without interpreting it in context to the given problem.

Behavioral engagement: Group A, a three-member team (Ethan, Elton and James) frequently engaged in off-task conversations with two of the three members of the group disengaged during the modeling task. For example, in one off-task exchanged while James was working on the task, Ethan and Elton discussed how bored and tired they felt during the task:

1. Ethan: This is like so boring! I can't wait to go home. Last night I had a fever. It was a 101.5 and I think it's coming back on. I took a Tylenol before coming to school.
2. Elton: Why are you sick?
3. Ethan: Yes practically
4. Elton: Ok, I'll be over here.

Here, Ethan was successful in derailing the group's attention intermittently from the task. Overall the group demonstrated moderate behavioral engagement given that James continued to edit the model in spite of having an off-topic conversation with Ethan.

Social Coordination: Social coordination during model creation and revisions fluctuated between moderate to low. There was a few attempts at initiating a group discussion or aimed at integrating everyone's opinions. Multiple references to "I'm going to" and "My turn" indicated low group cohesion, as the task seemed to be conceptualized as an individual rather than a group task (Figure 3.5).

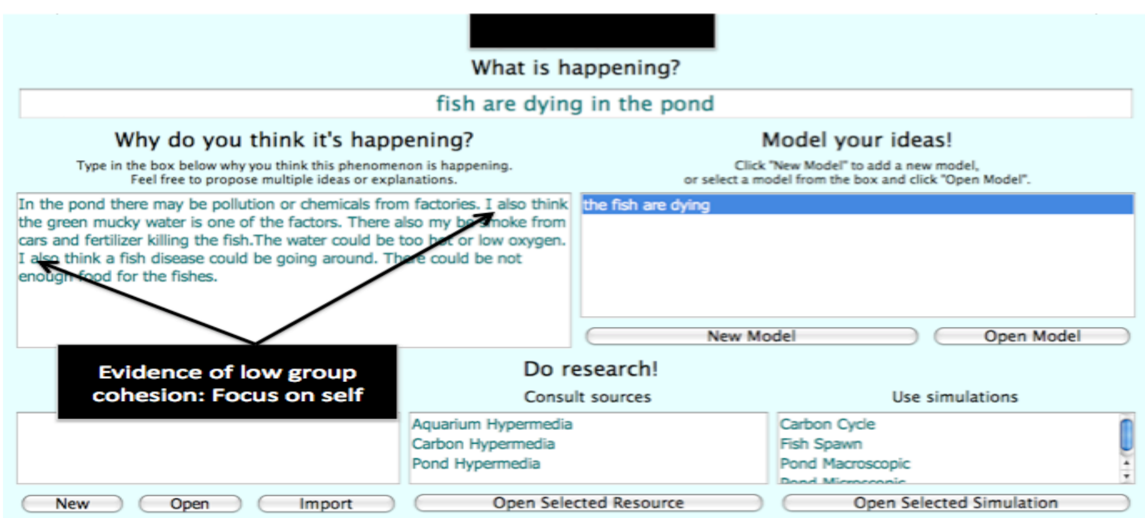


Figure 3.5 Evidence of low group cohesion by Group A

Beyond these more implicit indicators of low quality social coordination, we observed that even when group members' contributions were acknowledged, these ideas would not necessarily be discussed or further incorporated. For instance, group members ignored one another's questions and ideas or would simply add their own disconnected contribution:

1. Ethan *(reads from a sheet of paper):* There also may be smoke from cars and fertilizers getting into the lake. Could there be acid rain in it? (*Elton and James do not respond. After Elton finishes typing he steps away.)*

2. James: It could be a disease. Do we have that? *(Ethan and Elton do not respond to his question. He turns the laptop towards himself and starts typing.)*

Low quality social interaction led the group to conceptualize the task as individual efforts rather than strive for coordination to solve the assigned problem. A direct implication of this was that collaborative planning focused on superficial aspects of the task, such as spelling, color of components and who did what.

As observed earlier, while working on the task Ethan and Elton continued to engage in off-task discussions while James worked independently. He sought their inputs intermittently during the planning process.

Task engagement: Low quality task engagement seemed to be a consequence of being unresponsive to one another's contributions and limited coordination. The group did not explicitly express how to represent their explanation for fish death. For example, in the following excerpt Elton remained vague and did not refer to needing to connect components with evidence (turns 4 and 5):

1. Ethan: Why do you think this is happening?
2. Elton: Low oxygen.

3. Ethan: Should I just list the reasons [for why the fish are dying]?
4. Elton: Well remember what we did yesterday with the evidence [referring to yesterday's consensus model developed in the whole class]?
5. Ethan: Yes. *(During this time James was observed to be writing on a sheet of paper and Elton was looking at the computer screen periodically. Ethan had the computer facing him while typing.)*
6. Elton: You forgot to write an 'a' here. *(Points to a spelling mistake)*
7. Ethan: In the pond there may be pollution or chemicals from the factory. I also think that the green mucky.... Go ahead Elton. *(Slides over the laptop to Elton)*
8. Elton: Ok, I'll type.
9. Ethan *(reads from a sheet of paper):* There also may be smoke from cars and fertilizers getting into the lake. Could there be acid rain in it? (*Elton and James do not respond. After Elton finishes typing he steps away.)*
10. James: It could be a disease. Do we have that? *(Ethan and Elton do not respond to his question. He turns the laptop towards himself and starts typing.)*

The group considered planning of content contributions to be the responsibility of individual group members. The shared monitoring was focused on spelling of components (turn 6). Similarly low quality task engagement was observed as group members focused planning on who should type or add contributions to their model, rather than it's content (turn 8).

However, the primary takeaway from this exchange was that the group, especially Ethan, conceptualized the task as listing factors responsible for low oxygen levels in the water, rather than planning on modeling their understanding of cause of sudden fish death (turns 1-3). Specifically, he identified multiple causes such as *pollution, chemicals from the factory* and *green mucky water* (turn 7). He also listed *smoke from cars, fertilizers getting into the lake* and *acid rain* (turn 9). This might have influenced other team members to share this understanding of the task. For example, James thought that *disease* could also be a likely cause (turn 10).

Overall, low quality task engagement led them to posit possible causes for fish death. However the group did not engage in planning to explore their relevance to the problem during the modeling process.

Conceptual-to-consequential engagement: The group displayed low quality conceptual-to-consequential engagement while working with the EMT to uncover the factors leading to fish death. This was a result of sustained low quality task engagement that focused on superficial levels of monitoring (such as color and spelling). It was augmented further by low quality social coordination where each group member individually added components.

Prior to creating group models, the groups participated in whole class discussions where the primary focus was on identifying relevant factors that may have led to the sudden death of fish. After reviewing information gathered from multiple data sources (such as video of the fish dying suddenly in the pond, data about water quality, its temperature, fish necropsy reports, pond hypermedia, pond macro and micro simulation) the class created a 'consensus model' using the modeling tool. All members of Group A were present in class during such discussions. However, individual group members added smoke, pollution from the air and the presence of fish disease as possible factors, without giving any rationale backed by evidence (Figure 3.5). As one indicator of low CC engagement, it was notable that these ideas were not discussed at the whole class level, nor did the available evidence substantiate them.

There were several aspects of the group's final model (Figure 3.6) that provided evidence for their low quality conceptual-to-consequential engagement. To begin with the group clearly stated in the explanation box (located on the top left hand corner of the model) that they thought low levels of oxygen led to fish death. In effect the group did not extend their conceptualization of the modeling task to go beyond listing factors that led to low oxygen. This was evident as components, such as carbon dioxide, nutrient run-off and dead matter were connected to oxygen. Explanations of connections between the components reported simulation outputs (such as “If the dead matter increases, oxygen would decrease” and “If oxygen increases, carbon-dioxide decreases”) without accounting its relevance to the fish problem.

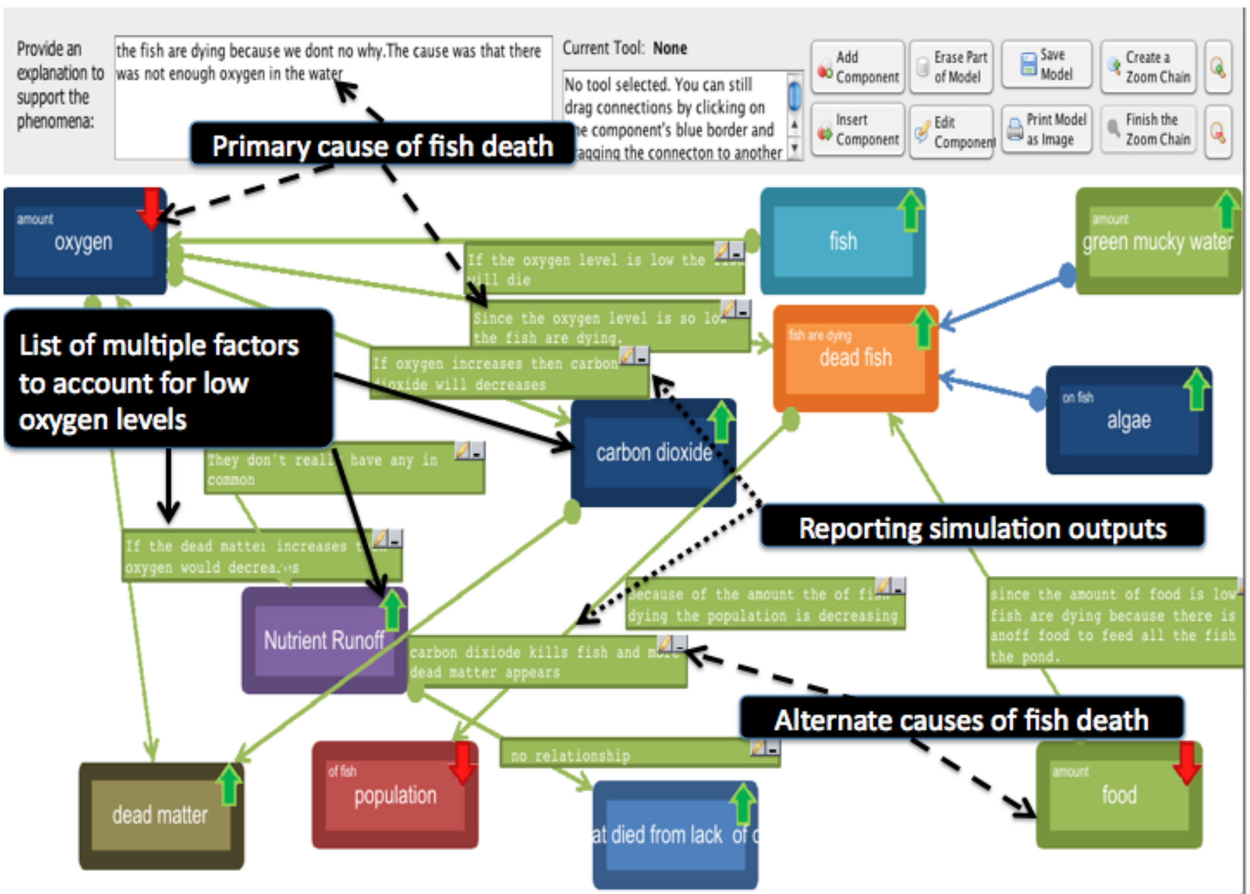


Figure 3.6 Group A’s explanation of the fish problem

Next it appeared that the group also explored the possibility of alternative causes of fish death, such as decreased quantities of food and presence of carbon dioxide. However there was no evidence in the curricular resources that supported their reasoning that fish could have died due to these factors.

Overall we concluded that the group's low quality conceptual-to-consequential engagement could be accounted for by multiple possibilities. The most prominent causes were monitoring on superficial task features and misunderstanding the objective of the modeling task. In addition low quality social coordination augmented the problem by creating an environment where tasks were conceptualized to be attempted by individual members as opposed to establishing a community of collaborative learning.

Group B's engagement patterns. In contrast to some of the low quality interactions observed for Group A, Group B was primarily on-task and engaged in respectful and responsive social interactions. However, what differentiated this group and proved to be a hallmark of Group B's engagement was the maintained high quality task engagement and conceptual-to-consequential engagement during the modeling task.

Behavioral engagement. Video recordings showed that members of Group B, Matt, Kylie, Maya and Joshua, displayed an overall level of high behavioral engagement. During the modeling task, all group members remained on-task and did not engage in any off-topic conversation. In addition to being focused and attentive, the entire group worked towards finding a solution that would help explain the problem.

Social Coordination. Group B displayed moderate-high level social coordination during the modeling task. A predominant pattern of the group's social interaction was Matt taking on a role as leader in facilitating the group's responses on their shared model. For example, it was common for Matt to initiate a concept or mechanism and it present it to the group for discussion as to whether everyone agreed to integrate the concept into their model. He consistently solicited each group member's opinion, even if it conflicted with his ideas. In this way, Matt made efforts at being respectful and responsive in interactions with his group members to ensure that everyone felt that their ideas were being heard (turns 1-4):

1. Matt: Yes, yes ok because when the algae grew on the fish's skin, that's a possible way they could have died right?
2. Kylie and Joshua: Yes.
3. Matt: I agree with this. How about you Maya? Do you agree with it?
4. Maya: Yes

Matt's facilitation of group interactions was effective in that group members typically responded to his idea for inclusion in the model. On rare occasions we observed tension between group members as Matt consistently presented his ideas and made edits to their model (despite his respect for other team members). However, when group Kylie and Joshua introduced concepts and mechanisms for inclusion, Matt was similarly responsive in discussing and integrating these ideas.

Task engagement. Group B engaged in high quality planning by taking a step back to discuss the purpose of the model. Their planning discussion occurred early in the group exchange and focused on the purpose of the model creation and what the model needed to explain (i.e. how the fish died based on evidence they gathered). Specifically they were able to differentiate between the two i.e. planning on editing their model and identifying factors that caused fish death:

1. Matt: Can I explain something now? She [the teacher] wants us to explain how the fish could have died now. Not what we thought before or the possible ways. Unless you think that the fish died as the water was dirty, after you see the evidence, then I will put it in.

This high quality task planning was revisited during the task, as the group revisited the larger purpose of the concept to explain the group returned to this high quality planning to inform their task monitoring:

2. Matt: To tell you the truth, in my opinion, even through chlorophyll and nitrates were present in our data, are not really necessary. Wouldn't you agree? Chlorophyll and nitrate, even though they are a part of the algae they are not really necessary to explain why the fish died.
3. Matt: It says it is washed into the rain. Does it say what effect it has on the pond? No…or why the fish died? So do we agree that we can take the two components out? *(Refers to chlorophyll and nitrates)*
4. Kylie: Well we can take chlorophyll out.
5. Matt: What do you think? *(Turns towards Maya)*
6. Maya: We can take chlorophyll out.
7. Matt: Should we take nitrate out?
8. Maya: I don't think so. Did we find anything important to nitrate?

The above excerpt was beneficial for the group as it set the stage for informing the planning of their model and what specific components should be included to fully explain fish death (turns 3-7). The monitoring and providing feedback related to relevant evidence drawn from the resources (turns 2and 3)

We noted that the group returned to the high quality plan related to the model needing to explain fish death to monitor their task enactment. This was important as the concept map was conceptualized as developing an explanation for the death of fish and not isolated relationships.

Their discussion maintained a focus on monitoring the development of explanations and not other superficial monitoring. Decisions made while editing the model were based on information gathered from multiple data sources (turns 3 and 8).

Conceptual-to-consequential engagement. The high quality planning that led to a shared understanding of the concept map's focus on explaining fish death encouraged the group to focus their discussions on developing explanations for fish death. This can be contrasted with the lower quality conceptual-to-consequential engagement observed for Group A where posited relations were individual and did not relate to the larger problem.

Throughout the task, Group B grappled with varying explanations for fish death. While early in the group activity the group considered the role of the cleanliness of the water, the group spent a considerable amount of time considering the role of algae resulting in decrease in oxygen:

9. Kylie: Then how does the algae affect the water if it's affecting the fish?
10. Maya: It's on the fish's skin.
11. Matt: Well, it made the water look green but it didn't affect the fish.
12. Kylie: Then that means that the algae affected the water.
13. Matt: Well the algae and the fish affected the water. The fish caused the smell and the algae caused the green.
14. Kylie: But you said that the fish affects the algae, so wouldn't there be a line there? *(Points in the direction of algae and fish)*
15. Matt: No, I don't think that the fish affect the algae. So maybe we should just get rid of this line all together*? (Points to the line between fish and algae)*

16. Kylie and Maya *(together):* No!

17. Matt: So what do you think about the connection between the fish and the algae?

18. Joshua: The algae affect the fish.

19. Matt: Yes, yes ok because when the algae grew on the fish's skin, that's a possible way they could have died right?

20. Kylie and Joshua: Yes.

Members of the group justified their algae focused explanation based on the fish necropsy that reported that algae was found on the skin of the dead fish (in turns 9- 12, 19). It led them to question this hypotheses (that algae caused the fish to die) as lack of oxygen would have led to death to algae as well, which contradicted the evidence presented to them from the video where they saw abundant algal bloom on the water making it green in color (turn 13). In turns 17 and 18 the group questioned the consequences of the behavior of algae that led to the phenomena. They justified exploring this line of thought based on the evidence gathered from the curriculum data (turn 19). It was interesting to note how their interpretation of decreased oxygen led them to question the role of algae.

The group maintained high quality conceptual-to-consequential engagement by being willing to continuously revise their explanatory model. Early in the period, the group revised their explanation in light of peer feedback (see social coordination). Relevant to conceptual-to-consequential engagement, the group revised their explanation for fish death in light of a newly introduced resource mid-activity, Group B relied on the hypermedia in combination with other sources as grounds to shift their explanation to include nitrates. In the exchange below, they included nitrates as a component and discussed its mechanistic behavior in context to the problem. This led the group to consider the likelihood that, other factors that may have led to the fish problem:

21. Matt: I don't think anything's important to nitrate.
22. Maya: On the hypermedia?
23. Matt: All it says on the hypermedia is that it gets washed into the pond. It doesn't really say what it does.
24. Maya: Let's go through it once again. Click home. *(Matt opens the hypermedia homepage)*
25. Kylie: What is the role of nutrients? *(Reads the question on the screen)*
26. Matt*:* Ok, here it is. Living things use carbon and nitrogen to build and repair their bodies and carry out important processes…
27. Kylie: So wouldn't the algae use the nitrogen to grow?
28. Matt: Ok, now that we found that we can add it [into our model].

This excerpt also serves to highlight when working toward a high quality explanation they consistently worked to ensure their model could be justified using the evidence drawn from the available resources. For instance, information gathered from the hypermedia along with experimentation with simulations led the group to disregard factors such as chlorophyll and concentrate and refocus on factors such as nitrates and decomposing bacteria to be pertinent to the problem. Matt acknowledged the fact that even though information about those specific components was presented to them as evidence, it was insufficient to tie it in to cause of fish death.

The group displayed high quality conceptual-to-consequential engagement by going beyond identifying relevant components to discussing mechanistic behaviors of those components in context to the given problem (turns 13, 23, 26 and 27). This was evident while reviewing their model (Figure 3.7).

In comparison to the model created by Group A, that concluded that the fish died solely due to lack of oxygen, Group B's model presented the possibility that interaction between multiple components was critical to explain the phenomena. The modeling process resulted in the inclusion of components such as *decomposing bacteria*, *fertilizers* and *nitrates.* Interpretation of behavior of such components (based on explanations in the green boxes) indicated that the group attempted to portray their understanding and interpretation of the eutrophication process that led to fish death.

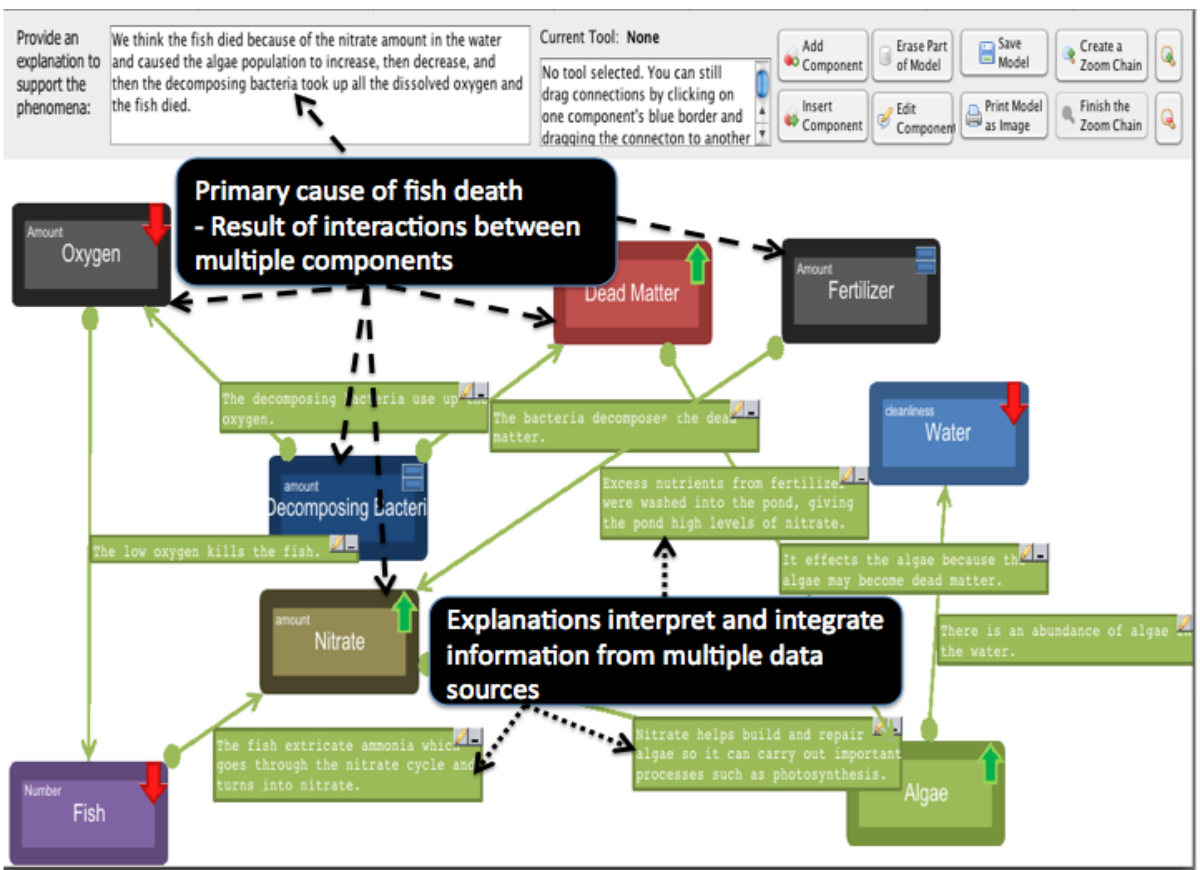


Figure 3.7 Group B's explanation for the fish problem

Overall we concluded that this group demonstrated high quality conceptual-to-consequential engagement as the group envisioned the modeling process as an opportunity to revise their evolving understanding of the problem. High quality task engagement led them to consistently monitor their planning to move them towards understanding factors leading to fish death and not get derailed by superficial aspects of the task, as was the case for Group A. The group's social coordination also contributed towards establishing high quality engagement as opinions of all group members were respected, incorporated and explored with the intent of bringing them closer to unpacking the problem.

3.5 Discussion

Previous research has identified design features of technologies that foster self-regulation and high quality engagement (Azevedo, 2005; Gresalfi, et al., 2009). Current research suggests that students can be engaged if given opportunities to work in computer-supported learning environments (Järvela & Salovaara, 2004; Veermans & Järvela, 2004). As learning scientists we assume that computer-supported inquiry learning environments, such as simulations and modeling tools are engaging and provide affordances for high quality participation. But is this necessarily so? Krejins et al (2002) caution us that purposeful interactions may not necessarily occur even though they are afforded by available technologies. Importantly, we have limited understanding of the range in quality of engagement fostered in these contexts. Prior studies in the field of computer-supported learning environments have focused on singular aspects of engagement, such as on-task behavior (Hu & Hui, 2012), enhancing conceptual understanding (Hug, Krajcik & Marx, 2005) and being able to use such technologies to solve curricular problems (Gresalfi et al., 2009). Our study adds to this body of literature by conceptualizing engagement multi-dimensionally (in terms of behavior, task, conceptual-to-consequential and social coordination) to afford a closer examination of the more and less successful episodes of engagement.

Technological Affordances

In the field of science education, computer-supported technologies afford opportunities for students to engage in inquiry-based practices that mirror practices of scientists (Krajcik et al., 2000; Novak & Krajcik, 2004; Metcalf- Jackson et al., 2000). For instance, in the case of our study the simulations are intended to provide the participant groups opportunities to engage in hypothesis testing (to identify factors that led to fish death) by formulating questions and receiving dynamic feedback that reflect their actions.

Besides simulations, computer-supported modeling tools also have the potential for students to emulate aspects of scientific research. Such software tools encourage inquiry-based practices such as analyzing and interpreting data, planning, building and testing models (Edelson & Reiser, 2006; Lehrer & Schauble, 2006). This provides students opportunities to make sense of the problem by conceptualizing their evolving understanding of the problem in the form of models. The modeling tool used in our study, i.e. the EMT affords opportunities to build upon prior understanding of factors leading to fish death. Groups create initial models based on prior understanding. However they are encouraged to engage in a process of ongoing revisions to their model based on their evolving understanding of the problem. This may be a result of group interactions, discussions with the teacher and information gathered from multiple curricular resources (such as simulations, hypermedia and data related to the pond). During this process groups are expected to account for multiple sources of evidence and resources.

Technological Affordances and Engagement

Quantitative data analysis indicated that task engagement and conceptual-to-consequential engagement were closely associated. In addition social coordination had a high correlation with behavioral and task engagement. These findings were supported by qualitative data analysis of the two groups' engagement patterns while working with the modeling tool.

Primarily, we observed that differences in groups' engagement with the technologies stem primarily from the extent to which they plan the use of the tools to make sense of factors leading to fish death. We observed a strong influence of quality of task engagement on informing the group's conceptual-to-consequential engagement. For instance Group A conceptualized the task as creating a list of possible factors that led to decrease in oxygen levels. This led them to identify irrelevant components and think about possible cause-effect relationships that were not supported by evidence in the data.

In contrast, members of Group B planned for using the tool with the understanding that it was a work in progress, with the scope of modifications based on evidence gathered from multiple data sources. As a result it led them to think about the problem as a complex web of cause and effect relationships based on observed behaviors of relevant components.

Our findings also emphasize the relevance of social coordination on behavioral and task engagement. As noted in Group A, low quality social coordination made it easy for group members to engage in frequent off-topic discussions. Feedback from the group was solicited while using the tool to plan for superficial aspects of the task such as spelling and color of components in the model. While Matt did take on a leadership role in Group B, he ensured the participation of all his teammates. The group monitored their plan to use the tool to bring forth evidence to support their hypotheses and continue to edit their model based on their understanding.

Limitations and Implications for Design

Our findings imply that group's abilities to use technologies to engage with the problem from a conceptual-to-consequential perspective is heavily influenced by a combination of task engagement and social coordination. Such findings are at the heart of our research agenda. While we have been successful in showcasing a few of them, we acknowledge that a larger participant pool would have reinforced generalizations of the findings and also brought forth a wider spectrum of engagement trends. Usage of the tools in varying contexts, i.e. beyond the unit on the fish problem in the pond ecosystem would have highlighted additional group engagement characteristics. Another limitation of our study was that our curriculum was centered on two technologies-simulations and a modeling tool. Introducing a suit of varying kinds of technologies would have been valuable as they given us the opportunity to compare variations in characteristics of engagement with each tool.

Based on our findings we envision refining the design of these technologies to enhance groups' engagement. For instance, there is potential to redesign the modeling tool to scaffold inquiry-based practices. Built-in prompts can pop-up on the screen when groups add new components or write explanations connecting two components. These prompts can ask the group to consider the relevance of the component in context to the larger problem, compel them to identify and cite the source of evidence that led them to consider a particular factor and think about their observed behavior and function in the complex system. In addition, the teachers can reinforce the idea that the modeling tool is a medium for the group to evolve and revisit their conceptual understanding.

3.6 Future Research

There is a general concern that schools do not give students opportunities to engage with curricular content in conceptually and consequentially meaningful ways (Gresalfi et al., 2009). Designing such rich learning environments is a challenging task. Unpacking student engagement in such complex learning environments may help in overcoming this challenge. This study is a step towards observing characteristics of students' engagement in curriculums that encourages such high quality engagement. Specifically, the engagement-coding scheme helps to tease apart influences and interactions between various kinds of engagement that have a bearing on uptake of affordances. The study unpacks factors in computer-supported learning environments that promote positive participatory practices. Further research in this area will highlight strategies to increase engagement and its influence on learning and transfer.

Chapter 4:

Charting mechanistic reasoning across aquatic ecosystems

Abstract

Engaging in mechanistic reasoning is central to scientific inquiry. Students' mechanistic understanding of scientific content has a strong influence over various aspects of scientific inquiry such as implementing control of variables strategy, engaging in scientific argumentation and data analysis. Current research on students' scientific inquiry processes primarily focuses on their accuracy. The goal of this study is to observe students' abilities to transfer mechanistic reasoning skills within a computer-supported inquiry learning environment and use it solve new problems. The actor-oriented lens presents evidence of transfer from the students' perspective. It sheds light on the influence of classroom experiences, such as collaborative engagement with curricular tools, interactions with peers and creation of artifacts that lead to generalization of mechanistic reasoning. Findings reflect that students to pay attention to specific aspects of mechanistic reasoning on the basis of their engagement with the learning context. Individual case studies demonstrated variations in transfer of reasoning skills.

4.1 Introduction

An important goal of science educators and researchers is to support students' inquiry as they learn about the big ideas in the discipline of science (Duschl, Schweingruber & Shouse, 2007). Research suggests that instruction designed to support inquiry focuses primarily on assessing accuracy (Marx et al, 2004). However, Russ & Hutchison (2006) argue that, "certain aspects of inquiry are ultimately more valuable than correctness" (p. 641) and propose that mechanistic reasoning is central to scientific inquiry. Mechanistic reasoning is typically used to explain “how a phenomena comes about or how some significant process works” (Machamer, Darden & Craver, 2000). Scientific reasoning prepares students to think about specific mechanisms that are part of processes that bring about an effect (Koslowski, 1996; Schauble, 1996). Students describe mechanisms in the form of explanatory models that describe structures and processes that are responsible for the observed phenomena (Abrams & Southerland, 2001; Schauble, 1996). Keil, Levin, Richman & Gutheil (1999) discuss that students engage in mechanistic reasoning by accumulating experiences within a domain to develop understanding of mechanisms that are “in essence highly concrete mental models of how things work in a particular area” (p. 316). DiSessa (1993) attributes prior experience as a key determinant of mechanistic reasoning, meaning that students draw upon "phenomenological-primitives" while engaging in reasoning to "assess the likelihood of events and explain what may have happened given the current state and assign causal credit for what happens in certain circumstances" (p. 106).

In this research we will examine how a learning environment that promotes engagement with mechanistic reasoning practices can support transfer. In the sections that follow, we will briefly review research on mechanistic reasoning and theoretical perspectives on engagement and transfer.

4.2 Literature Review

The National Research Council (2011) recommends that science curricula encourage mechanistic reasoning as it is fundamental for predicting and explaining the behavior of physical systems and, is necessary for the modeling processes at the center of knowledge construction in science and engineering. Chin & Brown (2000) discuss that reasoning mechanistically prepares students to consider connections between visible and invisible entities through their observed behaviors and functions within a system. Domain-specific mechanisms that “explain how one event (the cause) brings about another (the effect)” (p. 268) are especially crucial in the field of biology (Carey, 1995; Schauble, 1996).

Research in the field of biological sciences has identified the importance of mechanistic reasoning over teleological and anthropomorphic reasoning for understanding natural phenomena (Louca, Elby, Hammer, & Kagey, 2004; Southerland, Abrams, Cummins, & Anzelmo, 2001; Tamir & Zohar, 1991). As a point of comparison, current research on mechanistic reasoning in physics uses simple machines as all its parts and interactions are visible to students (Brewer, Chinn, & Samarapungavan, 1998; diSessa, 1993; Hammer, 2004; Metz, 1991; Schauble, 1996; White, 1993). However, visibility of parts does not ensure that students are able to make sense of cause and effect (Bolger, Kobiela, Weinberg & Lehrer, 2012). A possible explanation for this could be that while some conceptual entities map on directly to parts of the system others are more abstract and may not be clearly associable to any component of the system (Chin & Brown, 2000). So children’s difficulties in constructing mechanistic explanations may lie in their struggles to first, identify and causally relate the relevant entities of the particular mechanism, and then to place these causal relations mentally into a dynamic sequence of motion (Metz, 1991).

This is intriguing as the skill of reasoning about causes and effects emerges very early during the course of human development (Gopnik, Sobel, Schulz, & Glymour, 2001; Nazzi & Gopnik, 2003). However, Bolger et al. (2012) draw our attention to the fact that formal learning environments are unable to build upon and enhance such reasoning skills. As a result, students find it challenging to align their intuitions about cause and effect with mechanistic explanations that are specific to scientific disciplines, such as physics or biology. Russ, Coffey, Hammer & Hutchison (2009) confirm that knowledge of domain-specific mechanisms is distinct from domain-general causal understanding.

The components-mechanism-phenomena (CMP) conceptual representation, adapted from Structure-Behavior-Function theory (Goel et al., 1996; Hmelo-Silver et al., 2007), has been proposed as a framework that encourages mechanistic reasoning in biological sciences. Phenomena refer to the problem or outcome under investigation. Components are the entities that display specific behaviors or mechanisms based on their properties. Mechanisms are characterized as causal explanations of how phenomena occur. They are typically used to explain how a phenomena comes about or how some significant process works.

Russ, Scherr, Hammer & Mikeska (2008) build upon Machamer et al.'s (2000) claim that a description of phenomena (or the final outcome) is incomplete unless one traces the set-up of initial set of components, properties and intermediate interactions that result in mechanistic behavior. Specifically, CMP as a framework is useful while thinking about these three stages:

Set-up stage: In the initial set-up stage the students' attention is drawn to the relevant components and their properties. Focus on the structural properties is important, as it is an indicator of the mechanisms that the components will carry out at the first stage of the mechanism.

Intermediate stage: Students are drawn to think about behaviors of components and their participation in mechanistic processes.

Termination stage: The final stage describes the overall phenomenon that is the focus of the problem. It is a result of interactions between several components based on their properties and mechanistic behaviors.

Based on their analysis using this framework, Russ et al. (2008) report that students' (as young as first-graders) discourse display mechanistic reasoning thinking episodically. However in order to establish that the framework truly captures meaningful reasoning strategies employed by students, they stress the need to extend research in the field of mechanistic reasoning.

4.2.1 Assessing and Tracing Mechanistic Reasoning in Science Classrooms

Research in the field of assessing mechanistic reasoning in the classroom context is still in its infancy. Russ et al. (2009) argue for a shift of assessments from textbook correctness to designing curricula that encourage mechanistic reasoning and paying close attention to student discourse to evaluate the quality of their thinking. Bolger et al. (2012) propose that responding to interview questions can provide opportunities for students to predict, describe, explain and compare mechanistic behavior. Conlin, Gupta, Scherr & Hammer (2007) couple Russ' (2006) discourse analysis framework with Scherr's (2006) observation of student behaviors to explore students' mechanistic reasoning in collaborative Physics tutorials. Given the limited body of literature that explores assessment of mechanistic reasoning, we need to expand on strategies that bring forth students' reasoning about mechanisms.

We suggest evaluating students' mechanistic reasoning based on their performance on transfer tasks. However, researchers also need to select an appropriate transfer lens that allows us to look beyond accuracy and focus on the quality of students' reasoning skills. As a result, traditional transfer lenses that focus on the abstraction of schemata to identify structural similarities between problems (e.g., Holyoak, 1985) are inadequate for our purpose. In addition, traditional transfer researchers consider contexts as the unit of analysis independent of how students construe meaning in situations (Cobb & Bowers, 1999; Greeno, 1997). This implies that they do not account for the fact that each student may construe meaning differently. Furthermore, comparisons with expert performance are not beneficial in this case. This is because our objective is to understand the means by which students take up opportunities to learn a framework and use it to reason mechanistically. As a result, we need to rely on alternate theoretical transfer lens that highlights interactions that are engaging for students and subsequently, lead them to generalize their learning experience.

4.2.2 Selection of Appropriate Transfer Lens

From the current pool of alternative lenses of transfer such as preparation for future learning (Bransford & Schwartz, 1999) and developmental transfer perspective (Konkola, Tuomi-Grohn, Lambert, & Ludvigsen, 2007), the actor-oriented transfer approach (AOT; Lobato 2003) is best suited for our purposes as it allows us to shift our focus from the expert perspective to put the spotlight on how the actor (student) perceives similarities between new problems and prior experiences. We conjecture that this can be useful to understand how students' earlier experiences with mechanistic reasoning affect later mechanistic reasoning practices. For instance, if using CMP as a tool to engage in mechanistic reasoning, the AOT lens will focus on specific aspects of CMP that students transfer to make sense of novel problems - even if it results in non-normative or incorrect use of CMP. Importantly, it is anticipated to bring forth aspects of CMP that students notice as a result of social and technological interactions that are a part of their learning environment. Lobato, Rhodamel & Hohensee (2012) propose that *noticing* is a transfer mechanism that prompts students to generalize their learning. As a result the AOT perspective adds to the literature of mechanistic reasoning as it allows us to focus on *what* content is transferred on the basis of influencing experiences. It sheds light on interactions of prior learning experiences, affordances, discursive interplay with others, and personal goals as setting the stage to solve new problems (Lobato, 2012).

Another significant advantage of the AOT perspective is that it highlights specific aspects of the learning environment that the student (actor) pays attention to. We anticipate that observing students' engagement will be helpful in tracing their reasoning strategies. This is so as engagement has the potential to " link the antecedents and consequences of how students behave, how they feel, and how they think, especially in the context of new pedagogical and technology-based learning environments" (Jarvela et al., 2008; p. 299).

4.2.3 Engagement and Mechanistic Reasoning

Engagement drives how students take up opportunities to participate in inquiry based practices (Krajcik et al., 2000; Novak & Krajcik, 2004; Metcalf- Jackson et al., 2000). Lee and Brophy (1996) define task engagement in terms of strategies or procedures that students use to achieve required classroom goals. In our work, we extend this definition to include the sociocultural context (Vygotsky, 1978, 1986). As a result, task engagement (TE) is conceptualized as attempts to solve the problem at hand, monitor the execution of a plan of action, and move beyond focusing on superficial features. We anticipate that TE will illuminate reasoning that promotes students to make sense of mechanistic processes, explore connections between components and reveal questions students are tackling in the context for mechanistic reasoning to take place.

We envision that high levels of TE may set the stage for students to strengthen their conceptual understanding by engaging in the practice of sense making. Gresalfi et al. (2009) argue that, “conceptual engagement captures the work of sense making” (p. 22). Using knowledge as a tool for problem solving resonates with Gresalfi et al’s (2009) notion of consequential engagement. As a result, we define conceptual-to-consequential engagement (C-C) as attempts at content connections on a continuum that range from simple knowledge telling (low engagement; Chernobilsky, DaCosta, & Hmelo-Silver, 2004; Bereiter & Scardamalia 1996), to content connections (moderate engagement), to connections to prior knowledge, everyday experiences or the larger problem (i.e., consequential engagement; Gresalfi et al., 2009).

We regard social interactions as a key influence on C-C engagement as they serve a basis for developing a shared understanding of concepts. It is anticipated that high quality C-C engagement will draw students’ attention to the phenomena, focus on identifying relevant components and enhance the understanding of mechanistic processes.

Overall, we conceptualize that collaborative TE and C-C engagement has a bearing on mechanistic reasoning and subsequent individual transfer of CMP (Figure 4.1). Each group member has a prior understanding of mechanisms as causal explanations of how phenomena occur. It is possible that their knowledge of CMP may be challenged or enhanced as a result of collaborative engagement with the learning environment. Importantly, interactions with the learning environment may direct the group to pay attention to specific aspects of CMP. We predict that this has a bearing on individual students' understanding and generalization of CMP.

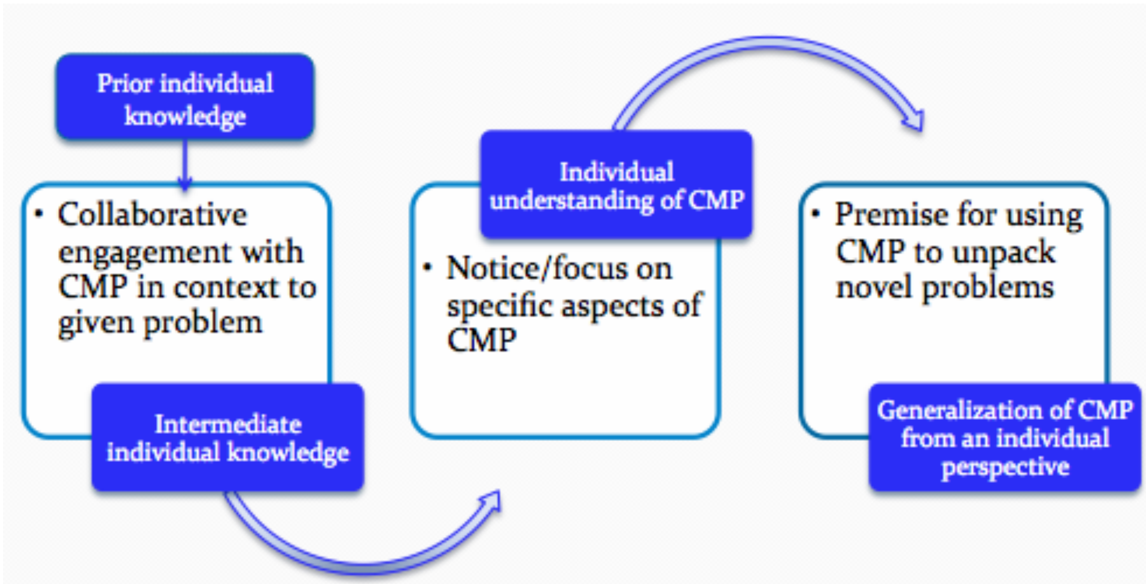


Figure 4.1 Developing and transferring mechanistic reasoning

Current research calls for developing tools that advance research of mechanistic reasoning in science education (Russ et al., 2009). This aligns with the need to extend literature in AOT in science as current research in that area has focused on observing transfer in the field of math education (Hannula & Lehtinen, 2004, 2005; Lehtinen & Hannula, 2006; Lobato, 2003, 2012; Thompson, 2011), physics (Cui, 2006; Cui, Rebello & Bennett, 2006; Rebello et al., 2007) and professional development of teachers (Sinha et al., 2013).

We aim to integrate and extend these areas of research by focusing on the following research questions:

1. How can students' mechanistic reasoning be assessed and traced across multiple scientific contexts?

2. How does collaborative engagement with components-mechanism-phenomena framework affect individual transfer of mechanistic reasoning from an actor-oriented transfer perspective?

4.3 Methods

As our goal was to trace engagement with the learning environment and assess CMP transfer, we relied on a case study approach (Stake, 1995; Yin, 1994). Case studies were utilized to examine the processes that members participate as well as the outcomes (Merriam, 1988). Stake's (1995) collective case study approach helped us to consider a number of cases to observe variations in group engagement and subsequent transfer of CMP understanding by individual group members.

4.3.1 Instructional Context

The study was part of a technology-intensive curricular unit that facilitated middle-school students understanding of aquatic ecosystems (Hmelo-Silver et al., 2011). The curriculum was divided into three units focusing on aquariums, ponds and marine ecology, was six to seven weeks long spread over the academic school year. Each unit had a driving question in the form of a problem. For instance, in the aquarium unit students were asked to estimate the number of fish that a ten-gallon aquarium could safely accommodate. The sudden death of fish in a local pond was the driving question for the pond unit. For the unit on marine ecology, students were expected to explore three different phenomena that some scientists think may have a common cause. Students collaborated in small groups to investigate possible causes of problems in each case. They had access to the same curricular materials and computer tools in all classrooms. Classroom instruction was a mix of whole class and small group activities organized around CMP.

4.3.2 Description of technologies

The learning environment included several technological tools, in the form of Net Logo simulations (Wilensky & Reisman, 2006) and the Ecological Modeling Toolkit (EMT; Vattam et al., 2011), which, along with the curriculum materials provided numerous opportunities for students to use CMP as a framework to engage in mechanistic reasoning.

Net Logo simulations were designed to allow the students to construct an explanation by making the mechanistic behavior visible and open to inspection. The simulations afforded students the opportunity to generate and test their hypotheses by manipulating the properties of components to observe their behavior within the context of the phenomena they aimed to investigate. As an illustration, the simulation on macroscopic aquatic processes (Figure 4.2) students focus on setting up initial conditions by deciding the properties of components, such as algae, fish ('amount'), sunlight ('intensity' - high, medium, low) and nutrient runoff present in the water ('quantity' - high, medium, low). As students manipulated the variables they had the opportunity to set up the initial conditions of components such as algae, fish, sunlight and nutrients. Students could set up test conditions and observe interaction between the components, based on the properties of these components

Another critical affordance of the simulation software was feedback in the form of output data boxes, graphs and simulation screen. This drew students' attention to noticing the continuity between the initial set up, intermediate and final stages. That is, students had the opportunity to observe (on the simulation screen) the behaviors of components by interpreting the information presented in the form of colored dots, graphs and data boxes. They could try to identify patterns within the graphs, such as note the number of days after which there was a decline in carbon dioxide and rise of oxygen in the water or try to uncover connections between the colored dots on the screen and the graphs related to algal-mass, fish-mass and dead matter. In this example students observed that in the termination stage (Figure 4.2) i.e. after 116 days, 1078 fish died from lack of oxygen when sunlight and nutrient level was high, there was a significant amount of algae and 63 fish in the initial condition.

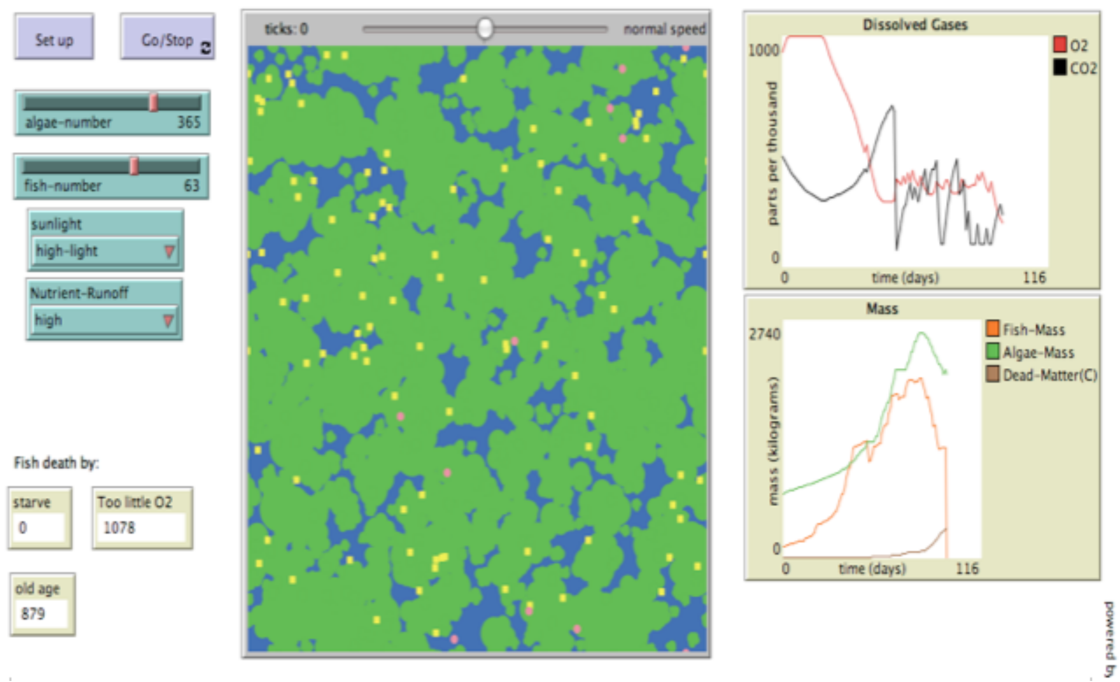


Figure 4.2 Macroscopic pond simulation

While interpreting the results at the final stage students could speculate on the observed behaviors of various components (that may have interacted with each other) to result in the phenomena. They could test their hypotheses by changing the properties of some of the variables or determine the behavior of a single component by keeping it constant while varying the others.

EMT prompted students to articulate their interpretation of the conditions that led to the phenomena. As they worked on creating models of their evolving understanding of the problem the students could identify relevant components and their mechanistic behaviors that might help to explain the phenomena under investigation. In the model (Figure 4.3), the entire problem reflected the phenomena, the rectangular boxes represented components that were linked together by explanations of their mechanistic behavior. The component box was designed as a platform for students to think about a single component in terms of its properties and behaviors it exhibits within the context of the phenomena.

Each curricular unit was assigned a driving problem (phenomena). This meant that students were introduced to the final outcome and were expected to trace the events (from the starting and intermediate stage) that led to that particular outcome. To help them make sense of conditions that resulted in the outcome, students were expected to gather information from multiple data sources such as the curriculum materials (information related to water temperature, fish necropsy reports, video footage of problem in the lake), hypermedia, simulation outputs, the modeling tool and attempt to draw connections between components on the basis of their behavior.

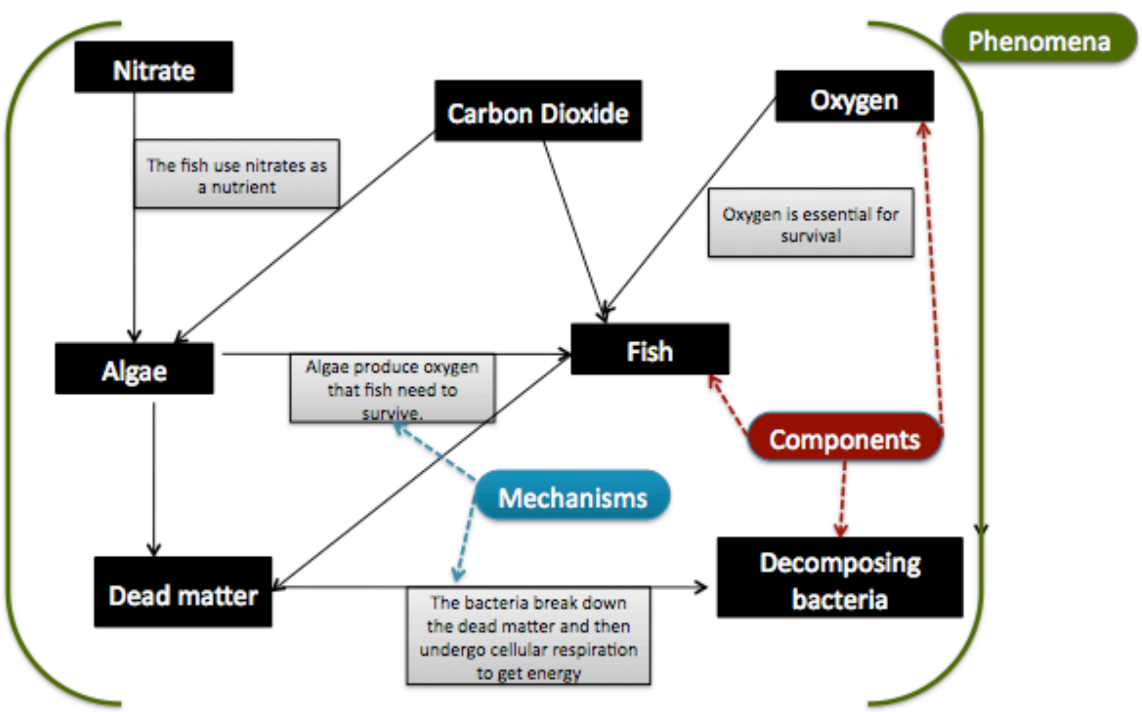


Figure 4.3 Sample EMT model

As students worked in small groups during the curriculum implementation, the collaborative engagement afforded opportunities for sense making as students used the tools to display their understanding and engage in thinking about the phenomena in terms of CMP. Even though collaboration was not an affordance of either of the two technologies directly, indirectly it played a very critical role in helping students focus on critical aspects of mechanistic thinking while working with the tools (Figure 4.4). For instance, collaboration during model creation was intended to lead to discussions where students could present their own ideas about possible causal connections between components. This afforded opportunities to present multiple perspectives regarding conditions that may have led to the phenomena. Collaboration with simulations was anticipated to afford opportunities to make sense of the observed behaviors of various components in the intermediate stage. Having groups interpret simulations outputs was intended to help them discuss interactions between components that led to the phenomena. Other curriculum materials such as handouts accompanying simulations and whole class discussions were also geared towards reinforcing CMP as the focusing phenomena (Lobato et al., 2003). That is to say, a combination of factors such as curriculum materials, artefacts, and teacher’s instructions were equally important for directing and focusing students' attention towards the intended content.

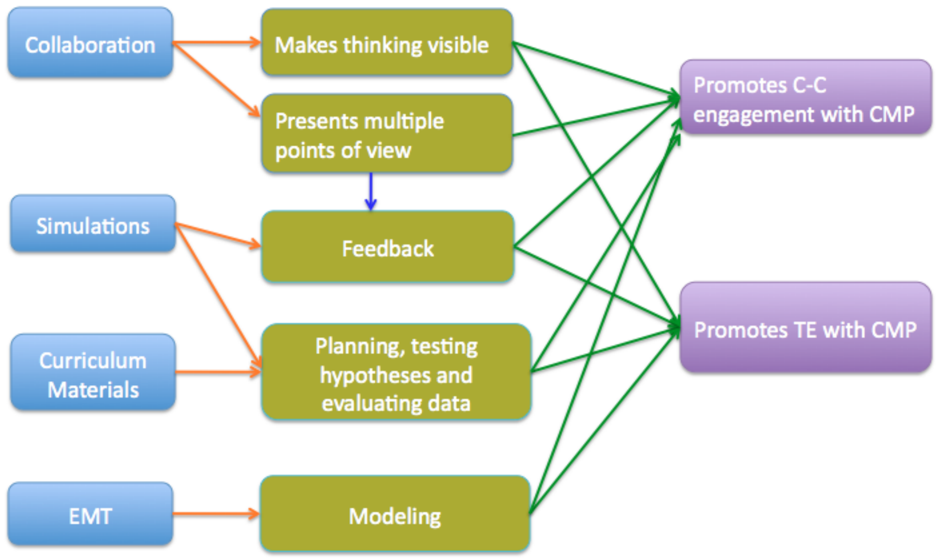


Figure 4.4 Influence of the learning environment on mechanistic thinking

4.3.3 Participants

From a total of 109 students who participated in a larger study, 36 students were randomly assigned to ten groups as participants of our study. Overall there were 19 male and 17 female participants. Students were grouped heterogeneously to represent mixed gender and ability. Each group comprised of three to four students.

4.3.4 Data sources

Keeping with the case study approach, we relied on multiple data sources. Data were recorded electronically from three sources: interviews with each of the 36 participants before and after curriculum implementation (pre and post-interview), videotapes of group interactions with the technologies and group models created using the EMT software. Student worksheets while working with simulations were an additional source of data.

After the last day of curriculum implementation, three researchers interviewed each student individually. Interview questions were designed to assess students' generalization of mechanistic reasoning and to make sense of new problems related to aquatic ecosystems (Appendix I). In order assess students understanding of CMP as tool to engage in mechanistic reasoning, we introduced a transfer task at the end of the post-interview. Students were expected to use CMP in two contexts. In one context task A, students were shown a paper copy of their group-created EMT model depicting factors that may have led to fish dying suddenly in a local pond. The students were then asked to label the model in terms of CMP and explain their reasoning. In the second context task B, students were told that there has been a sudden increase in geese population around a lake that has resulted in changes to the aquatic ecosystem. They were shown three versions of EMT models (the first consisting only of components, the second had only mechanisms but no components, and the third consisted of numerous components, mechanisms connecting them and phenomena). Students were first asked to rank each model on a scale of one to three, with three being the most complete explanation about what happened to the lake ecosystem as a result of the overpopulation of geese. Next, students labeled the model they had ranked the highest and were asked to explain the criteria for making their selection. Interviews were recorded and transcribed.

4.3.5 Data Analysis

To assess students' understanding of CMP from an AOT lens, we compared each student's labeled model in task A with that in task B. We identified items they labeled as identical in terms of CMP in both tasks and also kept track of areas where they exhibited differences (i.e., identified phenomena in one task as the entire model and in the other had it labeled as a mechanism). As our goal was to observe generalization of mechanistic reasoning we were not focused on assessing conceptual accuracy. Along with the labeled model artifacts we also reviewed transcribed interview responses for indicators that would allow us to observe how students viewed similarities between the two tasks and made use of mechanistic reasoning. For example, if a student identified photosynthesis as a mechanism in both diagrams that would be consider transfer, but from an AOT perspective, it would also be transfer if that student identified photosynthesis as a component. Although not canonically correct, this would provide a formative window into the students thinking.

To trace experiences that may have led to generalization of mechanistic reasoning we relied on two coding schemes. The first coding scheme (Table 4.1) drew inspiration from Russ et al. (2008) and Machamer et al.'s (2000) work on mechanistic reasoning. According to Russ et al. identifying entities involves recognizing "objects that affect the outcome of the phenomenon" (p. 14). Further they discussed the importance of identifying properties of entities as critical for specific mechanistic behavior that led to the phenomena. We integrated both these aspects (of identifying entities and properties of entities) as *components* and *properties* in our coding scheme as we wanted to understand the kinds of entities and nature of properties that students identified during the course of mechanistic reasoning.

Machamer et al. (2000) discuss that "the stages of a mechanism are organized linearly, but they also may be forks, joins, or cycles. Often, mechanisms are continuous processes that may be treated for convenience as a series of discrete stages or steps." (p. 12). This was the premise on which we coded students' understanding of mechanisms. It implied that based on their understanding and content knowledge, students may describe the complete causal mechanism (in terms of initial, intermediate and final stages) or their description may be incomplete. We applied this coding scheme for transcribed responses for each of the pre and post interview questions.

Table 4.1

Mechanistic reasoning coding

Coding categories and subcategories	Descriptions	Examples
Components	Components are the entities that display specific behaviors or mechanisms based on their properties.	Fish, water, people, trees
Properties	Description of characteristics of components that is necessary for a particular mechanism to run.	Amount of dissolved oxygen, number of fish, temperature of water
Mechanisms	Mechanisms are characterized as causal explanations of how phenomena occur. They are typically used to explain how phenomenon comes about or how some significant process works.	
Level I Mechanisms explain cause-	Noting causal associations between the two	Dirty water kills fish.

effect at superficial level A→B	components, without further explanation of the basis of this association.	
Level II Mechanisms are co-relational causal explanations dependent links A←>B	Description of causal associations between components as being dependent upon each other.	Trees absorb carbon. So when they are cut, carbon in the water increases.
Level III Mechanisms explain cause-effect in a sequence of activities A→B→C	Students identify actions and interactions that occur between components without very detailed explanations.	Well, fish that swim in the water, if the water isn't clean or safe enough for them, they could die.
Level IV Mechanisms explain cause-effect in sequences that are complex (i.e., multilink webs) sequence	These mechanistic explanations constitute a qualitatively more adequate account of the phenomenon and build upon elaboration of mechanistic reasoning demonstrated in earlier levels.	Okay, so what will happen here is people have lawns and a lot of them use fertilizer on those lawns and now, one problem in a lake can be eutrophication. Now, basically what happens here is if when it rains soil will run off into

the water with a lot of nutrients. Now, all that nutrients, too much nutrients, is not going to turn out well in the end. So the algae are going to benefit from a short time from that nutrients, their population is going to skyrocket, but no population can go to infinity. So once they hit that limit, they are just going to die. Most of them are going to die and they are not going to produce oxygen. Bacteria are going to use more of that oxygen, but it's not going to be replaced, thus causing organisms that need that oxygen to die.

To get an overview of students' reasoning skills, we applied this coding scheme for transcribed responses for each of the pre and post interview questions. Responses were analyzed to identify the appropriate level of reasoning (about mechanisms) demonstrated by the participant. Two hundred and sixteen responses were coded overall. The first author coded pre and post interview responses for each participant. A co-author coded 20% of the responses from this pool. A 90% inter-rater reliability was achieved between the two independent coders. To determine if there were mechanistic reasoning gains from pre to post interviews, we computed maximum likelihood chi-square (G^2). In order to get a sense of overall gains from a group level we calculated the means and standard deviation at the pre and post-interview stage.

The second coding scheme was used to identify experiences during the curriculum implementation that may have driven students to notice specific aspects of CMP. Video recordings of group interactions with simulations and the modelling tool were coded for engagement. In total we analyzed ninety-eight video clips accounting for all the ten groups. Videos were segmented at five-minute intervals. Each segment was coded as low, medium, or high quality engagement on a scale of 1 to 3 (with 1 being low, 2 medium and 3 high) for each of the two engagement categories (Tables 4.2 and 4.3). All codes were accompanied with justifications. The first author coded all ninety-eight videos. A research assistant coded 20% of the videos from this pool. An 86% inter-rater reliability was achieved between the two independent coders.

Table 4.2

Coding task engagement: This refers to the focus of engagement on efficient planning and what steps to take next to accomplish the task.

Low (1)	Moderate (2)	High (3)
Planning focuses on superficial aspects of the task (for e.g. spelling, neatness, who does what, which handout, placement of components within the model) rather than planning for task solution. Planning is inefficient, time consuming and does not clearly result in a group plan. Group seems to lack a specific plan all together for engaging with the technology, and is simply "playing" or tweaking elements of the tool without	Group discuses a plan of action. Group may not follow a plan. Planning may be somewhat inefficient and time consuming but a plan is ultimately set by the group. Task plan or tool use may be more haphazard rather than thoroughly thought out (e.g., multiple variables are modified).	Planning is efficient and the group ensures that the plan is followed (monitoring) or appropriately modified through by the group. Focus primarily on moving toward the task solution and problem solving, rather than only on superficial task elements. Group plans to solve the task with a thoughtful and purposeful discussion: regarding which variables to manipulate, interpreting data gathered from graph and data boxes (within

reflection or rationale.		simulations) and addition/deletion of components and relations (within EMT).

Table 4.3

Coding conceptual-to-consequential engagement: Conceptual engagement is considered a continuum that ranges from content connections that are focused on the key question or task problem or relating to the real world/experiences to simple knowledge telling.

Low (1)	Moderate (2)	High (3)
Group task work is only grounded in low-level declarative knowledge; facts, no connections.	Group discussions and task work aim to build content connections and build conceptual understanding, but do not necessarily reflect or take a step back to solve the central question or relate to the real world.	Group attempts to connect to other sources of knowledge and experiences; Connections to the larger question or problem of the task is sustained and group reflects/takes a step back to the larger question or problem (e.g. why do fish die). Evidence of transfer attempts present.

Data analysis was designed to answer our research questions. As our primary goal was to assess students' generalization of the CMP framework, we analyzed responses of each thirty-six participants on the transfer task. To trace influence of factors from the learning environment (that drew students' attention to focus on CMP), we coded collaborative TE and C-C engagement with the tools during curriculum implementation (Figure 4.5). We created histograms of cumulative TE and C-C engagement for each of the ten groups.

In order to take a closer look at individual students' CMP thinking and transfer, we selected four students as case studies from our pool of thirty-six participants. Matt and Tanya were members of groups that demonstrated high levels of TE and C-C engagement with the curricular tools. In contrast, Ethan and Andy were from groups that displayed moderate-to-low levels of TE and C-C engagement. Names of all participants are pseudonyms.

4.4 Findings

Mechanistic Reasoning Generalization

Analysis of responses from the transfer task (from the last post-interview question where students were expected to label two problems related to aquatic ecosystem in terms of CMP) indicated that students' generalization could broadly be categorized into four categories (Table 4.4). Thirty-three percent of students generalized CMP thinking across the contexts. Approximately 60% of the students demonstrated at least partial CMP transfer. Very few students displayed no evidence of transfer at all.

Table 4.4

Frequencies of students' generalization of CMP

	Levels of CMP transfer				
Students	No Transfer	Only C transfer	Only C&P transfer	Only C&M transfer	CMP transfer
N = 36	3	13	7	1	12

As we compared students' labeling of models, it was evident that a majority of students generalized the concept of components and phenomena. We observed that students would either circle the entire model or focus on the primary problem under investigation when asked to label phenomena. Additionally, almost all the students were quick to tag components as factors that may have led to the problem. In the following excerpt, a student explains his criteria for identifying components and phenomena, first in task A and next in task B:

> "I thought the *death of the fish going up* was the phenomenon because everything is pointing at it. All the components are pointing at it, and they're all saying why the fish are dying, and I thought that these were some components because they're all saying why the fish are dying or saying that they are factors of the death of fish."
>
> "Geese would be the phenomenon because, as you said before, the problem is that there's a *high increase in geese population*, and it's affecting the ecosystem in the fish. I had grass and plants as a component because it is pointing to the geese, and it says that it attracts geese 'cause geese eat it."

Analysis from an AOT perspective indicated that that this student likely used his prior understanding of phenomena and components for mechanistic reasoning to make sense of the new problem in terms of changing populations of animals. In response to task A, he identified *death of fish going up* as the phenomena as the primary problem under investigation. He applied the same criteria of focusing on the underlying problem during task B when he identified that the phenomena in this case was *a high increase in geese population*. Similarly, when identifying components, he drew attention to the relevance of factors that are responsible for the fish dying in task A. He used the same approach to determine components in task A.

Given the extent to which students' generalized components and phenomena, we were intrigued, but not surprised, to note that understanding the role of mechanisms was one of the most complex aspect of mechanistic reasoning. During the interviews, 20 students asked researchers to define mechanisms. In addition, we observed students labeling components, such as nutrients and dissolved oxygen as mechanisms.

From an AOT perspective we attributed this conflation to a couple of factors. First, students may have found it challenging to identify causal mechanisms as some behaviors exhibited by components are visible and some are invisible (Feltovich, Coulson, & Spiro, 2001). It is possible that this led them to focus on interactions between invisible and visible components as the criteria for identifying mechanisms. This suggests that a fraction of students were unaware of the causal mechanisms that explain how phenomena occur in both tasks. Such students may have generalized a partial understanding of mechanistic reasoning. Second, given that both components and mechanisms in EMT models are rectangular boxes, it is also possible that students' conceptual conflation may be a result of the similar computer representation. This suggests that features of representations may lead students to perceive conceptual similarity.

Mechanistic Reasoning Tracing

We traced mechanistic reasoning before and after the curriculum implementation at two levels- group and individual interview questions. Descriptive statistics at a group level indicated that all groups (barring groups 6) demonstrated an improvement in terms of mechanistic reasoning. We conjectured that curricular materials, technologies used in the classroom and interactions with peers and the teacher might have influenced groups' abilities to use mechanistic reasoning to make sense of new problems.

Table 4.5

Means and Standard Deviations of Groups' Mechanistic Reasoning at Pre and Post Interview Stage

Group	Pre-Interview M *(SD)*	Post-Interview M *(SD)*
1	1.66 (1.00)	1.88 (1.05)
2	1.44 (0.72)	2.66 (0.86)
3	1.41(0.79)	2.33 (1.07)
4	1.44 (0.88)	1.88 (1.05)
5	1.66 (0.98)	2.50 (1.38)
6	1.00(0.00)	1.00 (0.00)
7	2.00(1.12)	3.16 (0.83)
8	1.00 (0.00)	1.50 (0.80)
9	1.66 (0.98)	2.75 (1.42)
10	2.16 (1.02)	3.25(0.45)

Note. M=Mean, SD= Standard Deviation, N= 36

For the three-interview questions majority of participants established causal associations between components at a superficial level in the pre-interview stage (Table 4.6). Their responses focused on identifying cause and effect between components without providing evidence for the basis of this association. Only a single participant displayed thinking about mechanistic processes in terms of complex, multi-link webs connecting components. In comparison, there was considerable variability at the post-interview as more participants demonstrated sophisticated reasoning abilities, but there was considerable variability in responses.

Table 4.6

Frequencies of levels of mechanistic reasoning demonstrated by participants

		Pre-interview stage				Post-interview stage			
MR Level		I	II	III	IV	I	II	III	IV
Questions	1	25	1	9	1	19	2	10	5
	2	28	0	8	0	17	1	15	3
	3	24	1	11	0	11	1	14	10

Given the small sample size and low expected frequencies, the maximum likelihood ratio chi-square test (G^2) was used to examine pre to post test change. For the first question that asked students to predict effects of increase in human population (along coastal areas) on aquatic ecosystem, G^2 (9)= 25.13, $p< 0.05$, indicating a significant improvement from pre to post test. Seventeen participants continued to make sense of effects of overpopulation on water quality (problem stated in the first question) at a superficial level at the pre and post interview stage. Only one participant demonstrated a shift from thinking about mechanisms at a superficial level to considering mechanistic processes as a complex web of relationships. For the second question on effects of release of fertilizer chemicals in a lake ecosystem we noted, G^2 (6)= 20.15, $p< 0.05$.

Similar to question 1, seventeen participants continued to make superficial connections between fertilizer chemicals and effects on aquatic life. The third question, that asked students to predict the effects of cutting down trees around a lake on the lake's ecosystem showed the largest shift from superficial to sophisticated level of mechanistic reasoning, G^2 (6)= 14.55, p< 0.05.

Overall this statistical analysis presented us with an overview of changes in levels of reasoning, before and after curriculum implementation. Given that all participants had access to the same set of technological tools and curricular materials, we conjectured that other factors such as engagement with tools might have contributed to variations in levels of reasoning. Focusing on the influence of engagement helped us uncover participants' learning processes.

Engagement and CMP. Observing overall TE and C-C engagement scores at a group level illuminated the differences in the ways groups took advantage of the technological affordances (Table 4.7). That is, some groups appeared to demonstrate overall higher levels of engagement than others.

Table 4.7

Group Engagement Scores

Group	Task Engagement	C-C Engagement
1	2.3	2.1
2	2.7	2.1
3	2	1.8
4	2.1	1.9
5	2	1.9
6	1.8	1.5
7	2	2.1

8	1.8	1.7
9	2.1	2
10	2.5	2.3

This prompted us to take a closer look at interactions that highlighted the plans made by group members, the conceptual connections that were established and overall group coordination that facilitated such experiences. This variability provides an opportunity to examine how these engagement patterns related to how groups made use of the technologies to focus on specific aspects of CMP.

High engagement and CMP. Our findings indicate that highly engaged groups attended to thinking about components and their mechanistic behavior in context to the phenomena (Figure 4.6). However analysis of findings from the two case studies (members of highly engaged groups) appeared to show variations in terms of what aspect of CMP framework each group noticed.

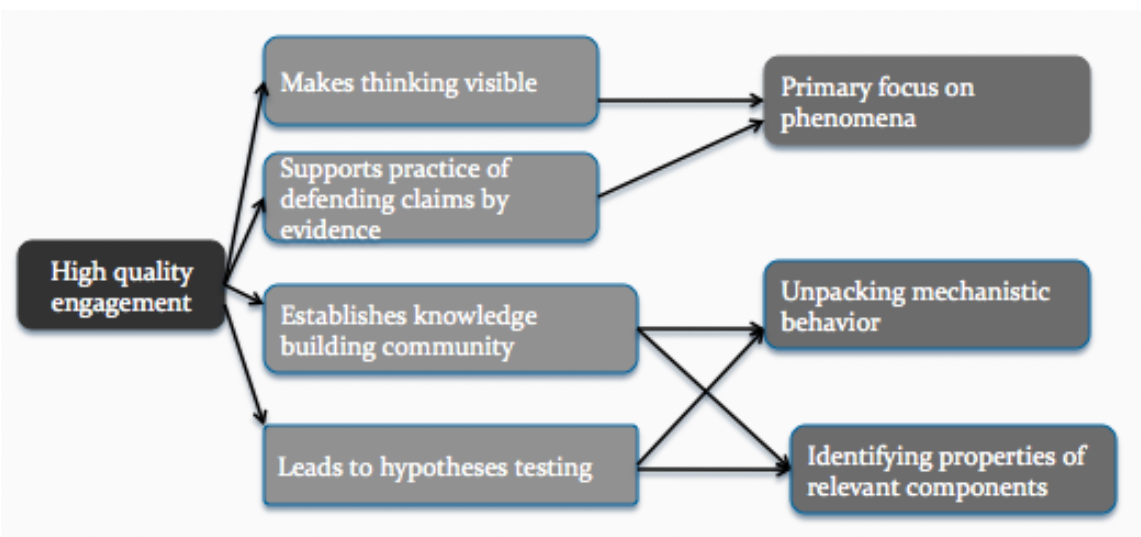


Figure 4.6 Influence of high quality engagement on CMP uptake

High engagement- high transfer of CMP. In response to task A (i.e. labeling group model created at the end of the pond unit in terms of CMP) of the transfer task, Matt circled the entire model and labeled it as ‘P’ or phenomena (Figure 4.7a). Next, he circled each of the green boxes with text as mechanisms and the colored boxes as components. In task B we observed that he followed the same criteria while labeling the EMT model that best explained what might have happened to the pond ecosystem as a result of over population of geese (Figure 4.7b).

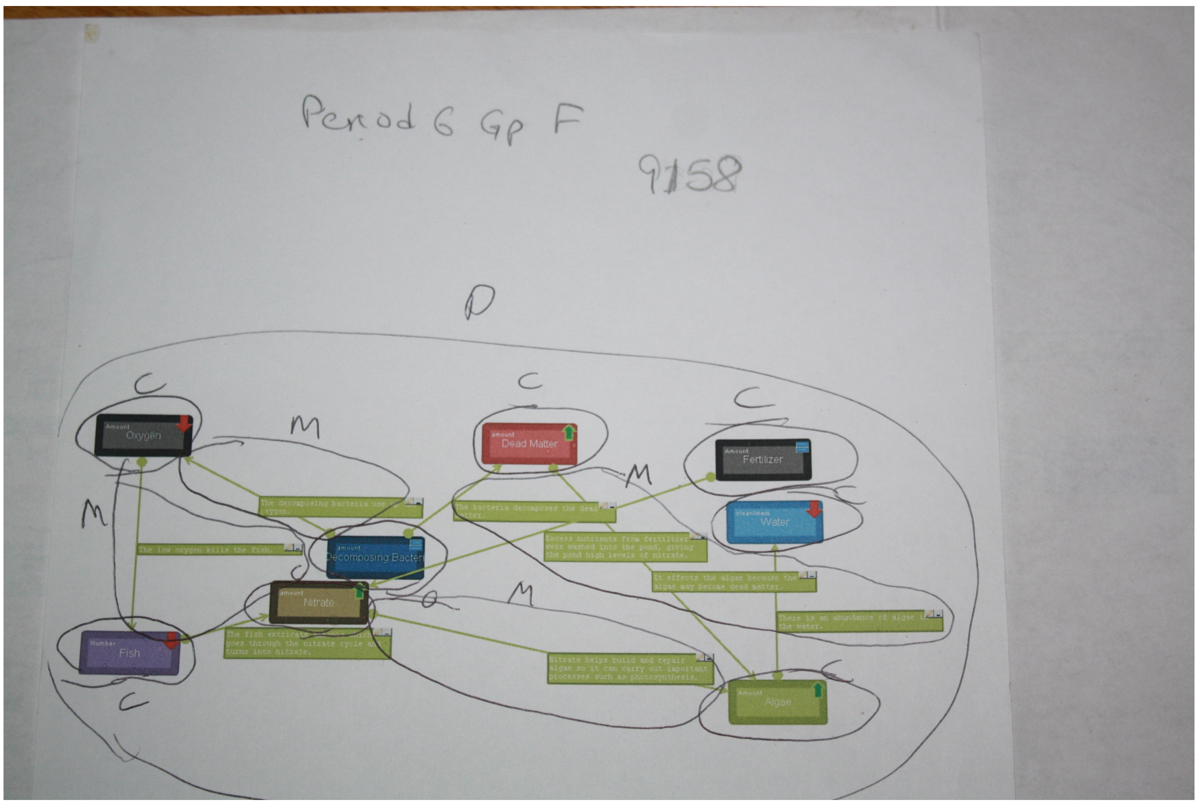


Figure 4.7a Matt’s labeling of the pond problem as CMP

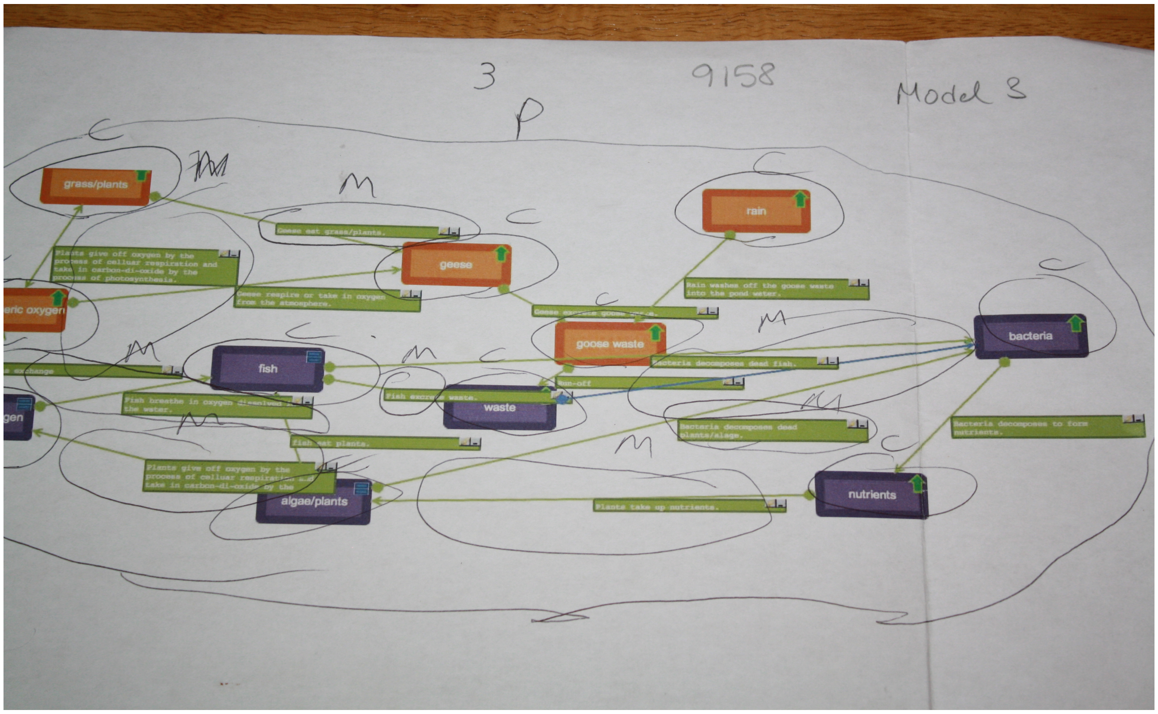


Figure 4.7b Matt's labeling of the geese problem as CMP

We noted that he selected the model that had multiple components connected on the basis of their mechanistic behavior as the one that best represented the problem. In turn 6 (from the following excerpt), he justified his selection by stressing on the fact that it was pertinent to the topic and presented numerous components. In addition, we noted that Matt understood the difference between the first and third model, in spite of the fact that they were structurally similar. This was evident from his comment in turn 8 where he clarified that the third model was supported by explanations between multiple components:

1. Interviewer: Okay. So, the best you ranked was number three.
2. Matt: And this is definitely better than this because this has nothing to do with this whatsoever. *[This refers to the second model based on mechanisms]*
3. Interviewer: Okay, so you think model number one is better than model number two.

4. Matt: Yes. This has nothing to do with the phenomena whatsoever, so then, looking at this.
5. Interviewer: Can you tell me, looking at number three? Can you explain the criteria you use for that selection, why you choose his to be the best.
6. Matt: Well, firstly, it stays on topic. It stays on the problem at hand. It gives a good amount of components.
7. Interviewer: Okay.
8. Matt: And it also has connections and explains those connections, unlike the first model had components and connections, but it didn't have the explanations of the connections.

Reviewing the labeled models and transcript of the last interview question shed light on Matt's MR skills. From an AOT perspective he drew upon his prior experience of CMP understanding with task A to make sense of the new problem. It was evident that he considered phenomena as the criteria for understanding the context of the problem. While he did not explicitly discuss that it was important to consider properties of components, Matt did indicate that it was important to consider that multiple components or factors might account for the problem. Importantly his response reflected that he was thinking about processes that were a result of interactions between multiple components in context to the phenomena (turn 8). Based on his MR ability, we wanted to take a closer look at his classroom experiences that might have influenced his thinking in terms of CMP.

In order to trace Matt's CMP understanding we started our analysis by comparing his pre and post interview responses. Matt's responses indicate that he was thinking about specific properties of components in context of the phenomena. This was evident from his response to the question on influence of increasing human population along coastal areas:

Pre-Interview Response	Post-Interview Response
Mainly because human population is increasing, that means also a lot more demand for food and a lot of food will come in like packaging, and then mainly a lot of pollution. And if the pollution gets into our water system, it could contaminate it, and make the water less safe and less clean.	Okay, so what will happen here is people have lawns and a lot of them use fertilizer on those lawns and now, one problem in a lake can be eutrophication. Now, basically, how this, basically what happens here is if when it rains soil will run off into the water with a lot of nutrients. Now, all that nutrients, too much nutrients, I should say, is not going to turn out well in the end. So the algae are going to benefit from a short time from that nutrients, their population is going to skyrocket, but no population can go to infinity. So once they hit that limit, they are just going to die. Most of them are going to die and they are not going to produce oxygen. Bacteria are going to use more of that oxygen, but it’s not going to be replaced, thus causing organisms that need that oxygen to die.

In the pre-interview Matt identified humans, food and water as key components. He held increasing human population as responsible for causing pollution in the water by releasing harmful chemicals in the form of food packaging. Matt's thinking displayed a basic level of understanding of mechanistic processes. He connected three components- human beings, food and water. But he did not provide the source or reasoning behind the association. In the post-interview Matt identified interactions between several visible and invisible components (such as water, soil, fertilizers, oxygen, bacteria and algae). Specific properties of the components, such as quality and quantity led them to interact with each other. In comparison to his pre-interview response, Matt displayed high level of understanding of mechanisms as he described the process of eutrophication.

In order to uncover factors that influenced Matt's understanding of CMP, we studied his group's engagement with the technologies. Specifically we paid attention to his actions and participation. Matt was part of a 4-member group, comprising of two males and two females. While reviewing video data we observed him taking on the responsibility of ensuring that the group stayed on task while working with the simulations and modeling software. The group engaged in lengthy discussions while working through problems in each unit. For instance, while modeling their understanding of the problem in the pond unit, the group's initial EMT model listed several factors. However, after reviewing additional data they decided to edit their model. The group engaged in collective sense making where all individual members shared their views:

1. Matt: Can I explain something now? She wants us to explain how the fish could have died now. Not what we thought before or the possible ways. Unless you think that the fish died as the water was dirty, after you see the evidence, then I will put it in.

2. Kylie: Then how does the algae affect the water if it's affecting the fish?
3. Maya: It's on the fish's skin.
4. Matt: Well, it made the water look green but it didn't affect the fish.
5. Kylie: Then that means that the algae affected the water.
6. Matt: Well the algae and the fish affected the water. The fish caused the smell and the algae caused the green.
7. Kylie: But you said that the fish affects the algae, so wouldn't there be a line there?
8. Matt: No, I don't think that the fish affect the algae. So maybe we should just get rid of this line all together*? (Points to the line between fish and algae)*
9. Kylie and Maya *(together):* No!
10. Matt: So what do you think about the connection between the fish and the algae?
11. Joshua: The algae affect the fish.
12. Matt: Yes, yes ok because when the algae grew on the fish's skin, that's a possible way they could have died right?
13. Kylie and Joshua: Yes.
14. Matt: I agree with this. How about you Maya? Do you agree with it?
15. Maya: Yes
16. Kylie: They affect each other. Because if the algae from the fish could get into the water, then that would make the water be dirty, that affects the fish.
17. Matt: Ok, I see where you're coming from.

Matt ensured that everyone's opinions were solicited, and that everyone was in agreement with the group's plan of action. This was instrumental as it led the group to achieve high quality TE and C-C engagement. As contributions from all group members were incorporated, it directed them to consider the relevance of multiple factors such as water quality (turn1), algae and fish (turn 6). Importantly, the tool provided a base for establishing a shared reference for the group to discuss possible factors that may have led to the problem (turns 2-16). This trend was repeated in turns 3-6 as the group drew upon evidence gathered from multiple sources in the curriculum (such as green colored water that was an important piece of information from the video data of the pond problem and analysis of the fish necropsy report that identified the presence of algae on the skin of the dead fish). Overall the flow of coordination between group members provided them opportunities to consider multiple perspectives.

From an MR perspective, turn 1 indicated that Matt set the stage for the group to focus exclusively on the assigned problem or phenomena under investigation. He directed the group to consider the relevance of each pieces of evidence before concluding that water quality was the culprit. Overall, the group identified multiple relevant components such as algae, water and fish. Specifically, they focused on the relationships between them in context of the phenomena (turns 2, 4-8, 10-16). Matt drew the group's attention to think about properties of water, such as its quality (turn 1), color (turn 4), odor (turn 6). This set the stage for them to consider interactions between components on the basis of their properties. We observed that they started discussing the problem from the termination stage and worked their way backward to determine possible factors that may have resulted in the specific outcome. This was salient in turns 2-6 as the group tried to make sense of intermediate stages by discussing possible interactions between the components fish, algae and water.

In the post-interview Matt focused on considering components, their properties and processes that led to the problem or phenomena. His responses were characterized by detailed explanation of causal mechanisms. Overall it appeared that engagement with technologies played a critical role in honing Matt's ability to reason mechanistically using the CMP framework.

We were interested in the extent to which collaborative engagement influenced students' understanding and transfer of CMP. This led us to our next case study, Tanya who was part of a group that displayed moderate to high levels of TE and C-C engagement.

High engagement- Low transfer of CMP. When asked to label her group's EMT model of the pond problem, Tanya circled *death of fish* as the phenomena. She labeled pollution as a mechanism and the rest of the multi-colored boxes as components (Figure 4.8a). In response to being asked to choose a model that best explains effects of increase in geese population on the lake ecosystem, Tanya decided that the model based on mechanisms was the best fit (Figure 4.8b). She circled death as the phenomena. Waste excretion and photosynthesis were marked as mechanisms and the remaining boxes were labeled as components.

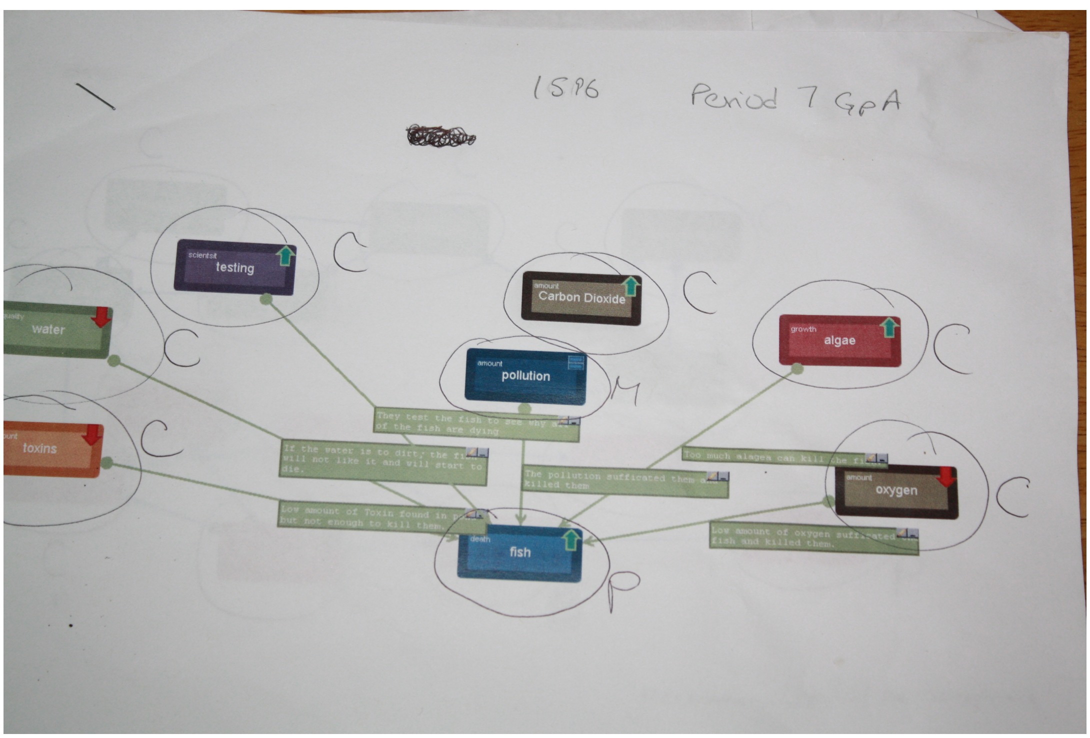


Figure 4.8a Tanya's labeling of the pond problem in CMP

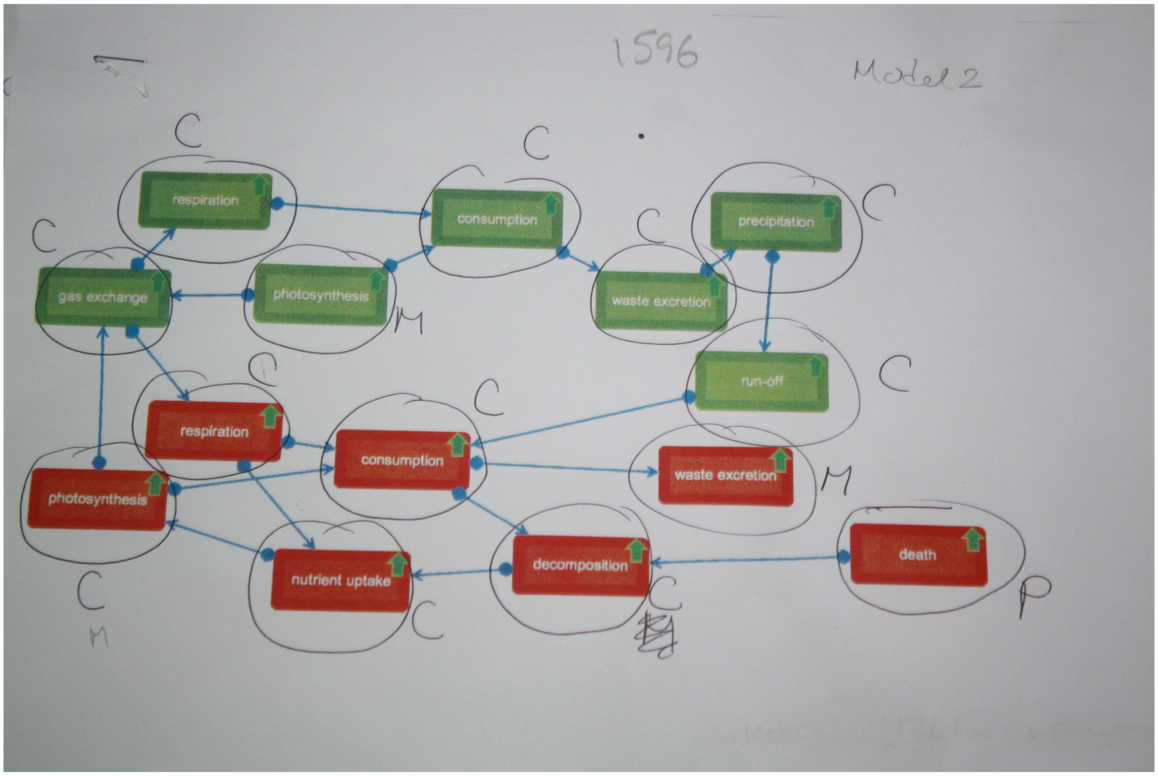


Figure 4.8b Tanya's labeling of the geese problem in CMP

Reviewing the interview transcript (while labeling the group's EMT model for the pond problem) we observed that Tanya circled testing as a component. In turn 2 she explained that scientists could engage in testing to identify the relevance of other factors that may have killed the fish:

1. Interviewer: Okay. So I see that you circled "testing" as a component. Can you explain why it is a component?
2. Tanya: Because it – testing could lead to – like if the scientist were testing the fish – like to see what could affect them, or what couldn't affect them – the stuff that did affect them, it could make – it could maybe kill them, and that could be making the fish – like the death of fish higher.
3. Interviewer: Okay, and I see you circled "pollution" as a mechanism. Can you explain why it's a mechanism?

4. Tanya: Well, because pollution, it could also lead to the death of fish. It could lead to the death of fish and pollution – and the death of fish could sometimes maybe even lead to pollution.
5. Interviewer: Okay, and then you circled fish as an example of phenomenon. So could you explain why that's a phenomenon?
6. Tanya: Because like the fish – cause of – fish is caused by so many other things so that could be the – that's why it's a phenomenon, I guess.

In the group model all the components pointed towards the increase in fish death. We conjecture that Tanya may have used this as a yardstick to make sense of the processes that led to the death of fish or the phenomena under investigation (turn 6). This was confirmed when she established a relationship between pollution and death of fish (turn 4).

When asked to identify the model that best represents effects of increasing geese population on the lake ecosystem, Tanya selected the mechanism-based model. The following excerpt highlights the criteria she used to make her selection:

1. Interviewer: So, let's say precipitation. You chose that's a component. Why do you think "precipitation" is a component?
2. Tanya: Because, well, precipitation –if it doesn't rain a lot, then the pond water amount could start to go down, because it's mostly made of rainwater, so that could go down and then that could also – that could affect the amount of fish in it.
3. Interviewer: Okay, and you circled photosynthesis as a mechanism. Can you explain that?

4. Tanya: Well, because that photosynthesis is a mechanism because the consumption for plants – if photosynthesis doesn't happen, and the plants don't consume a lot, and then it's also a reason for gas exchange.
5. Interviewer: And then you circled death as phenomenon. Can you explain that?
6. Tanya: Because the amount of geese around the pond or lake is causing more death, so that's the main reason for everything happening. That's like in this model.
7. Interviewer: Okay. Great. And can you explain to me why, again, you think Model Two is the best model? Like, what about it?
8. Tanya: Because it has a lot of reasons why it's happening, and most of these are like good reasons as well.

Tanya's responses displayed some interesting trends. It appeared she borrowed from her earlier criteria for identifying CMP. She regarded components as factors that influenced outcomes or phenomena (turn 2). For instance, she cited precipitation as a key component that may have led to the death of fish. Once again while describing mechanisms, she was thinking about causal connections between components. In turn 4 she tied in the process of photosynthesis as food for plants and one that results in exchange of gases. Her explanation was not canonically accurate and displayed a fractured understanding of photosynthesis. However it was valuable from an AOT perspective, as we observed that she used the same mechanistic understanding to make sense of two different problems. This trend continued as she described her criteria for identifying phenomena. Taking cue from her prior understanding that the final outcome or problem was the death of fish, Tanya used the same parameter to identify phenomena in the new problem. Even though her understanding of the idea was partially accurate, from an AOT perspective it helped us understand her criteria for engaging in MR.

We reviewed Tanya's interview responses and classroom experiences to trace her understanding of CMP. The following excerpt was taken in response to the question on possible effects of fertilizers leaked into a lake on the lake's ecosystem:

Pre interview response	Post interview response
Like the fertilizer could get into the water and if the fish like breathe in the water, it would get into their body systems. And then they would die from it, cause they're not used to it.	Well, fertilizers could affect it. It could affect the water quality, which is bad for the fish. It could make it dirty and put bacteria – – bad bacteria in it bad bacteria in it. Well, it could also be good for the seaweed underneath to grow, but then it would affect the fish because they're not used to breathing that in.

In the pre-interview response Tanya identified three components- fertilizers, fish and water. Her answer reflected that she was thinking about death of fish as a specific property in context to the phenomena. She reasoned that the fertilizer chemicals if leaked into the lake would cause the fish to die. Her explanation reflected a rudimentary understanding of causal mechanisms.

In the post-interview response Tanya identified fertilizers, water, fish, seaweed and bacteria as primary components. She focused on thinking about quality as a specific property of water. She conceded that while fertilizers would help in the growth of seaweed, they would be harmful for fish. This implied that she was considering causal associations between components. However her level of understanding of mechanistic processes continued to be superficial. Primarily this was because she did not provide a detailed explanation of the premise of her assumptions.

Overall, Tanya's pre and post interview responses displayed similar levels of CMP understanding. From an AOT perspective we were interested to uncover if her group's engagement with available technologies drew attention to specific aspects of CMP and observe her individual participation in such settings.

During the classroom implementation, Tanya was part of a three-member team comprising of two females and one male participant. Video footage indicated that the group was respectful towards each other. However while Tanya's opinion was sought, it was not always integrated in the group discussion. Her teammates took the lead in deciding how to use the technological tools to make sense of the assigned problem. For instance, while working on the simulations the group took up the opportunity to engage in multiple hypotheses testing where each group member got a chance to share their thinking. From a MR perspective, this activity would have been beneficial for the group from a dual perspective. First, discussing multiple hypotheses served as a basis for making sense of visible behaviors exhibited by the components. Second, manipulating variables or components had the potential to recreate conditions that may have led to the problem. Hypothesis testing provided opportunities for students to make sense of processes such as carrying capacity, eutrophication and the carbon cycle. This was evident from the transcript below as the group contemplated on possible outcomes prior to running the pond simulations:

1. Kelly: Ok, sunlight low, nutrient low. And hypothesis. What do we think could happen?
2. Tanya: Oh the algae could die.
3. Kelly: No, Tanya this is the one with the dissolved oxygen and CO2.
4. Tanya: Oh, the dissolved oxygen and CO2.
5. Kelly: What do you think? *(Turns towards Mike)*
6. Mike: I think there's going to be more dissolved carbon-di-oxide than oxygen. *(Kelly runs the simulation. They see the message: 'All algae have died').*
7. Mike: Guess Tanya was right on that one.
8. Tanya: Oh my God! I'm right. First time, I'm right.
9. Kelly: Yes you are. And there's more dissolved oxygen than CO2. Ok what is our hypothesis? I think that there's going to be a lot of dissolved carbon dioxide. *(The group reads the pop-up box that says: Oxygen amount is too low to support fish)*
10. Kelly: Oh, I was right. Let's just write that our hypothesis was correct of low oxygen.

In turn 1 Kelly decided on settings up components such as sunlight and nutrients to have specific properties such as low amounts. In addition she opened the discussion to think of possible outcomes that could be tested. Tanya's suggestion was not taken up (turn 2). Mike hypothesized that a possible outcome could be that (in comparison) there would be higher levels of dissolved carbon dioxide than oxygen (turn 6). We conjectured, from an MR perspective that it was possible that he was attempting to determine if specific properties of components in the initial stage led to certain interactions in the intermediate stage and one that resulted in the sudden death of fish in the final stage. It was interesting to note that even though Tanya's hypothesis was an outcome they observed while running the simulation, the group did not record it in their notes. The group's focus was on reporting Mike's hypothesis. Overall the group attained a moderate C-C engagement rating. Primarily this was because while they did take up the affordance of hypotheses testing, the focus of discussions was restricted to reporting outputs without interpreting the causes and processes that led to them.

Overall we concluded that Tanya's group did not engage with mechanisms in a productive way. However, they did generate hypotheses related to relationships between components. It is likely that this had a bearing on Tanya's understanding of the CMP framework.

Findings from Matt and Tanya's case studies highlighted specific aspects of CMP that groups focused on. From an AOT perspective it shed light on classroom experiences that could have possibly encouraged individual group members to develop their own understanding of this framework. From an MR perspective these findings helped us observe specific ways by which these students used their understanding of CMP to make sense of two problems. A common thread between these findings was that both students were members of highly engaged groups. As a point of comparison, this set the stage for us to observe effects of low group engagement on individual transfer of the CMP framework.

Low Engagement and CMP Transfer. Groups that displayed low levels of engagement appeared to focus on superficial aspects of CMP, such as shape and color of components. Their attention was drawn towards reporting simulation outputs without interpreting them. That is, they noted mechanistic behavior without connecting it to the larger problem (Figure 4.9).

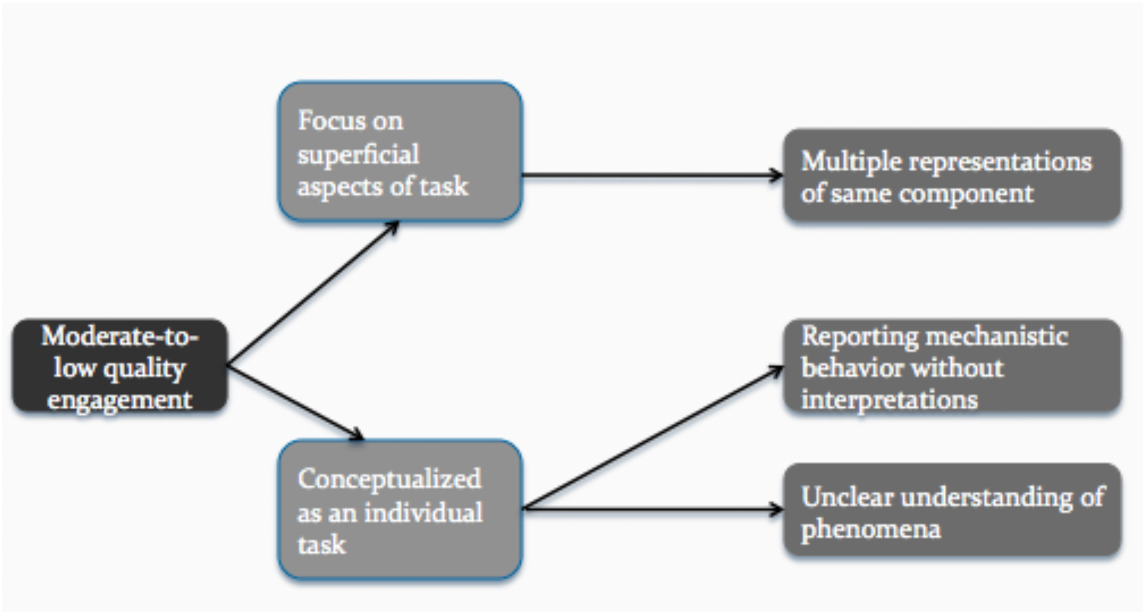


Figure 4.9 Influence of low engagement on CMP uptake

*Low engagement- moderate CMP transfer***.** For task A, i.e. labeling the group created model on the fish problem (in terms of CMP), Ethan identified two rectangular boxes as phenomena (Figure 4.10 a). He marked a few other boxes as components. There were no boxes identified as mechanisms. In comparison, for task B, Ethan selected the model that only had components as the best model (Figure 4.10 b). Once again, he identified two rectangular boxes as phenomena, three boxes such as mechanism and a few boxes as components.

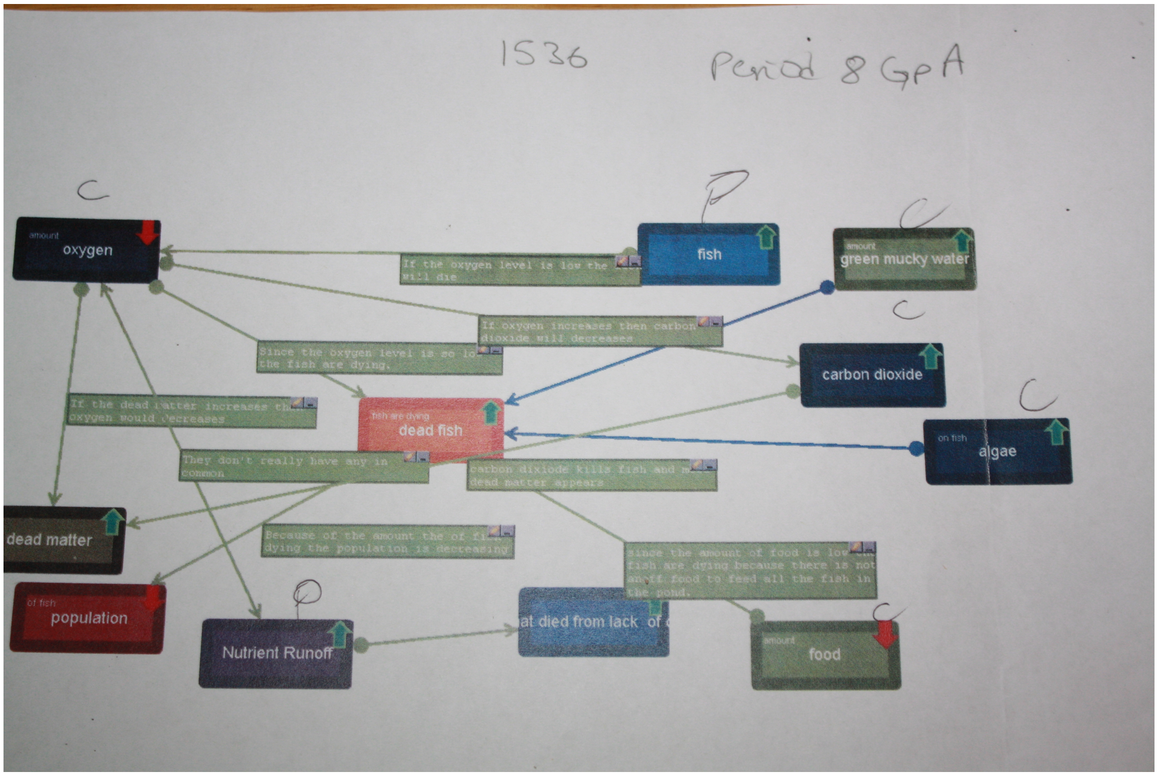


Figure 4.10 a Ethan's labeling of the pond problem in terms of CMP

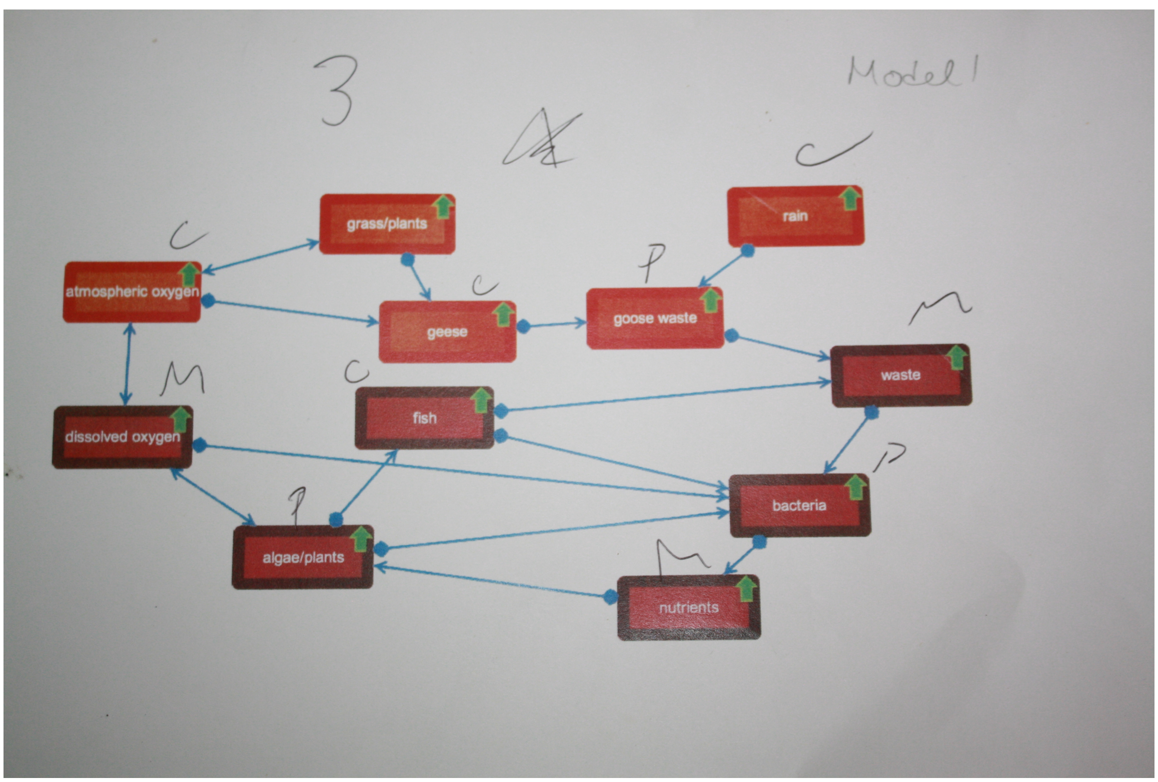


Figure 4.10 b Ethan's labeling of the geese problem in terms of CMP

Ethan's post-interview responses helped us understand his thinking in terms of CMP. His responses and labeled models indicated that he understood the role of components but had confusion regarding mechanisms and phenomena:

1. Interviewer: Okay. So I'd like you to label this in terms of components, mechanism, and phenomena. Like just circle what are components, write next to it "C", what are the mechanism, what's the phenomena.
2. Ethan: And I know I'll fail.
3. Interviewer: Okay.
4. Ethan: I don't even know what a mechanism is.
5. Interviewer: All right. Whatever you know, just do that.
6. Ethan: A component is like affects oxygen. And what's the other one?
7. Interviewer: Phenomena. Mechanism and phenomena.
8. Ethan: Yeah, I don't know what that is either.
9. Interviewer: So why are these phenomena?
10. Ethan: I don't know; I just guessed, 'cause I don't know what it means.
11. Interviewer: Okay. All right. You don't know what components or mechanism mean as well, right?
12. Ethan: Components are like things that like kind of like affect the problem. That's what components are. Then I have no clue what the other two are.
13. Interviewer: Okay, mechanism and phenomena you don't know?
14. Ethan: No.

Ethan admitted he was not confident that he would be able to label the model in terms of CMP (turn 2). Turn 8 confirmed this, as he was not clear about mechanisms and phenomena.

However, he was confident that components have a bearing on the final problem (turn 12). While reviewing his criteria for identifying the component-based model as one that best represented the geese problem, we observed that Ethan borrowed from his prior understanding of components:

15. Interviewer: Okay. All right, so what criteria did you use to make your selection?
16. Ethan: Well, I looked at the factors and I thought about which factors would be the best, and I thought that these two would be the ones – like both of them are the best, because they both included rain, which could be a key factor. But I chose this one-
17. Interviewer: This one, model one.
18. Ethan: -model one, because – 'cause I like the colors better.
19. Interviewer: Okay.
20. Ethan: No, just kidding. I don't know why; I just chose it randomly.
21. Interviewer: All right. So that's why you chose that this is the best one?
22. Ethan: Yeah, 'cause I just thought it like looked the best, 'cause this one is a little confusing with all the arrows and stuff. That one's all neat. And this one there's a lot of arrows too, but I just feel like that one-
23. Interviewer: That one is model one.
24. Ethan: Model one- has a lot more like better information on it.
25. Interviewer: Okay. So can you label this model one in terms of CMP, components, mechanism, and phenomena?
26. Ethan: Yeah, I can name the components. I'll just keep it the same.
27. Interviewer: Any mechanism or phenomena you know?
28. Ethan: I'm going to be guessing for these.

29. Interviewer: Any reason why those?

30. Ethan: No. I don't know what they mean, so I just guessed.

Turn 16 confirmed that Ethan regarded components played a key role in understanding the problem. He compared the component-based model to the one that displayed mechanistic connections between components. Between both of them he felt that the former would be an ideal fit as he liked the color scheme that was used, it had a clearer presentation and was more informative (turns 16, 22 and 24). Connections between components and mechanisms from the third model confused him (turns 22).

From an AOT perspective Ethan used the same criteria for unpacking both the problems. His responses indicate that he transferred his understanding of components as factors that help explain a problem. His confusions regarding the role of mechanisms and phenomena persisted between both the problems. This led us to consider experiences that led to Ethan's generalization of CMP. We turned our attention to Ethan's interview responses along with video footage of his groups' interactions with technological tools used in the study. The following responses were in context to the question on effects of cutting trees on the lake ecosystem:

Pre interview responses	Post- interview responses
Like there wouldn't be any birds anymore that would go around. There would be – it would like deserted, like nobody wants to live there. Like there would be no more shade if they cut down all the trees in the swamps and stuff. Alligators would like die probably, because they would have no	The lake would have no life whatsoever, 'cause the fish need oxygen, which there's none of because there's no more trees. Animals need fish to live, which the fish will die 'cause there's no more trees and oxygen. Animals also need oxygen. Then the microorganisms will also die and then it

food. And – yeah. No more tadpoles.	will just be a disaster.

From a MR perspective, Ethan identified trees, birds, wildlife and vegetation surrounding the lake as key components in the pre-interview response. His focus was on a specific property of trees i.e. their quantity. He established a linear cause and effect connection, explaining that cutting down of trees would affect the wildlife, causing them to die and not providing them the shelter that they need. In addition lack of trees would affect the vegetation such as swamps. In the post-interview response Ethan focused his attention on considering trees, fish, microorganisms and oxygen as components. Mechanistic relationships between components were linear in nature. For instance, he mentioned that aquatic life would be affected, as they would not get adequate amounts of oxygen.

Overall we noted that Ethan's thinking displayed similar levels of MR in both sets of responses. This led us to take a closer look at his classroom experiences that may have contributed towards his understanding of CMP. Ethan was part of an all male three-member group. While reviewing video footage of the group we noted that the group exhibited characteristics of low group cohesion, as there were multiple references to "I'm going to", "I also think" and "my turn". Primarily this was because tasks were conceptualized as individual rather than group work. This was important as it set the stage for the group's engagement with the curriculum.

For instance, prior to creating models in the pond unit the groups participated in whole class discussions where the primary focus was on identifying relevant components that may have led to the occurrence of the phenomena i.e. sudden death of fish. After reviewing information gathered from multiple data sources (such as video of the fish dying suddenly in the pond, data about water quality, its temperature, fish necropsy reports, pond hypermedia, pond macro and micro simulation) the class created a consensus model using the EMT software. All members of Ethan's group were present in class during such discussions.

When the class was instructed to use the modeling tool to construct their group model, each group member took turns to use the laptop. However, the group member in front of the laptop solely decided which components would be added to their model. Participation from others was expected to be restricted or minimal in nature. The video showed that Ethan added smoke, pollution from the air and presence of fish disease as possible factors when trying to explain what happened to the fish. Consistent with the group's participatory practice, other group members did not challenge inclusion of such factors.

Lack of collective sense making was obvious during model creation. While reviewing the group's model, we observed multiple representations of the same component (Figure 4.11). For instance, Ethan added fish, oxygen and dead matter. The component fish was added by his teammate Jake as well. Jake stressed the property that the fish are dying. In addition, he added another component called population that was also in context to fish. The third team member Elton also added fish, highlighting the fact that they are dying due to lack of oxygen. In effect, each group member added fish as component while stressing upon its varying properties and relations to other components. As a result the group's model reflected a partial understanding of how a specific component exhibits multiple behaviors on the basis of specific properties in the context of the problem. This resulted in low TE as the group did not have a definite plan for identifying relevant components and their properties.

Working independently also resulted in low levels of C-C engagement, as the group did no take up the opportunity to engage in collective sense making. This was evident as some of the connections between components were limited to reporting simulation outputs. For instance, Ethan established that oxygen and carbon dioxide had an inverse relationship by connecting the two components. However his explanation did not elaborate on the premise for this assumption or its connection to the phenomena. Given that group discussions were minimal in nature, justification for adding components was not apparent. As a result, overall low quality engagement fostered an environment where group members had limited opportunities to discuss multiple perspectives, make their thinking visible and engage in collaborative sense making, even though they were afforded by the modeling tool.

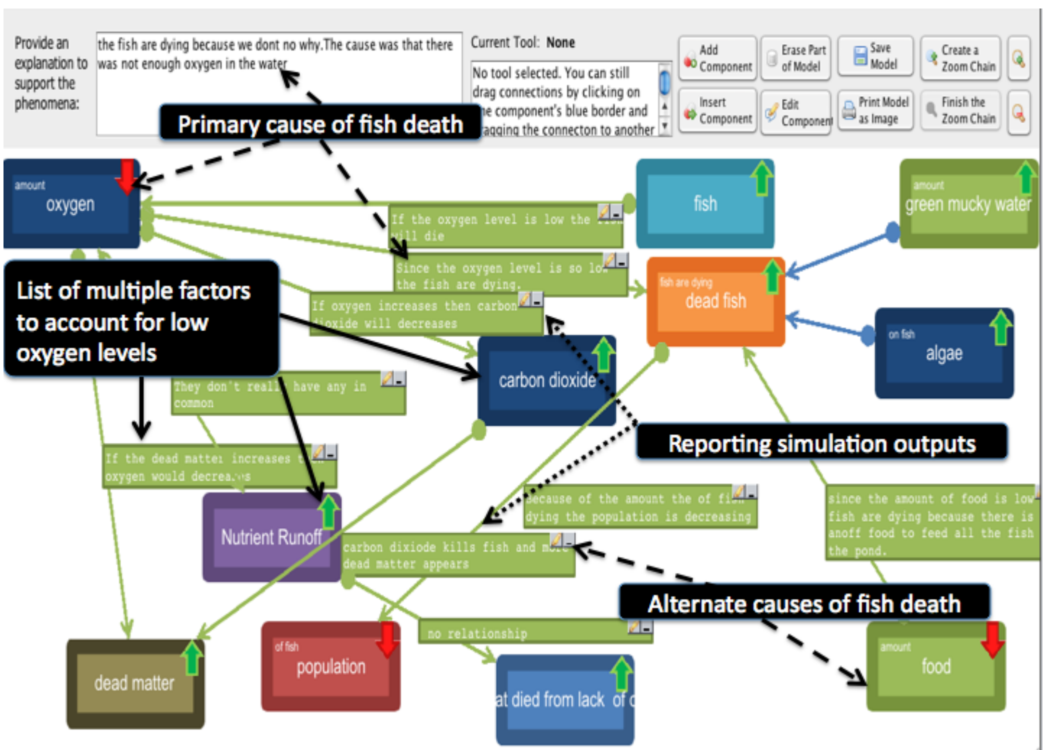


Figure 4.11 Duplication of components and reliance on outputs without interpretations

Considering his groups' engagement with the technological tools, Ethan's fragmented understanding of CMP was not surprising. We concluded that he accumulated pieces of knowledge about CMP based on his individual interactions with the two technologies. We conjecture that group dynamics made it challenging to fill in the gaps.

As part of our data analysis we identified several groups that displayed similar levels of engagement. Having analyzed influence of low engagement on Ethan's understanding of CMP, we were curious to know if it had similar effects on other students from such groups. This drew our attention to our final case study, Andy whose group displayed low engagement.

Low engagement-High transfer of CMP. Andy identified fish population going down as phenomena while labeling his group model from the pond unit (Figure 4.12 a). Other colored boxes were marked as components and the explanations of connections between the components were identified as mechanisms.

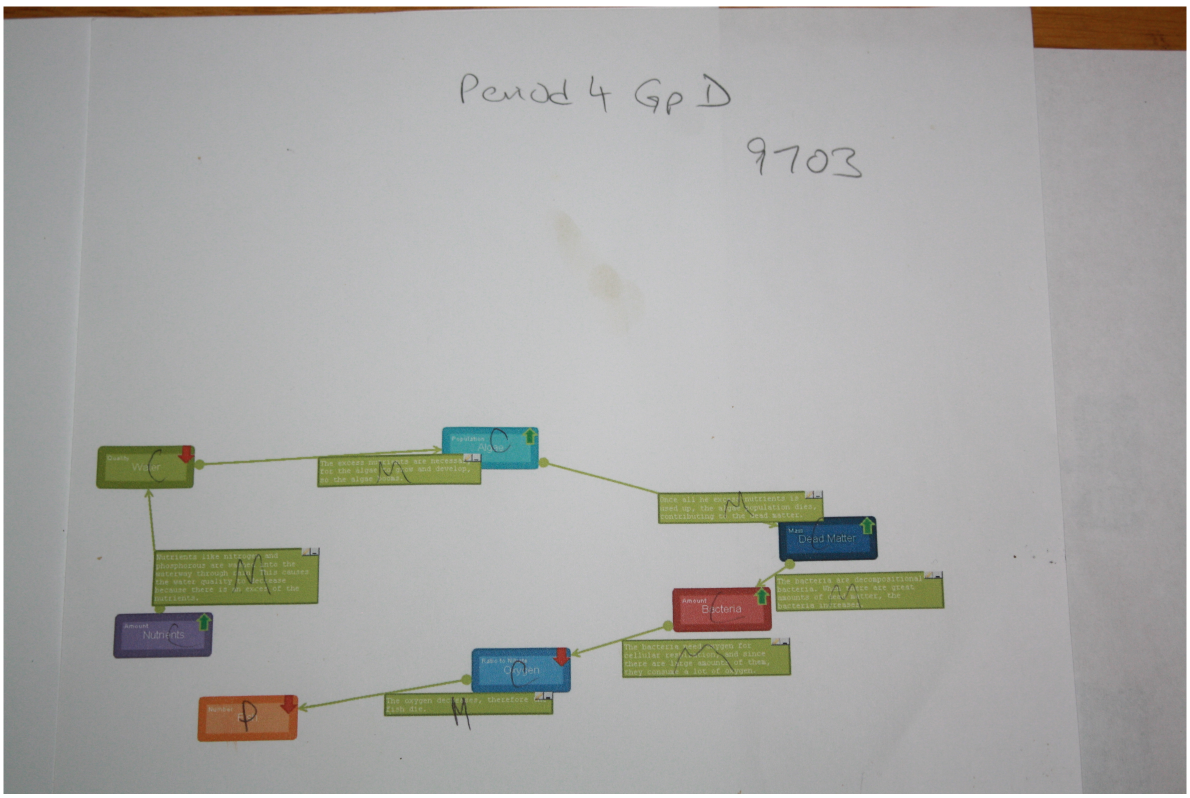


Figure 4.12 a. Andy's labeling of the pond problem in terms of CMP

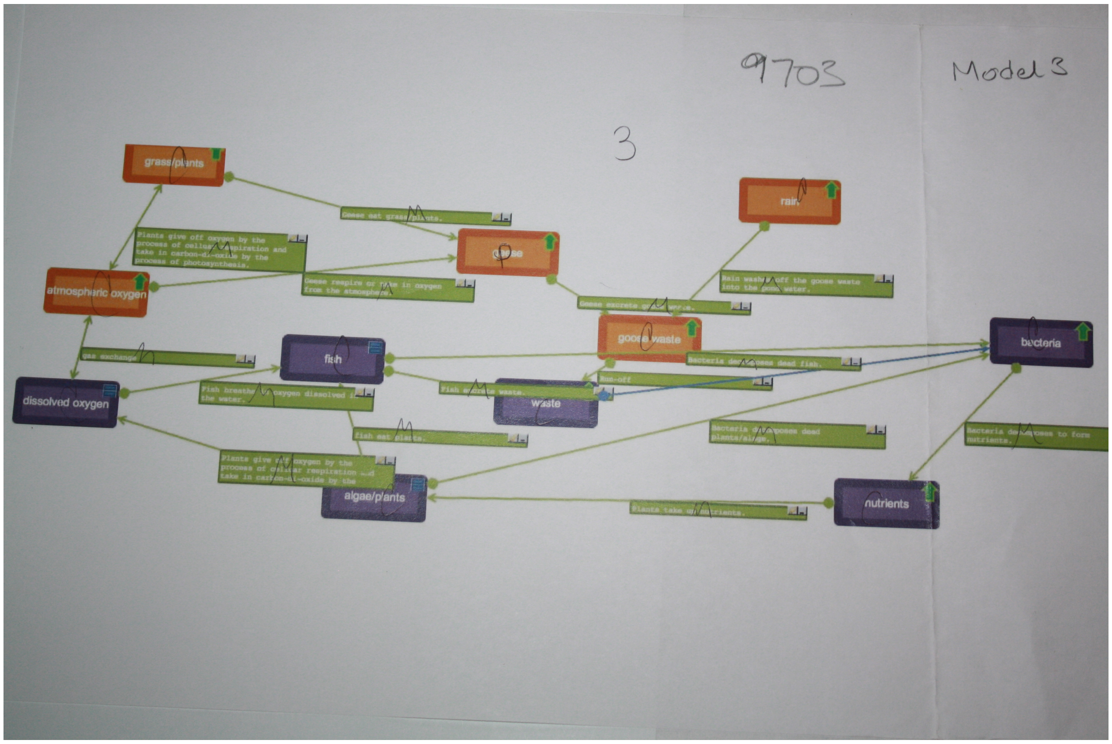


Figure 4.12 b Andy's labeling of the geese problem in terms of CMP

In the geese problem, Andy identified the model with detailed explanations between multiple components and mechanisms as the one that best explained effects of overpopulation of geese on the ecosystem (Figure 4.12 b). He marked increase in geese as the phenomena. The other colored boxes were marked as components and explanations connecting components as mechanisms. When asked to explain his criteria for identifying the third model as the best he said:

> I used it to explain what was happening between components. Um, I used how whether it included the subject on which the phenomena was about which was the geese, and whether it was easy to understand.

It appeared Andy had several criteria for model selection. The first was that the model that could be used to reason about processes or behaviors between components. The second was that it needed to include the phenomena as one of the components. And the third was that it needed to be easily understandable to him. Comparing the labeled models it was apparent that Andy relied on his prior understanding of CMP to make sense of the new problem.

This was apparent when we compared his responses to the interview questions. Post-interview responses indicated an enhanced understanding of CMP. The excerpts were taken from Andy's response to the effect of fertilizers leaking into the lake ecosystem:

Pre-Interview	Post-Interview
It will definitely kill all the fish if it's fertilizer. Fertilizer is poisonous to us. Imagine the effect on the fish. They would definitely no longer be able to breathe. They would absolutely die out in that lake. And then also frogs and then birds would move away. All other animals would move away 'cause it's no longer a viable drinking source. Humans probably wouldn't want to be there. I mean no one would want to live around that lake and even some plants would die out in the lake.	It would be like the eutrophication scenario like we learned about in the first unit.The fertilizer would be causing algae bloom and then they get, die off. And there's an increase in carbon and this causes the fish to die. Fertilizers contain nutrients that help create algae that are necessary for algal growth so when it leaks in, these chemicals enter the water.

In the pre-interview Andy displayed a predominantly linear MR i.e. explaining cause and effect without providing a detailed explanation. For instance, he discussed the relative effects of fertilizers being released in pond water as being dangerous for human beings and aquatic life. From a MR perspective his post-interview response indicated a sophisticated understanding of mechanisms as he was thinking about multiple processes that tied together several visible and invisible components. From an AOT perspective it was evident that Andy understood that the outcome for this question was similar to the pond problem as both were a result of the process of eutrophication.

In order for us to identify key experiences and incidents that may have influenced Andy's thinking about CMP during the curriculum unit, we took a closer look at his group's engagement with the tools. On multiple occasions, member of his group (Andy, Kevin, Gillian and Megan) conceptualized tasks as individual efforts. However when they did decide to work together, they took up the opportunity of considering multiple perspectives to pay attention to superficial aspects of the task. For instance, while using the modeling software, Andy and Kevin identified components to be added and possible content connections. At the same time, Gillian and Megan engaged in off-topic conversations and doodled in their notebooks. Collectively the group got involved in the editing process when deciding the color of components and when they sensed that the teacher was likely to approach their table to check on their progress:

1. Andy: What color should we do for living space?
2. Gillian: Did we do green yet? *(She goes back to drawing in her notebook.)*
3. Andy: We should do black. Ok, no we didn't do green yet.
4. Kevin: Green we should do green. *(Andy changes the color and begins typing.)*
5. Gillian: Why are you talking like an idiot?
6. Kevin: Ok, so we need to add amount of food.
7. Megan: Mrs. A is coming. *(At this point, Gillian promptly put away her color pens and leaned in towards the laptop.)*
8. Gillian: Guys, turn it more.

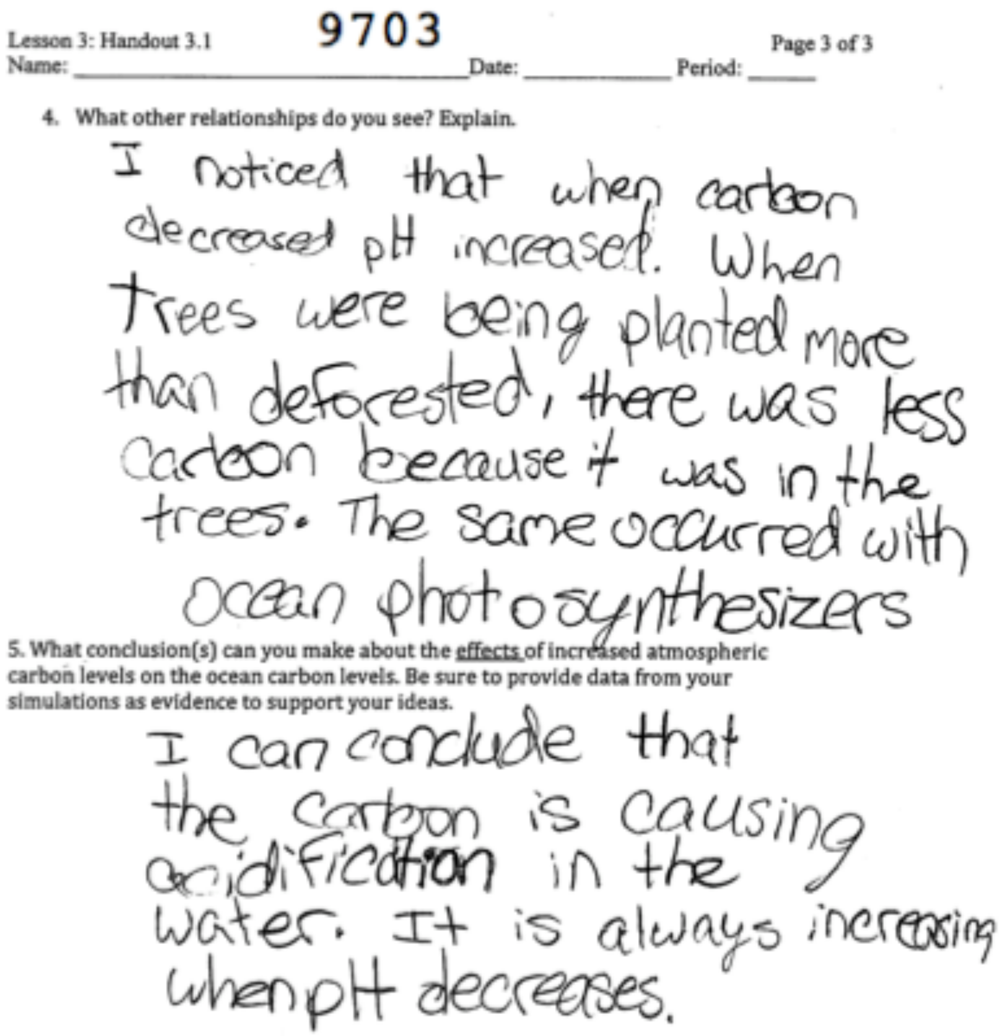
9. Kevin: You guys were not even paying attention.
10. Andy: Yes, you guys were doodling.
11. Gillian: Yes, 'cos this is boring.
12. Kevin: Yes but we still got to do this.
13. Megan: I think we should make this line blue *(Pointing to an arrow that had changed color from blue to green as Andy had finished writing a connection between two components.)*
14. Kevin: No, no... if we make it blue we'll have to erase it
15. Megan: We should make all of these blue *(Pointing to all the arrows that were green in their model)*
16. Andy *(to Kevin):* Ok let's finish up writing all this

There were a few occasions when members engaged in whole group discussions. Once was when deciding the color of components (in turns 1-4). The second time was when Megan alerted them that their teacher was going to come to their table (in turns 6-11). During such instances group participation focused on superficial features. This trend continued as the group discussed color of arrows (in turns 12-14). After the time period described above, Andy and Kevin continued to edit their model. The two boys were observed having brief conversations while making the edits. The girls continued to talk among themselves.

Overall, the group was moderately engaged as only Andy and Kevin were working on making the edits. As a result, their engagement with the task fluctuated between moderate to low level given that Gillian and Megan only participated in discussions related to color of components and arrows. The limited whole group interaction led the group to achieve medium to low C-C engagement with the tool. Primarily this was because the group used the affordance of modeling their thinking about the aquatic ecosystem to focus on superficial aspects such as shape and color of the model.

While working on the carbon simulation, in the unit on marine ecology, the group demonstrated a similar engagement pattern. This time it was Kevin who made the decisions on how to set up the variables and run the simulations. Andy looked intently at the screen without making any contributions. Megan and Gillian continued to engage in off-topic conversations.

While completing handouts accompanying the simulations, it was only Andy who wrote a detailed explanation of possible effects of increase in atmospheric carbon (Figure 4.13). Kevin wrote a brief description, saying, “It is destroying coral reefs and marine.” Megan and Gillian left their sheets blank.



Lesson 3: Handout 3.1 **9703** Page 3 of 3

Name: ______________________ Date: __________ Period: _____

4. What other relationships do you see? Explain.

I noticed that when carbon decreased pH increased. When trees were being planted more than deforested, there was less carbon because it was in the trees. The same occurred with ocean photosynthesizers

5. What conclusion(s) can you make about the effects of increased atmospheric carbon levels on the ocean carbon levels. Be sure to provide data from your simulations as evidence to support your ideas.

I can conclude that the carbon is causing acidification in the water. It is always increasing when pH decreases.

Figure 4.13 Andy's understanding of the carbon simulation

In his explanation Andy identified components such as carbon, oceans and pH. In terms of thinking about mechanistic behavior, he emphasized that carbon caused ocean acidification and that carbon and pH have an inverse relationship. He also discussed that the process of cutting down trees was causing decline in carbon levels. We concluded that Andy stayed very close to reporting simulation outputs while making minimal interpretations. Overall he identified relevant components but was limited in terms of focusing on conceptual connections that were a result of simulation outputs. A possible explanation for this could be that the group's collective sense making was successful in directing the members to take up opportunities that would draw their attention to superficial features.

There was an interesting disparity between Andy's group engagement level and his own transfer of CMP. Overall his group displayed moderate levels of TE and C-C engagement with the tools. Their primary focus was on identifying relevant components pertinent to the phenomena and on reporting simulation outputs. However Andy's post-interview transcripts indicated a sophisticated level of MR. As he reasoned about problems from a mechanistic perspective, his primary criterion was ensuring that he understood the problem as the phenomena. Next, he identified several relevant components and their properties in context to the problem. His responses reflected that he relied on his understanding of mechanisms to identify complex cause and effect between components.

This finding presented an interesting paradox. Andy's collaborative engagement with technological affordances did not have a bearing on his individual level of transfer. This implies that not all kinds of engagement can be captured by observational measures.

4.5 Discussions

The National Science Education Standards (National Research Council, 1996) recommends that students develop abilities for scientific inquiry. Russ et al. (2008) second this notion by emphasizing that the focus of elementary science curriculums should be to refine students' inquiry skills by giving them opportunities to engage in scientific reasoning. MR encourages inquiry-based practices as it promotes predicting and explaining behavior of components within the context of physical systems (Machamer et al., 2000; Nersessian, 2008). The National Research Council (2011) suggests that students can begin to reason about causal mechanisms by working with simple machines such as gears. A key aspect that makes it possible to reason mechanistically with simple machines is that parts or components of the system are made visible to the students. However, elementary school students find it challenging to reason about moderately simple machines even if all the parts are visible (Bolger et al., 2012).

To this effect our study introduces multimedia technologies that makes it possible for students to engage in MR by visualizing macro and micro level components. Affordances of the simulations and the modeling software make it possible for students to make sense of processes that lead to phenomena observed in aquatic ecosystems. Specifically, the tools were designed to encourage MR by using the components-mechanisms-phenomena framework. Our findings reflect that students' collaborative engagement with the tools determine the extent to which they notice specific aspects of CMP. This sheds light on one of our primary research agenda i.e. to trace students' MR across contexts. A limitation of this study is that students used the technologies (simulations and EMT) to make sense of phenomena observed in a single area of biological sciences (aquatic ecosystems). Using the same set of tools to make sense of problems in other areas of science would have been useful to measure their effectiveness in promoting MR.

While group engagement set the stage for groups to focus on specific aspects of mechanistic reasoning, our findings indicated unusual trends in terms of generalization of the CMP framework to solve new problems by individual group members. This addresses our secondary research agenda. In order to identify the exact nature of CMP understanding being transferred by individuals, AOT (Lobato, 2003) was best suited for our research purposes. This is because it helps to "understand the interpretive nature of the connections that people construct between learning and transfer situations as well as the socially situated processes that give rise to those connections" (Lobato, 2012; p. 239).

For instance Tanya's group displayed high levels of TE and C-C engagement in several instances. They focused on establishing connections between visible and invisible components. Discussions centered over making sense of mechanistic processes observed while running the simulations. However Tanya's group demonstrated a partial knowledge of CMP. This was evident from her responses on the transfer task where she focused on mechanisms as the criteria for making sense of the problems, without considering the relevance of components in context to the problems. We conjecture that even though her group was successful in engaging in specific aspects of mechanistic reasoning (such as testing for relationships between components), Tanya may have found it challenging to grasp intricacies of the concept as it may have been beyond her zone of proximal development (Vygotsky, 1978).

On the other hand Andy's group demonstrated moderate-to-low levels of engagement with the tools during curriculum implementation. Group discussions were focused on superficial aspects of the task such as deciding the color of components. They reported mechanistic processes without interpreting its effect on the phenomena. However, this had no bearing on Andy's understanding of CMP as a framework to engage in MR. His responses on the transfer task and interview questions reflected a sophisticated knowledge of CMP. From an AOT perspective we accounted that the source for his transfer was "distributed across individual cognition, social interactions, material resources, and normed practices" (Lobato, 2012; p. 241).

Findings from Matt and Ethan were also informative. In both cases individual transfer was a reflection of the extent to which their group engaged with the technological tools. Overall we observed variations of MR by each of our case studies. The cause for differences were a combination of factors, such as individual level of cognitive development, aspects of CMP that were given importance to by group members, group dynamics and engagement with technological tools. Observing CMP transfer by participants who were in the same groups as our four case studies would have positioned us to generalize our claims and report on additional transfer and reasoning trends.

4.6 Future Research

An implication of this study is to further refine and redesign the curriculum based on students' generalization of the CMP framework as highlighted by the AOT approach. As a result, findings from such studies provide valuable insights in terms of informing curriculum designers of iterative steps to be taken for redesign and implementation (Kelly, Lesh & Beck, 2008; Lobato, 2003, 2008). For instance, based on findings from the study, technologies such as simulations and modeling tools can be redesigned to draw students' attention to specific aspects of CMP that may influence subsequent transfer.

We would like to conclude by reiterating that the focus of this study has been to illuminate the unique ways by which students learn and transfer understanding of a complex reasoning strategy to make sense of natural phenomena. Findings from the study are a step towards emphasizing the relevance of the sociocultural perspective (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011) on understanding the relation between students' collaborative engagement and subsequent individual transfer.

Chapter 5: Conclusion

5.1 Introduction

The new millennium has seen an increase of science curriculums that encourage inquiry-based practices (National Research Council, 2000, 2007). Students are afforded opportunities to experience scientific practices such as experimentation (Kuhn, 1989), argumentation (Driver, Newton, & Osbourne, 2000), and modeling (Lehrer & Schauble, 2005). In the recent past, the National Research Council (2011) has pushed education reformers to incorporate technology-rich technologies in science curriculums as they have the potential to advance the desired inquiry-based practices. Learners are positioned to take on active roles such as predicting outcomes, experimenting with variables, in addition to observing and interpreting simulation outputs. From a situative perspective, the onus of learning in such contexts is distributed across teachers, students, curricular tools and artifacts. As a result it is pertinent to question the extent to which students engage with technology-rich learning contexts. This is important from dual perspectives. First, it is likely that such learning environments may not be equally engaging for all students. As a result, interactions with the learning environment may lead to variations in students' uptake of opportunities to engage in scientific inquiry-based practices. Second, the current emphasis on rewarding students' scientific thinking if it matches ideas presented in their textbook, does not account for the influence of the social environment on the development and subsequent transfer of scientific inquiry skills (Russ et al., 2009). The focus of this dissertation has been to illuminate the unique ways by which students develop understanding of a complex inquiry-based reasoning strategy in the context of technology-rich learning environments and use it to make sense of new problems.

5.2 Findings and Implications

As learning scientists we assume that computer-supported inquiry learning environments are engaging and provide affordances for high quality participation. Krejins et al (2002) caution us that purposeful interactions may not necessarily occur even though they are afforded by available technologies. This implies that there are differences in the ways students participate in inquiry-based practices in such contexts. As demonstrated in Chapter 3, characteristics of group engagement relate to how groups take up opportunities afforded by technology-rich environments to engage in inquiry learning. Findings from quantitative and qualitative data analysis indicate that social coordination has a bearing on the amount and quality of time spent on planning for tasks and discussing ideas for hypotheses testing. Highly engaged groups are equally successful in taking up opportunities afforded by simulations and the modeling software. Such groups rely on interactions with the technologies to develop a community where knowledge is constructed. All group members have equal opportunities to share their ideas and make their thinking visible. As a result, collaboration yields in making sense of the problems by carefully planning experimentation with variables, testing their hypotheses and interpreting and analyzing the outcomes in context to the problem.

Groups that display moderate-to-low levels of engagement focus their attention on superficial aspects of the task with both technologies (simulations and the modeling tool). Interaction with the technology is confined to active participation, either by a single group member or half the group in such cases. This implies that feedback from all group members is not solicited and integrated consistently. Such fractured interactions have a bearing on the groups' inquiry-based practices of collective sense making and hypotheses testing.

There are multiple implications for observing overall group engagement patterns in computer-supported inquiry based environments. First, from a situative perspective (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011) findings reflect that while collaboration in such contexts is a precondition for engagement to take place, the mere presence of collaboration does not necessarily imply that students will be engaged. We observed that all group members did not engage with technological tools or the assigned task with the desired and identical levels of intensity. Future research in this area calls for conducting the study with an increased number of participants. This is key to reinforcing generalizations of the findings and also brings forth a wider spectrum of engagement trends. This will also shed light on aspects of the learning context that encourage positive participatory practices.

Second, findings from the study advance the literature of using technologies such as simulations as an integral part of science curriculums (Clark et al., 2009). Existing research supports the use of simulations as a tool to promote conceptual understanding (de Jong, 2009; Quellmalz, Timms, and Schneider, 2009). Linn et al. (2010) propose that simulations can be designed to improve learning outcomes. They suggest that simulations can be used to present problems that are meaningful from a student's perspective. These are beneficial as they allow students to draw from prior knowledge and ask effective questions to make sense of such problems. However, the National Research Council (2011) stresses the need to look beyond improving upon the design of simulations and emphasizes conducting research that explores the possibilities by which simulations can advance science-processing skills. The design of studies in this dissertation, ensured that students had multiple opportunities to use tools such as simulations and modeling software to construct models of their evolving understanding, ask questions in the form of hypotheses testing and engage in experimentation in the context of aquatic ecosystems. Having students use the same set of tools to solve problems in other areas in science would have added to the literature on use of technologies to promote scientific inquiry and development of content knowledge.

Last but not the least, observing collaborative engagement sets the stage for identifying unique trends of learning and transfer established by individual group members. Focusing on engagement illuminates aspects of MR that the groups pay attention to. Technologies (such as simulations and modeling tool) facilitate MR by making it possible to visualize macro and micro level components. Affordances of the technologies provide opportunities for students to make sense of processes and mechanisms that lead to phenomena observed in aquatic ecosystems. Specifically, the designs of the tools encourage MR using the CMP framework. Findings from Chapter 4 demonstrate that while collaborative engagement set the stage for groups to focus on specific aspects of MR, the AOT lens (Lobato, 2003) highlights generalization of the CMP framework in unique ways. As a result there are differences in the ways the CMP framework is interpreted and applied to engage in MR by individual students.

Groups that display high quality collaborative engagement focus on establishing connections between visible and invisible components. Discussions are geared to make sense of mechanistic processes observed while running the simulations. In contrast moderate-to-low levels of engagement with the tools lead groups to focus on superficial aspects of the task such as deciding the color of components. Such groups report mechanistic processes without interpreting its effect on the phenomena. However, individual group members from such groups demonstrate variations in terms of understanding CMP and making sense of new problems by engaging in MR. It is likely that transfer by individual participants is a function of interactions with multiple facets of the learning environment. Observing collaborative engagement with technologies and individual CMP transfer by multiple participants who were members of the same group, as the four case studies discussed in chapter 4 has the potential to extend our understanding of students' MR skills.

Overall, findings from Chapters 2 and 4 advance research in the field of MR. Focusing on collaborative engagement with technological tools and individual transfer of CMP as a framework adds to the field of assessment of MR. Given that the focus of the dissertation is to uncover ways by which learners engage in and transfer reasoning practices, assessments in the field of MR need to look beyond accuracy of conceptual understanding. Alternate theoretical lens of transfer, such as PFL (Bransford & Schwartz, 1999) and AOT (Lobato, 2003) highlight interactions that are engaging for learners and subsequently, lead them to generalize their understanding of MR. For instance, findings from chapter 2 demonstrate a middle school science teacher's generalization of understanding of the SBF conceptual representation used to reason about complex systems. The study focused on uncovering processes by which she transfers her understanding of SBF to make sense of one natural system (an aquarium ecosystem) to another natural system (human cells and body systems). Findings indicate that the AOT lens is useful to reach backwards and see how the similarities were constructed.

Specifically, the AOT lens indicates the relevance of social environment and technological affordances. For instance, the teacher emphasized the importance of collaboration with fellow colleague and members of the research team that helped refine her understanding of the SBF framework. In addition, having a general-purpose tool that she could re-purpose to use for a new unit was instrumental in this process. Finally, she was able to use the hypermedia that the research team had created as a worked example that allowed her to explore the content and how SBF could be applied to a new domain.

The PFL perspective allows us to look forward at how applying SBF prepared the teacher for her future learning and practice. Findings indicate that the SBF representation focuses the teacher's attention on the behavioral connections and functional roles of components within complex systems. It prepares her to think about the actions or "how" components behave within a complex system in relation to their overall functions. Overall, this case study provides an existence proof that AOT and PFL can be used to explain a single case of transfer. An implication of this study is the need to conduct further research in complex classroom environments in order to generalize these findings.

As a result, the study in chapter 4 focuses on observing collaborative engagement and individual transfer of MR skills (from an AOT perspective) in a technology rich classroom setting. Multimedia tools that support the curriculum encourage learners to develop desired inquiry-based reasoning practices recommended by the National Science Education Standards (National Research Council, 1996). Findings demonstrate that collaborative engagement with technologies influences individual transfer of MR in unique patterns. An implication of this study is to further refine and redesign the curriculum based on students' generalization of the CMP framework as highlighted by the AOT approach. As a result, findings from such studies provide valuable insights in terms of informing curriculum designers of iterative steps to be taken for curriculum design and implementation (Kelly, Lesh & Beck, 2008; Lobato, 2003, 2008). For instance, based on findings from the study, technologies such as simulations and modeling tools can be redesigned to draw students' attention to specific aspects of CMP that may influence subsequent transfer. Specifically, simulations can draw students' attention to the termination stage and encourage them to identify components and their properties that result in the observed phenomena. Next, students can be encouraged to work backwards and focus on understanding properties of simulation variables that lead them to interact with other components in specific mechanistic processes. The EMT tool can be redesigned to prompt students to establishing mechanistic connections by relying on credible sources of information. In addition, an indicator that allows students to classify components as visible and invisible will be beneficial to reinforce the idea that interaction between several components (some of which may be invisible) may result in specific phenomena.

Findings from this dissertation emphasize the relevance of the sociocultural perspective (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011) on the relationship between learning and subsequent transfer. Further, the AOT lens identifies that the source for transfer is "distributed across individual cognition, social interactions, material resources, and normed practices" (Lobato, 2012; p. 241). As a result, identifying the importance of a single factor that influences individual transfer of reasoning skills is a complex task. The work in this dissertation suggests that patterns of reasoning are a result of a combination of factors, such as individual level of cognitive development, aspects of

CMP that were given importance to by group members, group dynamics and engagement with technological tools. Further studies with large participant pool, inclusion of a wide array of multimedia technologies and curriculums that encourage students to engage in MR in varying contexts is required in order to generalize findings of studies from this dissertation.

5.3 Future Research

There is a general concern that schools do not give students opportunities to engage with curricular content in conceptually and consequentially meaningful ways (Gresalfi et al., 2009). Designing such rich learning environments is a challenging task. Unpacking student engagement in such complex learning environments may help in overcoming this challenge. This dissertation is a step towards observing characteristics of students' engagement in curriculums that encourages such high quality engagement and provides opportunities to make use of the CMP framework to learn about systems thinking. Findings reflect that CMP and MR serve the dual purpose of promoting content understanding and scientific reasoning practices. Specifically, the engagement-coding scheme helps to tease apart influences and interactions between various kinds of engagement that have a bearing on uptake of affordances. The study in chapter 3 unpacks factors in computer-supported learning environments that promote positive participatory practices. Further research in this area will highlight strategies to increase engagement and its influence on learning and transfer. Qualitative data analysis would be beneficial to capture the richness of collaborative interactions with technologies and its influence on individual transfer.

This emphasizes the influences of the sociocultural perspective as it helps to identify factors that may possibly influence learning and transfer (Greeno, 1998; Hickey & Granade, 2004; Nolen et al., 2011). Specifically this research is consistent with alternate lenses of transfer that explore aspects of the learning environment that draw students' attention to learn new content and subsequently use this knowledge to make sense of new problems (Lobato, 2006; Bransford & Schwartz, 1999; aVan Oers, 1998). The analysis presented in this dissertation suggests the possibilities of extending research on alternative approaches to transfer. These new approaches to transfer suggest a much more complex and dynamic process than traditional cognitive accounts. The findings also suggest that different theoretical frameworks can be productively integrated in providing accounts of transfer. As exemplified in chapter 2, teacher adoption and appropriation of a learning framework is an exciting by-product of scholarly research because it provides evidence that classroom innovations can be appropriated and sustained. Overall, findings from this dissertation inform the development of curriculums and technological tools that have the potential to support and encourage sophisticated reasoning skills.

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Appendix A

Interview Protocol - Study 4

1. Scientists and city officials are concerned about the increase of human populations in coastal areas of the United States. They are particularly worried about water quality.
   a) Why do you think they are concerned about water quality?
   b) In what ways can water quality affect the ecosystem?
2. A company wants to build a fertilizer factory. The new factory will be located right near the lake.
   a) What would happen if the fertilizers leaked into the lake ecosystem?
   b) Why do you think (those things) would be affected?
3. A logging company is cutting down trees around a lake. What are its effects on the lake ecosystem?
4. Task A: I am going to show you the model your group created on the problem with fish dying in the pond. I would like you to label this model in terms of Components-Mechanisms-Phenomena. That is circle what you think are components, mechanisms and phenomena. Write next to it C, M or P.

   Task B: There has been a sudden increase of geese population around a lake. This has resulted in changes to the aquatic ecosystem in the lake.

   I’m going to show you three models that were created using the EMT software that describe the situation.

There are three things I would like you to do now:

(i) Rank them on a scale of 1- 3 with 3 being the one that best describes the situation. *Give them a pen/pencil to write down their choice on each of the three sheets of paper.*

(ii) Explain what criteria you used to make your selection. *If they ask, what do you mean by criteria, say how did you decide that model # (whichever one they selected) best explains the situation. If they choose model # 3 (i.e. the one with detailed mechanism-component connection) ask them to explain how the multiple connections help in explaining how over population of geese may influence what's happening to the aquatic ecosystem in the pond.*

(iii) Label this model (i.e. the one they selected) in terms of components-mechanism-phenomena. That is circle what you think are components, mechanisms and phenomena. Write next to it C, M or P. *Give them a pencil/pen to label their models.*