STUDENTS' VIEW TOWARD BIOLOGY AS A COMPLEX SYSTEM

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“STUDENTS' VIEW TOWARD BIOLOGY AS A COMPLEX SYSTEM”

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And hereby certify that, in their opinion, it is worthy of acceptance.

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DEDICATIONS

To the memory of my mother.
Maman, your appreciation of my tiniest efforts led me to reach the biggest accomplishments. Your great spirit and your larger than life presence is in my heart forever.

To my Marzie.
Your faith in me encouraged me to take this journey and you accompanied me on every step of it. I accomplished this because you were by my side.

To my Ahva.
May you always know that it is possible to live your dreams.

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ABSTRACT

System thinking is found to be a proper approach to address the complex problems of our modern world. However, while it is practiced in various science disciplines, it is not yet embedded proportionately into science education. In this study, through a mixed methods approach, I first examined students’ system thinking skills in response to complex problems and then, in a separate study, I investigated how concept map as an assessment tool could assess and enhance students system thinking skills. My results indicated that students tend to use simple causal reasoning to argue about complex biological problems and largely draw on domino causal pattern to show the relationship among biological concepts. I also found that students’ system thinking skills improved when they were prompted about complex causalities and scaffolded for making diverse causal relationships. At the end, based on the results of my studies, I developed a teaching framework for complex systems that provides instructors with guidelines on how to embed causal mechanisms and the features of complexity into their teaching practices.

Chapter 1

Introduction

Our world is composed of complex systems. These systems entail numerous heterogenous components that through interacting with each other develop various collective structures and demonstrate emergent behaviors (Baicchi, 2015; Bar-Yam, 2016). These features of complexity, while creating our world, also attribute to the most pressing challenges of our time such as environmental issues, disease pandemics, social inequities, etc. To address these challenges, researchers propose system thinking (ST). However, it is shown that even among well-educated people there is a lack of skill for ST (Moxnes, 2000; Sterman & Sweeney, 2002). Accordingly, in recent years there has been numerous calls for improving students' ST skills by education researchers (Yoon et al., 2018) and it is internationally emphasized in education documents (Boersma et al., 2010; National Research Council, 2010; NGSS Lead States, 2013). In this regard, in this study I attempted to explore students' view toward biology as a complex system and accordingly how we can improve students' knowledge and skills in regard to features of complexity in biological systems. To this end, three key questions guided this dissertation:

1. What reasoning patterns do students apply in response to complex problems and what those patterns tell us about students' view toward biology as a complex system?
2. What are the potentials of concept map as a tool to assess and enhance students' system thinking skills?
3. What would be a proper teaching framework for system thinking?

This is a three-manuscript dissertation. Each of the three main chapters are written with a specific journal and audience in mind. The following paragraphs provide a summary of each manuscript.

Chapter two is a research on students' knowledge of complex systems and their ST skills. Having different types of causal mechanisms as a theoretical lens, this study attempts to provide a holistic picture of students' ST in response to complex problems. In specific, it pursues to answer the following questions:

1. What patterns of ST emerge from students' reasonings about biological and environmental issues?
2. What is the relationship between students' knowledge and the types of reasoning they apply?
3. What is the relationship between the various forms of reasonings students apply?

To this end, through a mixed method approach, I analyzed undergraduate students' (n = 135) explanations to some biological and environmental problems. The results indicated that students used a variety of reasoning styles to address complex problems and that such reasoning styles were related to each other and dependent on students' background knowledge. The results were also informative about the role of education in students' ST. Drawing on the results of this study and the extant literature about students reasoning patterns, I propose a system thinking model that explains how students' background knowledge and their ST elements are interrelated to each other.

The focus of chapter three is on concept map (CM) as a tool to assess and enhance ST in students. CM is a graphical tool depicting the relationship of concepts within a domain of knowledge and is used to organize and represent the structure of conceptual knowledge (Novak & Gowin, 1984; Novak & Cañas, 2008). It is suggested as a helpful instrument for studying students' ST (Sommer & Lücken, 2010). However, CM is more known to represent students' knowledge of a system components and organizations and less recognized as a tool to examine and enhance students' understanding about the underlying causal mechanisms in complex systems. In this regard, I specifically answered the following questions:

1. What does CM reveal about students' knowledge of the causal mechanisms in complex systems?
2. How does scaffolding influence students' performance in showing the causal mechanisms in their CM?

In this study, I comparatively analyzed the CM of undergraduate students (n = 173) through a mixed method approach and investigated the potentials of CM in demonstrating students' ST and the effect of different scaffoldings on developing their ST skills. The results indicated that CM is a powerful tool to reveal students' knowledge of causal mechanisms in complex systems, while also having some limitations to show some system behaviors. The results also showed that students improved in demonstrating ST by CM when they were scaffolded for showing causal mechanisms and building CM. Eventually, this study concludes that the CM is a proper tool to increase and examine students' ST skills. But, to this end, students must be explicitly instructed on causal patterns and how to construct CM with the emphasis on showing the interconnection among concepts.

Chapter four is focused on providing a teaching framework for complex systems to a practitioner audience. It is based on the literature about students' learning and ST as well as the findings from the previous two studies. It entails four steps that each aim to improve students' ST competencies in some respects and starts from addressing easier concepts in complex systems toward more difficult ones. First, it starts with defining the concept of system to students. Second, it introduces the components of a complex system with their specific roles and organizational levels. Third, it focuses on the interactions among a system components and introduces causal mechanisms to students and have them practice the various cause and effect relationships by concept map building. Last, it focuses on introducing the causal features of complex systems to students through comparison discussions and open-ended questions.

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Chapter 2

Students' View toward Biology as a Complex System: Emerging Patterns of System Thinking

Introduction

Our world is composed of complex systems. These systems are highly interconnected and interdependent and demonstrate emergent behaviors. These characteristics, while creating our world, contribute to the most pressing challenges of our time as well. Take the COVID-19 pandemic for instance. It emboldens the interdependence of our modern world on all of its individual players and highlights the matter of interaction among those individuals in bringing about challenges at various health, social, cultural, political, and economic levels. Due to its complex dynamic behavior, the COVID-19 pandemic, despite its recency, is a classic “wicked” problem similar to climate change, social inequity, and crime (Alcendor, 2020). A wicked problem refers to a situation in which there is controversy about the existence or nature of the problem and thus what might be a proper solution (Rittel & Webber, 1973). To address such problems, Ison and Straw (2020) underline the need for a systemic response. But even among well-educated individuals there is a lack of required cognitive skills to understand the behavior of complex systems (Moxnes, 2000; Sterman & Sweeney, 2002). The denials, confusions, and lax responses to the COVID-19 pandemic also confirms this lack of system thinking (ST) skill among people with various levels of education at our current time. The lack of ST skill and indeed poor literacy about complex systems have been noted by education researchers for a long time (Yoon et al., 2018), but the acute persistence of the old complex problems and the emergence of the new ones call for more urgent actions to investigate and embed ST in education.

Complex systems are composed of numerous interdependent components that through multiple cause and effect relationships exhibit behaviors and structures at different scales (Bar-Yam, 2016). Accordingly, the study of complex systems is about understanding the behavior of systems at various scales concerning the interactions among their lower scale components and the emergence of behaviors at their larger scales (Bar-Yam, 2016). By learning about the patterns that emerge from the interactions within systems, scientists gain insight into the features of complex systems, such as non-linear relationships, feedback loop mechanisms, adaptations, and self-organizations. Emphasizing scientific thinking and practices in science education, NGSS proposes crosscutting concepts. Such concepts arguably relate to the research that complexity scientists undertake to solve current social and environmental problems (Yoon et al., 2019). However, research shows that students have difficulties in understanding and reasoning about complex systems. For example, comparing experts' and novices' understandings of complex systems, Hmelo-Silver et al. (2007) found that middle school students and pre-service teachers argue about a system largely based on the structure and components of a system and neglect the actual interactions among system elements. In their observations on the skills of high school students in connecting behavioral and quantitative aspects of complex systems, Wilkerson-Jerde and Wilensky (2015) noted that students lacked inferential reasoning to argue how individual behaviors yield to group-level patterns. Murakami et al. (2017) also identified tensions associated with bringing wicked problems in real systems-level agroecology to a classroom learning community.

Such learning and reasoning difficulties have been attributed to multiple factors. Considering human cognitive capabilities and limitations, Grotzer and Tutwiler (2014) ascribed those difficulties to the characteristics of complex systems. They elaborated that the characteristics of complex systems are challenging to learn for all ages because they are often hard to detect due to being non-obvious (Frederiksen & White, 2000), microscopic (Hogan & Fisherkeller, 1996), or in a different attentional space. Another group of researchers mentioned the role of education in reasoning difficulties about complex systems. Chi and colleagues (Chi, 2005; Chi et al., 2012) argued that the way students learn to write and communicate about events, such as using linear narratives to show that logically related causal relations lead to an event, makes it difficult for them to argue about complex causalities like nonlinear dynamic relationships. They also added that people's experiences fuel linear causal reasoning as in their daily lives, people notice events that unfold sequentially and perceive them as agent-based and goal-oriented.

In this study, I present how college students in an introductory biology course reason about complex system problems. I plot the pattern of their ST by identifying the reasoning style they apply to argue over complex systems. Then, based on my results and the results of the existing literature, I propose a model that demonstrates a plausible interrelationship between knowledge and different ST patterns. I believe my findings would contribute to better understanding of how students think about complex problems and how science education attributes to it. My model would provide a system for examining students' ST competencies through a dynamic and interrelated lens.

Conceptual Frameworks for Studying Students’ ST; A Literature Review

Researchers have developed various approaches to evaluate and facilitate students’ learning about complex phenomena. Improving students’ ST skills is one such approach that appear to address the need to enhance the public's ability to understand complex systems. It follows the line of many researchers' arguments on the importance of ST in dealing with the 21st century’s complexities (Meadows, 2008; Plate, 2010). In this regard, Richmond (1994) believed that a system dynamics community can offer a way of thinking, doing, and being that can help promote a more rational way of living on Earth and create a more promising future.

ST is a holistic approach to analysis that examines real-world complex systems through the interrelationship between system constituent parts, and studies the patterns and behaviors that emerge from those interactions over time and space (Assaraf & Orion, 2005; Meadows, 2008; Tripto et al., 2017; York et al., 2019). Learning scientists have developed and proposed several models for studying various forms and levels of ST. Ben-Zvi Assaraf and Orion (2005) represented ST Hierarchy (STH) model which entailed eight ST skills from an elementary level, such as analyzing the components of a system, up to higher order ST skills such as recognizing hidden dimensions of a system. The model has been used in multiple studies to support and investigate students’ learning about system complexities (Assaraf et al., 2013; Assaraf & Orion, 2005, 2010; Tripto et al., 2017).

Having a human body as the system model, Tripto et al. (2017) investigated students’ ST skills development. They found progress in students’ competency to demonstrate complexity in a system; students showed a wide range of concepts from different biological levels and referenced to more dynamic interactions within their models. But the students still had difficulty providing integrated knowledge about the human body system. For example, they struggled to illustrate how cellular level processes explain phenomena at the systems level. Overall, throughout their studies, Tripto and colleagues (2016) noticed that students had incoherent knowledge about the human body and had difficulties in recognizing the underlying mechanisms that run systems. To address these issues, they suggested that explicit usage of "system languages" such as "hierarchy, patterns and dynamism, and homeostasis" alongside explicit scaffolding of the ST to improve students' ST competencies.

Hmelo-Silver and colleagues used the Structure, Behavior, Function (SBF) model as a theoretical framework to investigate students, teachers, and experts understandings of complex systems (Hmelo-Silver et al., 2007, 2015; Liu & Hmelo-Silver, 2009). In this framework, *structure* refers to the components of a system. *Behavior* refers to the mechanisms of the system that make function of the components possible and *function* mainly focuses on the output of a system. They found that experts, besides recognizing the components of a system, use the behavior and function of a system to organize their thinking about a system, whereas novices rely more on the structure of a system and less on its behavior and function to explain a phenomenon (Hmelo-Silver et al., 2007). Drawing on SBF model and using a hypermedia conceptual representation in their study, Liu and Hmelo-Silver (2009) found that functioned-center conceptual representation can enhance students' understanding about complex systems. However, they also observed that students' mental models did not progress in regard to the dynamics of biological systems. To help students make complex interconnections across system levels, Hmelo-

Silver et al. (2017) refined the SBF model to the CMP conceptual representation. The CMP frames students' ST around a particular phenomenon (P) by encouraging them to generate or recall the mechanistic reasonings (M) that may lead to the phenomenon while exploring the components (C) that interact to result in the phenomenon. The CMP representation helped students to organize and examine both the mechanistic and the component elements of a system. Also, discussing their ideas with CMP, students could reason about system elements in a more generic way. Plus, operating as a cognitive support framework, CMP helped students to enhance their understanding of systems and be able to transfer their knowledge beyond a particular context.

Considering the structure and components of a system as essential parts of ST, both STH and SBF models are domain specific frameworks that examine how particular systems function uniquely. Krist et al. (2019) proposed essential epistemic heuristics for mechanistic reasoning (EEHMR) framework which is based on mechanistic reasoning and identifies thinking patterns across systems in different domains. The authors define mechanistic reasoning in science as a type of causal reasoning with two distinct features: it explains (a) how the sequence of underlying causal events leads to a phenomenon, and (b) how and why the behavior of one or more factors gives rise to a phenomenon (Louca et al., 2011; Machamer et al., 2000; Russ et al., 2008; Springer & Keil, 1991). They also theorized mechanistic reasoning as a form of practical epistemic knowledge in action (Sandoval, 2005, 2014), or epistemologies-in-practice (Berland et al., 2016), which guide the construction of students' knowledge.

EEHMR characterize mechanistic reasonings of the students as essential, epistemic, and heuristic. Students' mechanistic reasonings are heuristic because they are implicit, strategy-like knowledge that guide students' reasonings. This implicit knowledge has its roots in science classroom language and discourse that guide students to adopt particular norms and epistemological assumptions (Gee, 2014; Kelly, 2007) to reason about phenomena, even when they lack the knowledge about the underlying mechanisms leading to the phenomena. Students' reasonings are epistemic in the sense that "they reflect ideas about how to build science knowledge and the form it should take" (Krist et al., 2019, p. 163). Here, epistemic knowledge is a contextualized and fragmented idea of a phenomenon rather than a coherent theory. Eventually, they are essential because they are applicable in different areas of scientific content. Krist et al. (2019) demonstrated that students applied epistemic heuristics in their accounts about two phenomena in two different scientific domains. The epistemic heuristics enabled students to reason across scientific fields while being linked but at the same time distinct from the content knowledge of those fields. The authors concluded that by taking into account the elements of a crosscutting practical epistemology, EEHMR can support students in creating mechanistic reasonings, and can help researchers to characterize students' progress in their ST. However, they also acknowledged that their framework does not capture some essences of complexity in systems such as the matters of emergence and equilibrium.

Theoretical Framework

In this section, I first define what I mean by ST, then I introduce my theoretical framework and its components.

Thinking is the process of metacognitive self-regulation of inferences (Moshman & Tarricone, 2016). Here, inference refers to the construction of knowledge through processes that are often subliminal to the knower. In thinking, one is conscious and purposefully controlling inferences. In this sense, thinking is more about success in coordinating inferences to meet the objectives of the thinking individual, such as problem-solving, rather than generating new knowledge or acquiring a better understanding. When it comes to knowledge, one is also bound to consider the truth or justification of one's beliefs. According to Moshman and Tarricone (2016), “When people regulate their inferential processes in order to maximize the truth and justification of their beliefs, their thinking is epistemologically self-regulated and thus qualifies as reasoning” (p. 54). In this sense, reasoning is the process of epistemologically self-regulating thinking (Moshman, 2011, 2015). Among the various forms of reasoning, causal reasoning, which seeks to provide causal explanations about the phenomena, is the concern of science (Rosenberg, 2012; Sandoval, 2014).

I define ST as a process of coordinating knowledge about a complex system to solve or explain an issue in the system. Here, the individuals are not necessarily aware of the nature and source of their knowledge. For example, they may not know that the knowledge they rely on is associated with the structure or function of a system, and whether their knowledge come from their educational background or personal experiences. Therefore, considering thinking is a deliberate action, in this study, I sought the patterns of knowledge coordination in students' arguments about a system, rather than examining the nature of their knowledge about that system. And assuming that students tried to justify their beliefs to scientifically explain how systems operate, I looked at their thinking as a form of causal reasoning.

To find about students' reasoning patterns in response to complex system issues, I drew on the characteristics of causal complexity introduced by Grotzer (2012) in her book "Learning Causality in a Complex World." Based on literature about "reductive bias," Grotzer argued that people are tempted to simplify the causalities that exist in complex systems. Despite acknowledging their benefits, however, she also argued that those simplifications often lead to distorted explanations of phenomena. Below I elaborate on each feature of the causal complexity introduced by Grotzer alongside their simplified types. In my study, I refer to the simplified causal types as causalities in simple systems. In other words, I assume that when people reduce complex causalities to simple ones, they are indeed reducing and simplifying a complex system to a simple system. Therefore, in this paper, simple causality is a reference to the simplified type of a complex causalities. Overall, I held the features of both simple and complex causalities as my theoretical lens to study students' thinking patterns.

Proximal versus Distal Reasoning

In proximal reasoning, there is a relatively small gap between cause and effect. Generally, it refers to thinking habits that examine the causalities of an event in the spatial and temporal locality of the event. It also seeks for causalities in proximities of the thinking individual. For example, students believe that plants get their food from the soil rather than from the photosynthesis process using solar energy (Barker & Carr, 1989). Here, the immediate connection between plants and soil seems to be more convincing for students than the reasoning based on the plant and sun relationship. Plus, students might find soil, which is closer to them, to play a more significant role in plant growth than the sun.

On the other hand, distal reasoning occurs when an individual goes beyond the immediate cause and effects surrounding a phenomenon to explain it. In this sense, a phenomenon can have its roots out of our attention span and have its effects far apart from the cause. This thinking approach encourages an individual to acknowledge the possibility of distant and delayed causalities. Consequently, it entails causal patterns such as the *domino effect* wherein the ultimate impact of a cause can be temporally and spatially distanced, *accumulation* wherein affects need to be accumulated to be effective and noticeable, and *threshold level* wherein after a point a sudden and dramatic effect can be observed. In the COVID-19 pandemic, for instance, the concept of threshold level explains the rationale behind the *flattening the curve* strategy adopted by public health professionals, and the *accumulation* effect explains why the *social distancing* strategy had to be practiced by all the members of a society to a particular point of time so as to be effective.

Event-based versus Process-based Reasoning

Events are often distinct actions that have a beginning, middle, and end and unfold sequentially (Chi, 1997). Consequently, they are often discrete from their surroundings. Event-based reasoning indicates that people tend to think more about phenomena that are distinctively recognizable rather than thinking about ongoing processes with no beginning and end. Such reasoning may explain why an exceptionally cold weather would better rivet people's attention to global warming (Jacoby, 2008) than monthly and annual reports on Earth temperature.

On the other hand, process-based reasoning examines the steady states which are routinely ongoing processes. Humans' limited cognitive capacities drives them to neglect the ongoing processes surrounding them and not notice them until they are disrupted. Thinking about the complexity and behavior of systems requires that individuals take into account the ongoing processes in their reasonings before the disruption of those processes lead to possible disasters. For example, the idea to implement frequent testing to encounter COVID-19 pandemic was based on this understanding that the spread of the virus was an ongoing process, not a onetime event, and required constant monitoring to control its spread and diminish its disastrous effects.

Obvious-based vs Non-obvious-based Reasoning

Obvious-based reasoning comes from the human tendency to draw on obvious causes to explain phenomena. It implies that obvious causes get primacy over non-obvious ones and the latter is often neglected as long the former exists. For instance, Grotzer (2003) noted that students tended to think that worms change plant composts into soil. Then, about an ecosystem without worms, students argued that the compost would either not fall apart or that it would break down on its own. They received similar answers from adults demonstrating how a visible factor - worms - can get primacy over the invisible ones in explaining a phenomenon.

Non-obvious-based reasoning requires people to consider the possible effects of non-obvious causes in their thinking. These causes are hard to perceive and so they are mostly sought when an obvious reason does not endure. Attending to non-obvious causes needs awareness of their existence and deduction skills. In biology, for instance, knowing about the microscopic world and their role in biological phenomena will potentially contribute to people's reasoning about them. Understanding evolution also demands acknowledgement of non-obvious causes. But in the case of evolution, it is not a matter of size or effect to be noticed, but, like how Darwin did, it is about deducing a conclusion based on existing patterns.

Sequential versus Simultaneous Reasoning

Sequential reasoning is a causal thinking that argues things unfold to happen in a particular order. Therefore, there is a chain of cause and effect implying that any event essentially has a beginning and an end. According to Grotzer (2012), “sequentiality” is the predominant discourse of causal stories which allows them to exist within the flow of time. In the domino causal reasoning, causes occur before effects and effects turn into causes. This pattern of reasoning more fit to explain why, for instance, the introduction of a new species to an ecosystem might bring about far-reaching changes to that ecosystem and less qualify to describe the evolution in that ecosystem.

Simultaneous causal reasoning, on the other hand, suggests that causality does not necessarily require telling causes precede the effects. This reasoning style acknowledges the existence of bidirectional relationships between cause and effect where it is hard to say which factor precedes the other. Mutualistic symbiosis in which two species concurrently benefit from one another illustrates how the matter of cause and effect sequence does not apply. Causal simultaneity also explains relational causality where the relationships of equivalence and difference between two or more variables are taken into account. In this case, the outcome of an event depends not only on more than one variable, but also on the relationship dynamics among those variables. In this regard, predicting the fallout of a hunt between a prey and a predator requires an understanding of relational causality.

Intentional/Agential vs Unintentional/Non-agential Reasoning

Intentional/agential reasoning points out to the thinking habits that primarily seek to find an intentional agent or factor for any event. “Who did it?” or “Wat factor did it?” would be the first questions to pop up in this way of thinking. This thinking pattern may partly explain why people often find it easier to believe that COVID-19 was a virus intentionally designed by a group of people with vicious purposes, rather than considering it as an incident that could have happened randomly without any particular intentions. This thinking approach has its roots in the way we understand the world; Meltzoff (2007) argues that goal-oriented attempts to make things happen - intentional behaviors - are the key features of how we perceive causality.

However, not every causality can be explained by agential interferences or intentional behaviors. Unintentional or non-agential causal reasoning indicates that not only do actions not necessarily require intervention of an agent, but also they can be random and purposeless. Of this, natural selection is an illustration of a non-agential process in the sense that no particular factor or agent is in charge of it, and it aimlessly proceeds in no particular direction. This might be one of the reasons why it is hard for people to grasp the concept of evolution. For instance, it is noted that college students tend to explain natural selection as a purposeful process carried out by organisms to adapt to their environment (Moore et al., 2002) instead of describing it as a passive and aimless process.

Centralized vs Decentralized Causal Reasoning

Centralized or top-down causal reasoning refers to the human thinking tendency to attribute the actions or behaviors of a system to the instructions from a higher-ranked position. This reasoning approach considers a factor or agent controlling a system and downplays the role of the other components of the system in its behavior. The literature has shown that this pattern of thinking is prevalent among students (Barth-Cohen, 2018; Taber & García-Franco, 2010).

On the other hand, decentralized or distributed causal reasoning holds every member of a system accountable for the outcome of a system. It requires one to examine the cause and effects at different levels, acknowledging that they can manifest different behaviors as they go through the levels. For example, there are reports that students struggle to explain balance and flux in populations, largely due to their inability to see how scientific phenomena exist and function at different scales (Levy & Wilensky, 2009, 2011; Wilensky & Resnick, 1999). Decentralized causality also puts emphasis on the notion of emergence. Emergence refers to a behavior or function of a system that arises from the interaction of system components and it differs from the behavior of each individual in the system. In this sense, the system's behavior cannot be reduced to the sum-up of its individuals' actions. For example, studying the behavior of an individual animal may help us predict its response to an incident, but it will not necessarily give us the picture what the collective action of that animal's herd or flock would look like to the same incident.

Deterministic vs Probabilistic Reasoning

Deterministic reasoning comes from our expectations that causes reliably lead to effects (Schulz & Sommerville, 2006). This way of thinking brings the comfort that, if we learn the causes, we can predict the effects that will then allow us to exert control over the events. Leaning on this way of reasoning, for example, people may draw a linear reliable relationship between catching the influenza-virus (the cause) and catching the flu (the effect); arguing that the former necessarily dictates the latter. It is also evident in the literature that students tend to take a deterministic stance in explaining complex phenomena (Grotzer et al., 2017; Schulz & Sommerville, 2006).

Probabilistic causal reasoning implies that the relationship between causes and effects can be both reliable and unreliable. Accordingly, it argues that some events are unpredictable regardless to the amount of knowledge that exist around them. This reasoning style recognizes the uncertainty around any prediction as to the outcome of an event. In this regard, for instance, mating in animals does not always result in producing offspring. Indeed, probabilistic reasoning takes into account the existence of unreliable causal relationship between elements of complex systems and the possibility of random outcomes and behaviors.

Research Questions

My study had two assumptions about students' knowledge. First, by the end of K12, students have the basic knowledge to make causal reasonings on complex issues like climate change and the extinction of organisms. Second and similarly, by the end of their introductory biology course, students will have the necessary knowledge to make complex causal reasonings about complex problems related to their course content. Based on these assumptions, I sought patterns that emerged from the students' application of their knowledge. To this end, I investigated the following questions:

What patterns of system thinking emerge from students' reasonings about biological and environmental issues?

What is the relationship between students' knowledge and the types of reasoning they apply?

What is the relationship between the various forms of reasonings students apply?

Methods

In this study, I applied convergent mixed-method design. This approach compares and contrasts quantitative and qualitative data to provide a comprehensive understanding of a phenomenon (Creswell & Plano Clark, 2011). First, I spotted students' stand on some biological and environmental issues through a Likert scale survey. Next, using a coding scheme, I quantitatively determined the extent students applied particular forms of reasoning to explain their views on survey questions. Then, I qualitatively examined students' explanations and interviews about the questions. Finally, by triangulating my results, I discussed the overall thinking tendencies of students towards each question.

Research Design and Participants

To investigate students' ST skills, I designed a survey questionnaire with four statements (Figure 1). Statements were first approved by the course instructor to tap both the course content and students' general knowledge. Then, they were further refined and selected through a pilot study. Finally, based on the results of my pilot study, I carried out face validity to make sure that my survey items prompt relevant responses and are clear language-wise. Face validity refers to researchers' subjective assessment of their instruments in regard to having its items relevant, reasonable, and unambiguous (Oluwatayo, 2012).

The first two statements were related to the students' course content and the latter two addressed students' general knowledge. Students were asked to indicate to what extent they agreed or disagreed with each statement and then to provide their reasons for their stand. The survey was given to students late in the semester as a bonus task with two weeks of time to do it. Participants of this study were 135 students, the majority of which were freshmen and sophomores, from an introductory biology course at a public research university. The course was an entry level course for students majoring in biology and was also attended by a large number of students majoring in other STEM disciplines. Participants were recruited by signing the consent form that was attached to their survey assignment.

To better understand students' reasoning styles, I also interviewed them about their responses. Ten students were recruited by sending an email to the whole class and a five-dollar gift card was offered as an incentive. The interviews were conducted in a semi-structured format and followed the approach of "selecting and zooming" (Lee et al., 2008) in which for each statement the participants were asked to further explain some aspects of their answers. The interviews lasted around 30 minutes and were audio recorded and later transcribed for detailed analysis.

Before the beginning of the interviews, the participants were informed that from the perspective of my study, there were no right or wrong answers, and so they would be asked for further elaborations and the possibility of alternative explanations, regardless of their answers. To study the ability of early elementary students to explain the behavior of complex systems, Danish et al. (2011, 2017) in their interviews prompted and scaffolded their participants to connect the macro and micro levels in systems. Similarly, having my theoretical framework in mind, I also prompted my participants for complex causal reasonings, in cases where they had used simple causalities.

Figure 2.1

Survey questionnaire statements

1. The rate of cellular respiration in a muscle cell is determined by how quickly the organism is breathing.
Strongly agree Agree Disagree Strongly disagree

2. If we had control over genetic mutations caused by environmental factors, by sequencing all of the genes of an organism, we could provide an accurate description of what the organism looks like.
Strongly agree Agree Disagree Strongly disagree

3. Given that natural disasters such as wildfires and tornados do not happen, by thoroughly studying an ecosystem, we can predict which organisms will go extinct or survive in that ecosystem over the next half a century.
Strongly agree Agree Disagree Strongly disagree

4. Even without referring to scientific reports, based on our own observations, it is evident that climate change is happening.
Strongly agree Agree Disagree Strongly disagree

Coding Scheme and Analysis

To map out students reasoning styles, I conducted a deductive qualitative analysis. This approach draws on an organizing framework to direct data analysis (Saunders et al., 2009). It entails the processes of developing a code book, data analysis, refining and developing codes, and presenting and interpreting data (Saunders et al., 2009). Accordingly, drawing on my theoretical framework, I developed a coding scheme that contains seven reasoning styles, each having a pole of simple and complex causal reasoning (Table 1). Through the lens of my coding scheme, I conducted multiple readings on my data to both refine my codes and label students' reasoning patterns. Each answer could have multiple patterns. For example, if a student had said that evolution was an ongoing process and mutation was its driving force, this answer was scored one for being process-based and one for being an agent-based reasoning. However, multiple use of a same pattern was not counted more than one for each response. For example, if one student had argued that climate change was happening because there had been more and more tornados in recent years and that he himself also had experienced snow in summer, this reasoning was scored one for just being event-based. At the end, I counted the number of times each reasoning pattern was scored for each survey item. Therefore, the overall score is representative of the number of times a reasoning pattern was used by students to explain their answers to a survey item. In other words, the overall score demonstrates the frequency of a reasoning pattern in students' responses for each survey item and is considered showing students' overall tendency toward using that pattern to answer each question.

The data from the interviews was analyzed qualitatively for each student and the reasoning patterns were identified according to my coding scheme. Interviews worked as a complementary source of data to provide a deeper insight into students' explanations, but it was not used in the quantitative aspect of the study.

To validate my findings, a second researcher with science education background was provided with 20 percent of the data set, the scoring scheme and the findings of the study. Few discrepancies were brought up by the second researcher that were discussed and addressed through a meeting with the researcher.

Results

In this section, I show separately how students think about each individual survey item. I first reveal the quantitative aspect of students' stand on each statement and then show the frequency of each reasoning style in their responses. Here, frequency is the indicator of students' tendency toward a particular reasoning style in answering a question. Next, I qualitatively describe students' explanations for each style of reasoning.

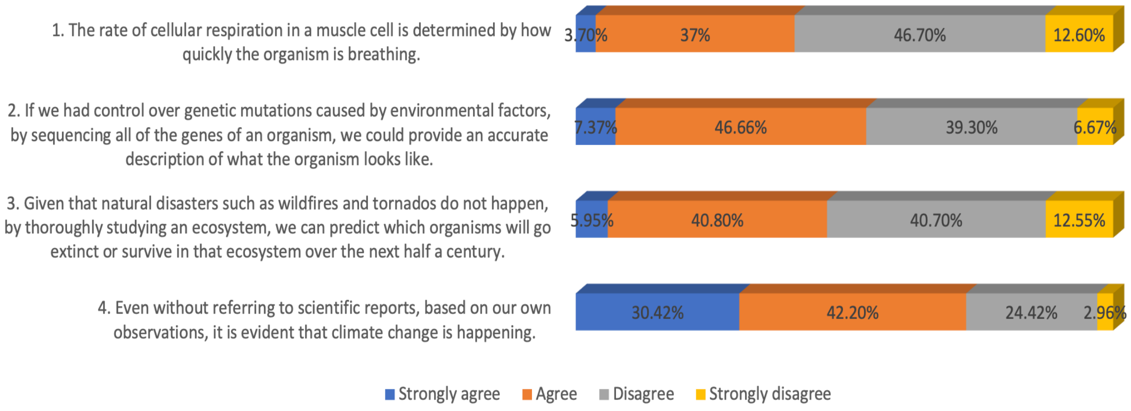
Finally, from students' interview data, I provide complementary insight into students' responses and their general view toward the complex systems in questions.

Reasoning Across Biological Levels; the Relationship Between Cellular Respiration and Breathing

My first question sought to investigate how students viewed the relationship between cellular respiration (CR) and breathing. According to the survey, about 40 percent of students (Figure 2) believed that the rate of CR in a muscle cell is determined by how quickly the organism is breathing. Subsequently, 60 percent of the students disagreed with this statement. To agree or disagree with my first question, students overall had four patterns of response to explain their views (Table 2).

Figure 2.2

Percentage of students' stand on each statement



Sequential Reasoning

These reasonings were suggestive of views that explained things unfold to happen in a particular sequence. 42 students (~31%) explained how CR or breathing worked and how one affected the other without referring to any bidirectional effects. In general, students who agreed with the statement argued that the rate of CR is dependent on oxygen and that the more O_2 there is, the faster the CR is. Jack (all names are pseudonym) explained that "O_2 is a reactant for the CR reaction: (the reaction); if you are breathing more heavily, you're supplying your body with more O_2 to undergo CR." On the other hand, many students who disagreed with the statement gave primacy to the matter of energy demand to explain the relationship between CR and breathing. Lila's explanation exemplifies this way of argument: "The rate of CR would increase due to increased energy demand, not increased O_2 supply." In general, these reasonings were focused on explaining what is first and what is next.

Proximal Reasoning

These reasonings were suggestive of views that sought explanations of a phenomenon in its proximal environment. 37 students (~27%) argued for disconnection between CR and breathing by explaining the mechanisms of each process. For example, some students believed that CR happens at a fixed rate, so it is not affected by the rate of breathing. Some others referred to CR mechanism to demonstrate the disconnection between the two processes: "The rate of cellular respiration is determined by how much ATP needs to be produced." Ellen brought up the lactic acid fermentation process to show how CR is independent of breathing as it could happen without oxygen: "Cellular respiration is the process by which organisms break down glucose. Muscle cells continue to produce ATP when oxygen runs low using lactic acid fermentation. I don't think CR is the same as just breathing." These arguments shared the similarity of dismissing the relationship between CR and breathing by explaining one process in disjunction with the other one.

Distributed Reasoning

These reasonings signified the views that considered the role of various factors in explaining a phenomenon. 25 students (~18%) argued that the rate of CR is not solely dependent on the rate of breathing. They acknowledged the role of other factors such as oxygen pressure in the environment or glucose availability in cells to argue that the relationship between the two process is too complicated to be explained by one determining the other. For example; one student explained that "There are many more factors like the pO_2 in the atmosphere, pO_2 in lungs, how well O_2 binds to the hemoglobin and myoglobin, how well it is released, etc." Overall, the emphasis in these explanations were on the existence of other factors and that the relationship between CR and breathing cannot be fully explained without taking those factors into account.

Simultaneous Reasoning

These reasonings presented the views that argued cause and effect simultaneously affect each other. The effect can be bidirectional, relational, and/or mutual. 13 (~10%) students made simultaneous reasoning either to argue how the relationship between CR and breathing is dynamic or emphasize the simultaneous occurrence of the two processes. For example, some of them brought up the correlation between the CR and breathing and pointed out the dynamic between the two; Jill argued that “lack of O_2 will slow reaction but the rate doesn't increase consistently with increase O_2, eventually you increase O_2 and the rate will not change.” Few students also mentioned that they are “ongoing process” or that they increase at the same time when we exercise. These reasonings acknowledged the dynamic relationship between CR and breathing without arguing based on their primacy of occurrence.

In the interviews, students were asked to elaborate their answers to the survey questions and were prompted to talk about the nonlinear and indirect relationship between CR and breathing. I observed the same response patterns in the interviews as found in students' explanations in the survey, as well as some changes in students' reasonings based on prompts. Kate, for instance, shifted from proximal reasoning to sequential. She had given lactic acid fermentation and asthma attack as examples to argue how CR and breathing were independent of each other. Getting the prompts regarding the possible relationship between the two processes, she connected CR and breathing by bringing up the role of oxygen in both processes. Eventually, her reasoning style shifted to be sequential by concluding that "breathing is based off of cellular respiration." Another shift was from sequential reasoning to distributed one. Paige brought up "other factors" such as "lung capacity" to argue that the relationship between the two processes were more complex than she had mentioned earlier. By bringing further elaboration to their answers, three of my interview participants argued for simultaneous relationship between CR and breathing which was a shift from their sequential reasoning in their primary responses. They brought up the matter of correlation between the CR and breathing by explaining that the increase in one would increase the other but not necessarily to the exact amount.

Given the chance to elaborate on their answers and getting prompts, all my interview participants mentioned that there is a relationship between CR and breathing; however, they had different views about the nature of the relationship. Some considered it negligible and did not mention it until prompted about. Giving the prompts, I found that most of my interview participants believed in bidirectional relationship between breathing and CR, despite their sequential reasoning, they had applied to explain their

Table 2.1

Types and features of simple and complex causal reasoning in systems

Types and features of causality in simple systems	**Examples from this study**	**Types and features of causality in complex systems**	**Examples from this study**
Proximal. Cause and effect are spatially and/or temporally close to each other.	Students make no connection between breathing and CR; instead they explain their stand just based on one of the two phenomena mechanism. Ex: students explain that the rate of CR is determined by the amount of glucose and O_2 available to the cells without mentioning any role for the breathing rate.	*Distal.* Cause and effect are spatially and/or temporally distant or delayed.	Students argue how the cause and effects of climate change are unnoticeable to them because they are temporally or spatially distance to them. Ex: students say that climate change is a long-term change that does not fall into our life span or it can have effects where we cannot notice it.
Event-based. An event must happen to make us think about the causalities, and we reason about the cause and effect surrounding the event.	Students present an event as the evidence to argue for or against a phenomenon. Ex: they regard warm winters or cold winters as indicators of approval or disapproval of climate change.	*Process-based.* There are ongoing causal processes and interactions within a system even when the system is in a steady state.	Students bring up the role of ongoing processes in the natural world. Ex: they say that the world is changing constantly, or that evolution and natural selection are ongoing processes that can change things and interfere in scientific predictions.
Obviousness-based. Cause and effect can be directly perceived by our sensory skills.	Students draw on obvious factors as evidences to argue for their accounts. Ex: they argue that natural disasters are unpredictable and bring uncertainty to scientific predictions; therefore,	*Non-obviousness-based.* Cause and effect are not noticeable to our sensory skills.	Students made deduction out of existing information. Ex: they argue that knowing just about the DNA will not reveal an organism's phenotype as, for instance, humans and many organisms

	their removal bring about accuracy to scientific predictions.		have big portion of their DNA similar, but they look very different. Students refer to unseen event to them. Ex: sea levels rising and ice cap melting.
Sequential. There is an order to the chain of cause and effects which makes things unfold in a particular sequence.	Students explain how breathing and CR are related to each other in a particular sequence. Ex: faster breathing leads to faster CR, or vice versa.	*Simultaneous*. The relationship between cause and effect is bidirectional, not one necessarily preceding the other.	Students acknowledge that the relationship between breathing and CR are bidirectional or non-linearly related. Students argue that genotype and environment together determine the phenotype.
Intentional/ Agential. A person or a factor is mostly responsible for an event, and there is an intention or purpose behind the things that happen.	Students refer to mutations as the decisive factors/agents of uncertainty in biological and ecological systems. Ex: we can't predict the extinction of an organism because mutations are random and unpredictable. We cannot accurately tell the phenotype from the genotype due to mutations.	*Unintentional/ non-agential*. Things can happen without anyone in particular in charge of them and without toward any particular purpose	Students argue that the collective work of genes and other biological factors might result in a phenotype which is unpredictable. Students mention that the outcome of natural selection in an ecosystem is unpredictable so that we cannot know of future extinction/survival of organisms.
Centralized. A central factor or authority controls the system. It has purposes and intentions.	Students refer to DNA/genes as the authority to control biological system behaviors. Ex: if we know about an organism's DNA, we will know everything about it including its phenotype.	*Decentralized*. All the components of a system attribute to its behavior. The final outcome/behavior of the system is emergent and differ from individual	Students take into account different factors to argue about a phenomenon. Ex: the rate of CR is not determined just by breathing rate, but other factors like glucose availability are also involved. Food availability and population migrations

		component's actions.	also affect the extinction/survival of an organism in an ecosystem.
Deterministic. There is a reliable relationship between cause and effect. Therefore, by learning about the causes we can predict the effect.	Students claim that if we know the underlying mechanisms, we will have control over the phenomena. Ex: by thoroughly studying an ecosystem, we will learn about the ecosystem and its organisms which would make us capable to predict the extinction and survival of the organisms in that ecosystem in half a century.	*Probabilistic*. The relationship between causes and effects can be both reliable and unreliable. A cause does not always lead to a particular effect.	Students may point out to the uncertainties and limitations of scientific causal explanations by referring to probabilistic nature of most scientific predictions.

answers earlier. Overall, I observed that students' explanation became more complex after they elaborated on their answers and received prompts; though, this was not consistent among all of them.

Table 2.2

Students' patterns of response to complex system issues and the frequency of different reasoning styles in their explanations.

	Pattern of response	Reasoning style	Frequency
Q 1	Explaining how Breathing determines CR or vice versa	Sequential	42 (31%)
	Making no connection between CR and breathing; explaining just how one of the two processes works	Proximal	37 (27%)
	Explaining that CR and breathing are related but other factors are also involved in the process	Distributed	25 (18%)
	Explaining that CR and breathing are related but the relationship is indirect and non-linear	Simultaneous	13 (10%)
Q 2	Indicating that genes/DNA determine everything about phenotype	Centralized	74 (54%)
	Arguing that mutations are random or inevitable and that makes the phenotype prediction inaccurate	Intentional / agential	23 (17%)
	Arguing that both gene and environment play role into shaping the phenotype.	Simultaneous	17 (13%)
	Arguing that similar DNAs show different phenotypes. Ex: cells of an organism have similar DNAs but different phenotypes.	Non-obvious factors	13 (10%)
Q 3	Arguing that by thoroughly studying an ecosystem, we can find trends and so we can make accurate predictions	Deterministic	47 (35%)
	There are more factors involved in ecosystems than natural disasters that make them unpredictable.	Distributed	35 (26%)
	Mutations bring uncertainty to the predictions.	Intentional / agential	27 (20%)
	We can't make accurate prediction because the ecosystem is constantly changing	Process-based	9 (7%)
	Removing natural disasters eliminates uncertainties and so increase the accuracy of prediction	Obviousness-based	5 (4%)
Q 4	Pointing out events such as harsh winters, hot summers, etc. as the evidence of climate change.	Event-based	61 (45%)
	Referring to non-obvious evidences such as the increase of earth temperature and its consequences like polar ice cap melting, etc. as the evidence of climate change.	Non-obviousness-based	33 (24%)

	Considering that climate change is happening beyond their immediate time and space and there are limitations to notice it by lay people.	Distal	13 (10%)
	Arguing that climate change is not happening either because they can't see any change in the climate or explaining that getting warm and cold is a natural cycle of climate.	Obviousness-based	7 (5%)

Reasoning across biological levels: The relationship between genotype and phenotype

My second question sought students' views about the relationship between the genotype and phenotype. The majority of students (54%) (Figure 2) believed that by sequencing all the genes of an organism, we could provide an accurate description of how the organism looks like. Subsequently, 46 percent disagreed with this statement. I identified four patterns of reasoning (Table 2) in the students' explanations to agree or disagree with my second question.

Centralized Causal Reasoning

These reasonings were suggestive of arguments that tended to consider a central power in charge of a system or a phenomenon. 74 students (~54%) used this way of reasoning to explain why they agreed, or disagreed, that it is possible, or not, to know the phenotype just from the genotype. They argued based on the centrality of DNA/genes in determining the features of organisms. The arguments of students who agreed with the statement varied from making general statements about the role of DNA/genes in organisms to providing mechanistic reasonings on how genotype determines the phenotype. For example, some students believed "Genes control what an organism looks like," or by knowing the genotype "You know basically everything about the organism" while the others provided details about the mechanisms of the process: "If we could sequence all the genes of an organism, then we could know which proteins they code for, and therefore, what functions they would have and how they would appear.” Some students who disagreed with the statement applied similar way of reasoning. They believed in the centrality of genes in determining the phenotype but believed that sequencing the genes will not give us the sufficient information about the genes/DNA; otherwise, the accurate prediction would be possible. These reasonings shared the similarity of looking at a central power responsible for the phenomenon.

Intentional Causal Reasoning

These reasonings were suggestive of arguments that sought for an agent or a factor to put in charge to explain why an event happens or not. 23 students (17%) believed that we cannot tell what an organism looks like by sequencing their genes due to mutations. They argued that mutations occur despite our control over the environmental factors elaborating that “not all mutations are environmental,” or one "cannot predict mutations." These reasonings found mutations as the agent that could probably make the prediction inaccurate.

Simultaneous Reasoning

These reasonings were based on simultaneous and the bidirectional effect of factors on each other. 17 students (~13%) applied this reasoning method. They either referred to the role of environmental factors or the matter of interactions between genes in shaping the phenotypes. For example, Pal disagreed with the statement arguing that “If you seq genes but feed organisms minimal food, they won't reach the coded height.” Another student mentioned that “the interaction between genes may have an unknown or unforeseen effect [on] the appearance of an organism.” These reasonings shared the similarity of considering the dynamic and relational relationship between the factors that contribute to an organism’s phenotype.

Reasoning Based on Non-obvious Causes

These reasonings were suggestive of arguments that required inferential thinking skills, since no obvious factor endured. 13 students (~10%) used this reasoning style to disagree that we can tell the phenotype from the genotype. Some of them mentioned that the genes of an organism can get expressed differently and argued that the different gene expression among cells of an organism indicates that just knowing about the genes is not enough to make accurate predication about the phenotype. A few other students did inferential thinking by comparing the genes and the appearance of different organisms. For example, Jonathon responded that “We share a large portion of our genetics with many other animals and we look different than them. So just looking at genes you couldn't know what the organism looks like.” These arguments shared the similarity of making an inference by comparing the similarities and differences among the cells and organisms.

In my interviews for question two, students were asked to elaborate on their answers and were prompted to talk about the role of environment in determining the organisms' phenotype. All my interview participants made centralized causal reasoning by arguing that DNA/genes are the ultimate determinants of an organism’s phenotype, and my prompts did not affect their reasoning style. I observed that students considered the role of environment in the phenotype of an organism being through mutation and/or evolution. Linda’s argument represented this view:

Interviewer: What determines an organism's phenotype?

Linda: The alleles and whether it's like recessive or dominant….

Interviewer: What do you think about the role of environment in determining the phenotypes?

Linda: I think they play a pretty significant role because mutations happen randomly and

happen whenever throughout your entire course of life. So yeah, I think they can play a significant role in your phenotype.”

Interviewer: What if we have control over mutations in our environment?

Linda: I think it would be a non-changing environment because there's no mutations to set others apart. Then, as they reproduce and pass down to the next generation, it’ll be kind of predictable to see what they look like.

A similar line of argument was also observed among my other participants. Explaining the role of environment, Sara believed that environment affects "through time" and elaborated that "I don't know if that (environment) would affect their genes but cause a difference in like how their offspring would look." I found students having a vague idea about the role of environment. For instance, Hana had passed advanced placement courses of microbiology and physiology at high school. She could explain the mechanism of gene expression well but when asked about the role of environment, she responded: “I didn't really understand like whenever they taught that part in class, the role of environmental factors.” She knew that the environment played a role in an organism’s phenotype but was unable to incorporate it into her arguments. Overall, all my interview participants considered a central role for genes and DNA in biological systems and either viewed the role of environment through evolutionary perspectives or regarded it negligible, given that mutations do not happen.

Reasoning about environmental issues: Predicting organisms’ extinction/survival in half a century

The primary goal of my third question was to examine the students’ views on the extinction and survival possibility of organisms in a relatively far future. Given that natural disasters do not occur, overall 47 percent of students (Figure 2) believed that by thoroughly studying an ecosystem, we can predict which organisms will go extinct or survive in an ecosystem over the next half a century. I found five patterns of response in students' arguments around the possibility of this prediction (Table 2).

Deterministic Causal Reasoning

These reasonings were suggestive of arguments that made a reliable relationship between cause and effect. 47 students (~35%) used this reasoning style. They argued that through learning the underlying mechanisms of an ecosystem and finding the patterns of organisms’ extinction and survival, we can predict the possibility of their existence in half a century. They explained that by thoroughly studying an ecosystem, we will know about the different factors such as food availability, organisms’ growth rate, and the “traits [that] have selective advantages.” This knowledge would help us predict the extinction/survival of the organisms. Of this, Kate explained that:

> If a thorough study of an ecosystem is performed, then there will be a great understanding of the environment and its interactions with animals. Therefore, using our understanding of favored genes traits vs. unfavored gene traits and

> natural selection, we could determine the survival rate of each organism within that ecosystem.

The arguments of this group of students were based on the belief that it is possible to find the favorable genes, traits, and factors that "are favorable for natural selection." And accordingly, upon those findings, a safe prediction is possible as "Things in an ecosystem tend to follow an evolutionary pattern." These reasonings shared the similarity of considering that the scientifically found mechanisms follow a reliable cause and effect pattern which would enable us to make confident predictions.

Distributed Causal Reasoning

These reasonings were suggestive of the arguments that mentioned the role of various factors to explain a phenomenon. 35 students (~26%) argued that it is not just the natural disasters that might make scientific predictions inaccurate, but other unpredictable factors, like disease and immigration, can also bring about extinctions to organisms. For example, one student explained that “the ecosystem can still change from factors such as resource reduction/alteration (by human involvement), competition, invasive species.” Overall, these reasonings took into account the other possible factors that could play role in organisms' extinction/survival.

Intentional/agential Causal Reasoning

These reasonings tend to put a factor in charge for why a phenomenon happens or not. 27 students (20%) believed that the extinction/survival prediction of organisms can be inaccurate because of the mutations. They argued that mutations are random, and their effects are unpredictable; therefore, they make the prediction about organisms impossible. One student explained it as follow: “The randomness of mutations and the potential increase/decrease in fitness that is brought about by mutations and genetic drift would make it difficult to calculate which species will live and which species will die in a given environment over a long period of time.” In these reasonings, mutations were considered as the primary reason causing uncertainty about the predictions about organisms.

Process-based Reasoning

These reasonings primarily referred to ongoing processes rather than referring to events. Nine students (~7%) mentioned that ecosystems are constantly changing, and evolutions are happening all the time, so it is not possible to know about them in 50 years. One student explained that “Nature is constantly changing and factors like disease can take place and wipe out most of the population….” These arguments acknowledged the role of ongoing processes and argued about the events as part of the process.

Reasoning Based on Obvious Causes

These reasonings mentioned obvious factors to explain their positions. Five students (~4%) argued that by excluding natural disasters the uncertainty in the predictions about organisms’ future will be alleviated and that accurate prediction would therefore be possible. One student put it as follows: "Natural disasters (in the short term) are the main reason that organisms unpredictably go extinct." These arguments drew on the obvious factors like natural disasters as the main source of uncertainty about scientific future predictions.

For my third question, besides elaborating on their answers, students were prompted to talk about the possibility and accuracy of predictions about organisms' evolutionary paths. The general line of arguments was that by scientifically studying an ecosystem, we would be able to find the patterns and trends to predict organisms' future, but discussions varied around the extent the predictions could be accurate. Victoria had a deterministic reasoning style to argue about scientific findings. She believed that by finding changing patterns in an ecosystem, the predictions would be very reliable because "Unless there's a like something disrupts the pattern, I don't see a reason for it to not keep going. Like simple physics, like something's going to stay in motion until stopped by another force." Based on a similar assumption, Eric and Christine explained that by having a deep understanding about an ecosystem, we would know which traits would help animals to survive in an ecosystem, and consequently, the animals that lack such traits would either extinct or immigrate. In response to how accurate the predictions can be, Adam believed that "We can predict all the way up until maybe a mutation will happen." The matter of mutation as a factor to interfere with the predictions was brought up with Eric and Christine as well.

On the other hand, four of my interviewees argued that there are limits to the scientific predictions about evolutionary paths. Emma argued that the predictions would have been more accurate if they were for a closer time. Kate made a process-based reasoning by arguing that even without natural disasters, "Ecosystems would still shift in other ways." However, when followed up to explain "other ways", she first said: "I don't know" then came up with the following explanation: "by mutations or maybe a new group of population whatever moves in and like they kind of start changing up the ecosystem." Indeed, I noted that Kate knew things are changing but lacked the language to explain it and so she drew on the mutation and immigration to justify unpredictable changes. Pete and Hana stayed with their distributed reasoning style by raising multiple factors other than natural disasters to explain the possible inaccuracy in scientific predictions.

Overall, I noticed that my interviewees were largely aware of ongoing changes in ecosystems and that multiple factors are involved in it. However, some believed those changes were trackable and could reliably inform us about organisms' future. The others believed that the scientific predictions could be inaccurate but mostly sought for factors and agents to explain the possible inaccuracies, instead of referring to the probabilistic nature of scientific predictions that make those inaccuracies normal.

Reasoning about environmental issues: observing climate change

My fourth question sought to examine how students think about climate change. About 73 percent of students (Figure 2) believed that even without reference to scientific reports, from their own observations, it was evident that climate change was happening. Subsequently, 27 percent of students disagreed with this statement. I found four patterns of reasoning in the students’ answers to explain their position on this question.

Event-based Reasoning

These reasonings were suggestive of arguments that referred to events as the main evidence to support students' view. 61 students (~45%) made event-based reasoning to explain why they believed that the climate change was happening or not. They referred to events to argue for and against climate change; for example, snow in April and harsher winters were used as evidence to affirm and deny climate change. One student explained her position as follows: “I completely agree with this statement because I feel like I have noticed signs throughout my own life. For example, the lack of snow in the winter in

Missouri, or a slight shift of seasons.” These arguments shared the emphasis on personal observations as the evidence to argue about climate change.

Reasoning Based on Non-obvious Causes

These reasonings were suggestive of arguments that relied on evidence that was hard to perceive unless brought to people’s attention by experts. 33 students (~24%) drew on non-obvious causes to argue for their answer. The majority of students brought up “ice caps melting” and “ocean level rising” as the evidence to argue for climate change. A few students referred to the gradual nature of climate change to argue for the need for scientific reports. For example, Ana believed that “the process of global warming is so gradual it would be impossible to notice it is happening.” These reasonings shared the reference to scientific reports – which otherwise they would have not noticed – as their evidences to argue for climate change.

Distal Reasoning

These reasonings were suggestive of arguments that considered the cause and effect of a phenomenon can be beyond the scope of a person’s attention. 13 students (~10%) argued that they cannot know about climate change based on their own observations because it is a very long process and happens at a very large scale. Some indicated that "we need the past data." Similarly, Arian put it as follows: “… how could one know climate trends previous to humanity's existence or let alone areas humans don't usually live?” These reasonings shared the recognition of the limits of their personal observations by referring to the times and places far from their immediate.

Reasoning Based on Obvious Causes

These reasonings were suggestive of arguments that tended to draw on obvious factors to explain a phenomenon. 7 students (~5%) made this type of reasoning. They explained that either they are not noticing any particular changes or that the changes are part of a natural process in nature. Of this, one student explained that “the temperature changes all the time and … we have a very wide variety of weather and [so] the climate probably isn't changing hardly any.” These reasonings shared the similarity of emphasizing on what visibly happens at students' surrounding and that they equated those changes with what scientists called climate change; therefore, they considered the changes as natural.

In my interview on the fourth question, students were prompted for possible alternative explanations for their answers. No particular pattern of change was noted in students’ reasoning style about climate change. Challenged by counter arguments about their responses, students who had agreed with the statement tended to provide more examples either from their own personal observations or from scientifically reported events to support their stand. Some students had referred to “sea level rising” and “ice cap melting” as their personal observations to evidence for climate change. When I explained that they were scientifically reported events, they acknowledged that there was a need for scientific data to argue for climate change, but did not necessarily agree that we can tell climate change is happening just based on scientific data. For example, Lily believed that her observations of “longer winters” and “hotter summers” were valid evidence for climate change. Students who had argued for the need for scientific data to support climate change also stayed on their position explaining that they cannot notice climate change themselves. Of this, Eric elaborated that “I would have to rely on scientific principles of the difference like weather and climate and how those patterns have worked historically.” Overall, all my interviewees argued for climate change with slight change in their reasoning type.

In sum, the majority of my participants argued for climate change. In this regard, the reference to events was prevalent among them. What distinguished students' reasonings, however, was on the type of the event they mentioned to. For example, "sea level rising" and "harsher winters" were both brought up as evidence for climate change, while the former is an on-going process, non-obvious to lay people and the latter is an event that can be experienced by anyone. In my study, I scored such examples non-obviousness-based and event-based, respectively. However, I noted that the difference between such events were not necessarily clear to all students, as they used those examples indifferently.

Discussion

My study revealed that students largely apply simple causal reasoning to explain their views about biological and environmental phenomena. This finding corresponds to the extant literature demonstrating students’ tendency to draw on simplified features of causality (Cuzzolino et al., 2019; Ferrari & Chi, 1998; Grotzer, 2003; Grotzer et al., 2017; Grotzer & Solis, 2015; Hmelo-Silver et al., 2007). Below, I discuss why students mostly use simple causalities and argue about the role of education in this respect.

Braaten and Windschitl (2011), drawing on philosophy of science literature, described causal model as a scientific way of explaining natural phenomena which considers “causation as the key attribute of explanatory power” (p. 647). Different modes of causal connections are discerned in the literature (Ahn & Kalish, 2000; Grotzer &

Tutwiler, 2014). Grotzer and Tutwiler (2014) introduced them as (1) covariance modes of causal induction (i.e. in my study probabilistic causal reasoning) that considers the possibility of connections between cause and effect based on statistical models, (2) specific generative mechanisms that are based on the knowledge we amass about the types of causes and functioning mechanisms of things, particularly in a specific domain like biology, and (3) testimony which relies on the information provided by others. Among these three modes of causal induction, my participants hardly made any probabilistic and testimony reasonings, instead explained their stand by specific generative mechanisms.

Due to the nature of my questions, it was not plausible for my participants to make probabilistic predictions, as it required some statistical information. However, my study revealed that students were aware of the probabilistic causal relationship but lacked the skills to argue based on it. In fact, students used deterministic language to discuss their ideas and, in this regard, they drew on reliable cause and effect relationship. But, at the same time, many of them brought uncertainty into their arguments by adding "but things can happen" or "[scientific predictions] are accurate to an extent." This showed that the students knew the scientific predictions could become inaccurate, but associated those inaccuracies mostly to accidents and errors, rather than associating them to the probabilistic nature of scientific predictions. In other words, I found that students intuitively knew about the unreliable causal relationships, but lacked the skill and language to discuss how probabilistic relationships justify some inaccurate scientific predictions.

My participants also rarely drew on testimony, in the sense of referring to a source of authority, to reason about their views. Comparing this to the findings that revealed children tended to refer to others' claims for making arguments (Grotzer & Solis, 2015; Harris, 2012), I may be able to argue that as individual's age and their knowledge increase, they assimilate the knowledge and take ownership over it, and thus become less likely to refer other's narratives as evidence. This was particularly evident in my fourth question. Majority of students regarded that without referring to scientific reports and just based on their own observations, they could see climate change occurring. And in this regard, many of them considered scientific reports as their own knowledge.

Students' reasoning modes were mainly causal mechanism in the sense that they drew on their biological and ecological knowledge to make scientific explanations about the cause and effects of the phenomena. Therefore, their arguments heavily relied on their knowledge from their science classrooms, and in the case of my study from their biology education background. Thus, it is crucial to argue about the role of science education in shaping students' arguments in response to complex problems.

In my study, I observed that students applied different reasoning patterns to respond to each question. Those patterns entailed both simple and complex causal reasonings. This indicated that it was possible for students to make complex causal reasoning with the knowledge they already had. For example, in students' arguments about how CR and breathing either unfold sequentially or occur simultaneously, both explanations provided mechanistic details. Therefore, I did not find correlation between students' reasoning style with their depth of knowledge about either of the issues in questions.

However, I noted that students' knowledge and their ST skills led them toward making simple causal reasonings, rather than complex one. For example, one explanatory pattern that emerged in students' responses was the tendency to explain the phenomena by providing an example. In this way, students first reduced the phenomena to simple cases, then generalized the cases to the whole phenomena. This approach of reasoning is unsurprising as it makes the phenomena in questions more tangible and reduces the cognitive load to explain them; plus, it is a common practice in science education to provide an example to elaborate a phenomenon. This way of thinking reflected the challenges ST encounters in general; the heavy load of cognitive processes involved in reasoning about complex systems, and the fact that education about complex phenomena is more focused on the elements and details of systems and less attentive to the phenomena as a whole (Hmelo-Silver & Azevedo, 2006).

Specifically, I found students' beliefs about the role of DNA an exemplar of how education promotes a simplified view toward a complex system. Majority of students considered a more significant role for DNA than the environment in determining an organism's phenotype. This centralized view acted counterintuitive for students to construct distributed or relational causal reasoning in which the phenotype emerged out of the interaction among various factors. For instance, some students explained in detail how genes are expressed and translated into proteins and how proteins shape an organism's phenotype, but found it hard to embed the environment into their explanations.

This finding, however, is not surprising. Dominated by reductionist methodologies, biology has moved toward explaining all biological phenomena in terms of the structural properties of macromolecules (Nicholson, 2014) and biology education has followed suit. However, there is a need to reconsider gene/DNA centered biology education, as it has been found to be problematic. For example, it is reported that DNA-centered biology feed into genetic essentialism (Dar-Nimrod & Heine, 2011). Genetic essentialism lowers self to a molecular entity (Nelkin & Lindee, 2004) and tends to associate a person's characteristics and behaviors to his/her genetic make-up (Dar-Nimrod & Heine, 2011). It is used to downgrade social interventions that attempt to reduce social inequities; prejudice (Dar-Nimrod & Heine, 2011) interethnic hostility (Kimel et al., 2016) and discriminatory policies (Soylu Yalcinkaya et al., 2017) are sometimes justified by genetic essentialist views. Thus, when addressing biology related issues, from disease epidemics to the matter of genes in determining race and gender capabilities, it is crucial to know about biological complexities; the significance of organisms' agency and autonomy as well as the role of environment in organisms' development and behavior.

In sum, my study revealed that students applied different patterns of causal mechanisms to explain their views toward biological and environmental issues and, to a large extent, those patterns fell into the categories of simple causalities. While acknowledging the general challenges in ST such as its high demand of cognitive load, I put the emphasis on the role of education in leading students toward simple causalities. Because, as noted, students constructed mechanistic reasonings which are based on domain specific knowledge. Furthermore, I found that in many cases students tended to stick to their simple causal explanations. This, in effect, worked as a barrier for them to expand their view to make complex causal reasonings. This finding correlates with the extant literature showing how simple casualties stand in the way of students to make complex causal reasonings (Cuzzolino et al., 2019; Woodward, 2007). However, as will be elaborated in the model below, simple causality does not necessarily impede complex causality, as scientists apply both of them. The issue, indeed, is that students do not have the skills to apply simple causalities in relation to complex causalities to explain complex systems. As a result, I suggest that to improve students' ST skills, we need to provide students with scaffolding that can help them build the knowledge about complex systems on their mechanistic knowledge and reasoning skills.

System Thinking Model

Drawing on my findings in this study as well as the extant literature, I propose a model in this section to picture a holistic view toward ST. My model attempts to make a logical relationship between knowledge and the elements of simple and complex causalities. By demonstrating the relationship among the elements of ST, it tries to provide a system for ST.

My study revealed that students use variety of reasoning patterns to argue about complex systems. On the basis of my theoretical framework, I identified the type of those reasonings and argued about them in two broad categories: simple and complex causal patterns. I also demonstrated that simple causalities were used more frequently by students than complex ones. The higher frequency of simple causalities could be a form of correlation between them in the sense that probably the use of one simple causality increased the chance of using another simple causality. This is significant as we observed that students' reasoning patterns did not occur in disjunction from each other; there were actually interactions and continuity among them. For example, I noted merge and continuity among simple causal reasonings. In some ways, students who made event-based reasonings demonstrated the obviousness-based and proximal-based reasonings as well. I also noted that when students had centralized view toward biology their arguments could be viewed as both centralized and/or agency-based, because in both cases one factor is in charge for the phenomenon or the event. Though, in my scoring scheme I had considered the subtle differences between the different forms of reasonings, it was not always clear-cut clear on which type of reasoning students' arguments were built on. I scored them based on their tendency toward one type of reasoning or the other, but my observation told me that I should acknowledge the overlap and sometimes indispensable relationship between some reasoning types.

In accordance with other studies (Barth-Cohen, 2012, 2018; Halverson et al., 2009), I acknowledge the fact that students' prior knowledge plays a significant role in their arguments and that these arguments fall within a spectrum of different reasoning patterns. Therefore, I developed a tentative model that portrays the potential relationship between prior knowledge and various forms of causal reasonings (figure 3). My System Thinking Model (STM) provides a systemic picture of reasoning patterns. It puts Personal Theories of Systems (PTS) at the heart of a reasoning system and acknowledges the relationship among different forms of causal reasonings. The model suggests that ST is too complex to be captured by isolated lenses of causal reasonings (e.g., centralized versus decentralized) and thus argues that students' ST skills should be viewed within a system of causal relations.

Personal Theories of Systems (PTS) refers to students' knowledge and beliefs about a system and comes from their life experiences and educational background. It is the source of knowledge students draw on to reason about complex systems. In other words, PTS encompasses an individual's general knowledge, including its domain specific knowledge, about a phenomenon and serves as a foundation for ST. Therefore, PTS is more focused on an individual's knowledge about a complex system and less concerned about his or her ST skills.

Paradigm of Simple Causality (PSC) refers to an approach of thinking that is mostly heuristic and brings about speed and efficiency in human reasoning. It entails the following seven reasoning styles: intentional/agential, centralized, event-based, obviousness-based, proximal, sequential, and deterministic reasonings. For two main reasons, I consider intentional/agential reasoning closely associated with PTS and propose it as the first layer for making perception of complex systems. First, goal-oriented attempts to make things happen – intentional behaviors – are found to be the key features of how humans perceive causality (Meltzoff, 2007). Second, agency is found to be a potential developmental primitive that influences how students frame their causal explanations (Cuzzolino et al., 2019). Accordingly, intentional/agential reasoning serves as the base layer for PSC in two ways; first, it is the primary way people make sense of their experiences, and second, it leads to other simple causal reasonings.

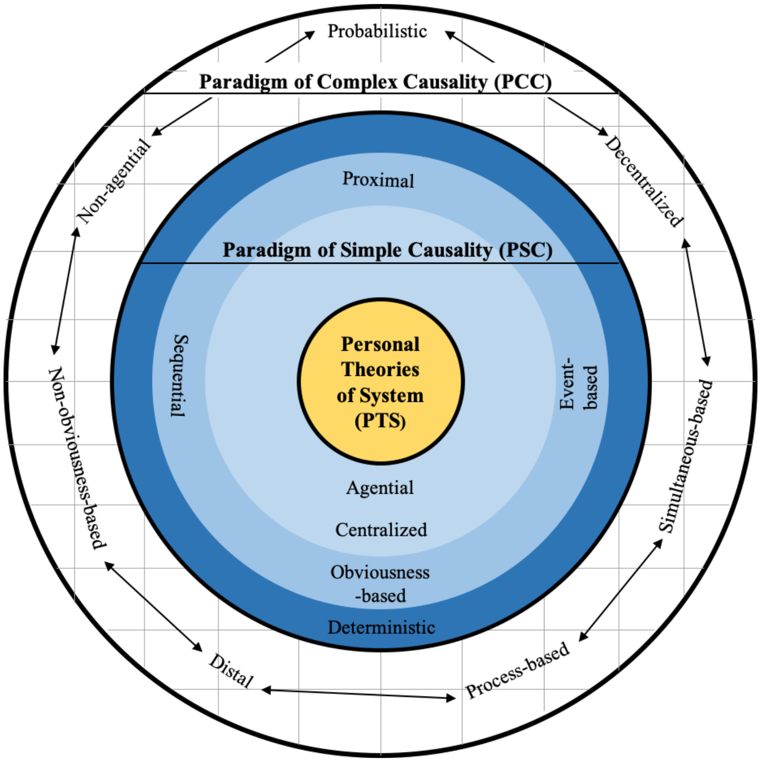
In my model, centralized causal reasoning jointly associates with agential causal reasoning. They both share the similarity of having a factor or agent in charge of a phenomenon or system. For example, students' arguments on how mutations (agents) had decisive effects on phenotypes had its base on the belief that DNA has a centralized role in dictating organisms' features. Plus, I found an overlap between centralized and agential reasonings when students considered DNA as the agent responsible for organisms' behaviors and evolution. Consequently, I believe that it is plausible to say that centralized causal reasoning often has some forms of agential causal reasoning embedded in itself.

I found proximal, event-based, visibility-based, and sequential causal reasonings more intuitive to be jointly together as the next layer of PSC. They have in common the feature of being noticeable to the reasoning person in one way or another and accordingly sometimes overlapped in my study. Events are distinctive actions with a beginning, middle and end which unfold sequentially (Chi, 1997). Based on this definition, events are by nature noticeable;

therefore, event-based reasoning often embodies obviousness-based reasoning. Events are also sequential, and thus, their examination invokes sequential causality where there is an order of cause-and-effect chain. Consequently, arguing based on the chain of cause and effects often necessitates reasoning based on the temporal and spatial proximity of cause and effect that make proximal reasoning embedded into sequential reasoning. The close association and occasional overlap among these types of reasonings were evident in my study. When students referred to harsh winter to argue for climate change, for example, they actually referred to an evidence which entailed features of being an event, being noticeable, and happening in the time and place proximity of them. Explaining how more oxygen increases the rate of CR based on CR mechanism, students were making sequential reasoning while also drawing on proximal factors involved in CR mechanism.

Figure 2.3

System Thinking Model (STM)



System Thinking Model (STM) entails three major zones. The outer zones are built upon the inner zones, and also the outer zones encompass inner zones. Personal Theories of System (yellow zone) refers to an individual's knowledge and beliefs about a system and works as a source of information. Paradigm of Simple Causality (the spectrum of blue colors zone) is an approach of thinking which is largely heuristic and brings about speed and efficiency to human reasoning. It represents a worldview in which there is a reliable relationship between cause and effect and adopts the language of control and predictability to explain the natural phenomena. Causal reasonings within a same color in this zone associate with and affect each other. Paradigm of Complex Causality (the meshed white circle) represents the worldview in which the relationship between cause and effect is nonlinear and sometimes unreliable. Accordingly, it adopts the probabilistic language to discuss about world phenomena.

Deterministic causality is the characteristic feature of PSC wherein there is a reliable relationship between cause and effect. In my model, deterministic causal reasoning encompasses all other features of PSC. In this sense, while reasoning within the paradigm of simple causalities, one argues with the essence of certainty about the underlying mechanisms of phenomena, and hence applies the language of possibility to control and predict them. For instance, in this study, many students argued that we could accurately predict the extinction and survival of organisms in half a century. The essence of this argument laid in the belief that the interaction between organisms and their environment was based on identifiable factors with linear and reliable causal relationships. The assumption, indeed, had its roots in a web of simple causal reasonings; factors involved in an organism's extinction/survival are present and detectable at the time of study, the pattern of species life in a habitat is a sequence of events that unfold predictably, and events are the major factors of unpredictability and so by removing them our predictions would be accurate.

Similarly, deterministic causality was prevalent in the language of students who made centralized and agential causal reasoning. They believed that we could accurately tell an organism's phenotype from its genotype, and that mutations were the prime agents in determining organisms' extinction and survival. These reasonings were valid based on the assumptions that DNA had a linear authoritative role in determining organisms' features and that a one-directional and reliable causal mechanism existed between genotype and phenotype.

Overall, seeing deterministic causal reasoning present in other forms of simple causalities, I placed it as the outer layer of PSC in my model to demonstrate its two features. First, deterministic causal reasoning encompasses other forms of simple causalities. In other words, as longs as individuals only apply simple causalities, their arguments would fall within the circle of determinism and certainty, which is the main feature of PSC. Second, in order to make complex causal reasonings, individuals need to go beyond making deterministic arguments.

The Paradigm of Complex Causality (PCC) is a thinking method that not only regards immediate issues, but also examines the possible causalities that may stand out of an individual's convenient circle of attention. It encapsulates both PTS and PSC while also entailing the following seven reasoning styles: unintentional/passive, decentralized, process-based, non-obviousness-based, distal, simultaneous, and probabilistic reasonings. PCC acknowledges that phenomena occur within the network of multiple interconnected, interdependent, and interacting factors indicating that reasoning about natural phenomena requires consideration of multiple factors that may reside both within and outside of an individual's attention span. Furthermore, it considers that the relationship between cause and effect is nonlinear and sometimes unreliable, and accordingly adopts the language of probability to make predictions and demonstrates uncertainty as a rational part of causal reasoning.

My model indicates that the elements of PCC are interrelated to each other. I have demonstrated this by placing the elements of PCC within a meshed circle and having them related to each other through bidirectional connections in a cyclic fashion. This demonstration does not intend to show how causal features of a complex system are specifically connected to each other; rather, it attempts to illustrate that, likewise simple causalities, different forms of complex causalities can probably feed into each other. This means that having the skill to make one form of complex causal reasoning, decentralized causality for instance, may help an individual to make other forms of complex causalities such as unintentional/passive causal reasoning. For two reasons, however, my model did not show any specific pattern of relationship among PCC elements. First, my results did not reveal any specific pattern of relationship among students' complex causal reasonings. Second, I found it counterintuitive to show that the causal elements of complex systems could be reduced to particular patterns of interconnection. However, I acknowledge that this is a subject requiring further investigation.

In sum, STM is comprised of three major grounds: personal theories of system (PTS), paradigm of simple causality (PSC), and paradigm of complex causality (PCC). PTS entails an individual’s knowledge and beliefs and stems from a person’s life experiences and education backgrounds. Having PTS at its heart, my model illustrates that a person’s perception of the world, based upon his/her background, is the primary factor that guides the individual's tendency toward a particular type of reasoning. Built upon PTS, PSC provides the array of causal types that allows the reasoning person to have an immediate explanation about any phenomena he or she encounters. PSC is the paradigm that relies on reliable cause and effect relationship. Accordingly, thinking within this paradigm leads to deterministic explanations about the world phenomena and brings about the belief in human capability to control and predict natural phenomena. PCC, on the other hand, by engulfing PSC within itself, acknowledges the possibility of control and prediction about natural phenomena, but at the same time considers uncertainty as the natural part of causal predictions. Accordingly, thinking within this paradigm guides an individual to take into account that not only different forms of unnoticeable factors might be involved in a phenomenon but also the interaction of the known factors can bring about unpredictable results.

Conclusions and implications

The findings of my study revealed that college students use a variety of types of causal reasoning to discuss about natural phenomena. However, they largely applied simple causality to explain their views. Aside from the human tendency to simplify complexities, I noted two main factors for the tendency of students toward simple causalities: first, the type of knowledge they had about a topic, second, their skills to make causal reasonings. My results also showed that students' different reasoning types did not happen in isolation from each other, but rather were related to each other. In other words, I noticed that when students made simple causality, their reasoning type often was in association with other simple causalities.

Upon my findings, I proposed STM. My model offers a holistic picture of ST and the factors that play role into it. It is a multi-component model that provides a system framework for investigating ST across scientific content areas. First, in its core, it acknowledges that content knowledge influences students' causal reasonings, but emphasizes that ST is more about students' skill to coordinate their knowledge to discuss about a system, and less about the knowledge itself. As shown in my results, students happened to make different causal reasonings based on a same knowledge and information. Accordingly, STM suggests that teaching students about the contents of a complex system would not necessarily improve students' ST skill. But, students need to learn about the various features of causal reasonings and have the opportunities to practice coordinating their pieces of knowledge so as to improve their skills in addressing complex problems.

Next, STM suggests that studying students' ST requires to be examined through a system; otherwise, it might not be fully informative about their actual reasoning skills. Because, as discussed above, students' reasoning could fall within a spectrum of simple causalities or fall between a spectrum of simple and complex causalities. Therefore, examining just one pair of a reasoning type in students (e.g., centralized versus decentralized), despite its value in showing students' skills in that particular reasoning type, would not necessarily be informative about students' overall ST skills. In this regard, STM proposes that students' ST skills to be studied within the paradigms of simple and complex systems as distinct worldviews, each constituting a share of beliefs and perspectives toward how systems operate. In this way, students' ST skills can be studied more holistically and there would be a higher possibility to detect the factors involved in developing students' ST skills.

Finally, STM suggests that the teaching and research about ST does not need to exist in duality between simple and complex systems. Though each system has its own distinct features, and it would be more intuitive to discuss about them in contrast to each other, my model proposes that simple causality should be instructed and studied as a part of complex causality. I acknowledge that this claim may seem contrary to part of my results in which simple causalities barred students from making complex causal reasonings. However, I believe that the issue was more related to students' lack of skills in understanding and making complex causalities, rather than being attributed to their skills in making simple causalities. On the other hand, I also observed that students who made simple causal reasoning were able to make complex causalities as well. Therefore, I conclude that the two system are not opposite to each other by nature. They just need to be taught as separate paradigms with specific features that at the same time are also related to each other.

Limitations

My study attempted to map out students' pattern of reasoning regard to complex systems. To this end, it had some limitations. First, my study was limited to four questions to prompt students for their various types of reasonings. The questions asked for particular responses that naturally favored some reasoning types over the others. Thus, students applied some reasonings more frequently than others without necessarily being skilled in using some particular reasonings over the others. Another limitation was that many students provided just one reason to explain their stand on each question. This confined my examination on how their different reasoning patterns were related to each other and if possibly they rendered or impeded each other.

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Chapter 3

Students' View toward Biology as a Complex System: Concept Map as a Tool to Assess and Enhance Students' System Thinking Skills

Introduction

Every day, we encounter complex problems ranging from disease epidemics and environmental issues to novel challenges raised by social media. Addressing such problems requires system thinking (ST) skills. ST is the ability to conceptualize complex problems and systems and involves understanding the dynamic interrelationship between system components and the patterns and behaviors emerging from them (Hammond, 2017; Jacobson, 2001; Meadows, 2008).

The significance of ST has been well recognized among science education researchers over the past two decades (Yoon et al., 2018) and is underlined in science education documents internationally (Boersma et al., 2010; National Research Council, 2010; NGSS Lead States, 2013). There are many benefits in embedding complex systems and ST practices in science education. It is found that engaging students in thinking about complex systems improves their science literacy (Assaraf & Orion, 2005; Ke et al., 2020; Sabelli, 2006). Jacobson et al. (2017) relate the value of learning about complex systems “both to the importance of these ideas in modern science as well as for the potential of complexity ideas to provide conceptual interconnections across different science subjects as a new perspective about scientific literacy’’ (p. 1). Furthermore, it is reported that instructors who have applied the system approach in their teaching have observed students gain a deeper understanding of content (Mathews et al., 2008; Verhoeff et al.,

2008) and make more interdisciplinary connections between concepts (Fisher, 2011, 2018; Jacobson & Wilensky, 2006).

Science education researchers have proposed various methods to foster students' knowledge about complex systems. Many of them have suggested that explicit instruction on system characteristics is the best approach to improve students' ST competencies and develop their system language (Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018). Considering ST as a metacognitive skill, Verhoeff et al. (2018) indicated that system characteristics, derived from different system theories, should be used as metacognitive tools to help students practice ST throughout their learning trajectory. Gilissen et al. (2020) came up with four design guidelines in teaching to improve students' ST: (1) introducing the seven characteristics of systems in relation to system theories; (2) providing students opportunities to apply system characteristics in different contexts; (3) focusing on individual characteristics at a time; (4) attending to system language and encouraging students to use them. Regardless of the teaching approaches, an appropriate assessment tool is needed to examine students' skills in ST. In this respect, concept map (CM) has been suggested as a helpful tool (Sommer & Lücken, 2010).

CM is a graphical tool depicting the relationship of concepts within a domain of knowledge and is used to organize and represent the structure of conceptual knowledge (Novak, 1990; Novak & Gowin, 1984; Novak & Cañas, 2008). Considering that the structure of knowledge is an indicator of the quality of understanding (Mintzes et al., 2005), many researchers in science education have found CM a suitable tool to assess students' knowledge construction (Baxter et al., 1996; Edmondson, 2005; Hucke & Fischer, 2002). CM is indeed an external representation of one's mental model and entails concepts (nodes) connected to each other by labelled lines, in each case building a proposition (Yin et al., 2005). Propositions are regarded as the building blocks and meaningful units of CM that allow an individual to express his or her knowledge of a content area by them (Novak & Musonda, 1991; Yin et al., 2005). In other words, CM is a particular way of constructing and representing knowledge in which a concept finds its meaning in connection with other concepts, and the final product is a visual representation of students' cognitive structures (Nesbit & Adesope, 2006). CM building is often associated to "constructivist" view of learning and it is believed that its practice, on one hand, helps students integrate new information to their prior knowledge and visualize their understandings of a content area, and on the other hand, help teachers get informed about the integrity of students' understandings in a domain of knowledge (Brandstädter et al., 2012; Conradty & Bogner, 2012; Schwendimann, 2015).

CM was suggested as a helpful instrument for studying students' ST (Sommer & Lücken, 2010). As an external representation of mental model, it was used to evaluate students' conceptual understandings and abilities to solve a problem in a complex system (Johnson-Laird, 2001). It was also employed to examine students' mental models of abstract concepts such as hierarchy and homeostasis in the human body (Chang, 2007; Henige, 2012). Tripto and her team used CM to externalize and analyze students' conceptual knowledge of the human body to draw conclusions about students' ST skills (Assaraf et al., 2013; Tripto et al., 2016, 2017, 2018). Furthermore, Buckley and Boulter (2000) found CM building a helpful approach for teaching and assessing students' understanding of multilevel structures such as complex and nonlinearly organized biological systems. It was also reported that CM provided insight into students' thinking and revealed the processes by which students constructed their cognitive structures (Hay et al., 2008; Ifenthaler, 2010; Shavelson et al., 2005).

Despite its benefits in ST studies, CM has been found to be more representative of a system's components and their organization and less representative of the underlying processes and mechanisms of a system. For example, Tripto et al. (2013) examined the effectiveness of CM as a tool to assess students’ ST skills. Using the Systems Thinking Hierarchy model (Assaraf & Orion, 2005), they found that students’ CM more emphasized on a system’s structural components than its processes. Similar findings were evident in other studies as well; students tended to demonstrate the components of a system on their CM with little understanding about the interactions between system components (Hmelo-Silver & Azevedo, 2006; Hmelo-Silver & Pfeffer, 2004). Tripto et al., (2013) also noted that students had difficulty in demonstrating the underlying mechanisms and dynamic natures of a system by CM; in fact, they found CM to be a static representation of students’ conceptual knowledge about systems, and so not being a proper tool to display higher-order ST skills like expression of multistep simultaneous processes.

Students need scaffolding to improve in ST (Hmelo-Silver & Azevedo, 2006), and they need it for their ST practices through CM building as well. Scaffolding is the practice of providing students with temporary supports to achieve learning goals and it gets gradually faded away as students get more and more skilled in achieving the learning goals (Lajoie, 2005). The literature indicates that scaffolding assists students to increase and integrate their higher order thinking skills to generate solutions to complex problems (Belland et al., 2017). It is also shown that scaffolding students’ CM building improves their learning and reasoning skills (Eggert et al., 2017). Yet, despite the benefits of scaffolding in students' learning, there are scarce studies that examine how scaffolding students' construction of CM improves their ST skills.

In this paper, I examine CM as a tool to study students' ST skills and how scaffolding students' CM building improves their ST competencies. Through a theoretical framework of causal patterns, I present a new perspective on what CM reveals about students' ST skills and what are its limitations in showing system complexities. In specific, I will discuss about the patterns of causal mechanisms in students' CM and what those patterns tell us about students' ST. Plus, through a comparative scaffolding strategy, I demonstrate that, accompanied with a proper scaffolding, CM is a powerful tool to examine and promote students' knowledge about the underlying causal mechanisms in complex systems. To this end, I sought to answer the following research questions:

1. What does CM reveal about students' knowledge of the causal mechanisms in complex systems?
2. How does scaffolding influence students' performance in showing the causal mechanisms in their CM?

Theoretical Framework

Thinking is a process in which individuals coordinate their inferences from their knowledge to address their needs such as solving a problem or making a decision (Moshman & Tarricone, 2016). Based on this definition of thinking, I define ST as a process to coordinate one's knowledge of a system to explain the behavior or function of a system. In this sense, an individual's awareness about the components of a system is a matter of their knowledge about the system and how they interrelate and interconnect the system components to make meaningful patterns to explain the system's behaviors and functions is the matter of ST. Emphasizing on the thinking aspects of students' view to complex biological phenomena, in my study, I provided my participants with the components of the systems so as to examine the interconnections they make between system components to build meaningful patterns to explain biological phenomena. To study those patterns, I drew on the patterns of underlying mechanisms in complex systems introduced by Grotzer (2012).

In her book "learning causality in a complex world", Grotzer (2012) introduces six causal patterns that underlie complex causalities: simple linear, domino, cyclic, spiraling, mutual, and relational causalities. Below, except for spiral causality, I explain these patterns of causal mechanisms and their role in determining features of complex systems.

Simple Linear Causality

Stemming from the works of David Hume (1739-1740), simple linear causality is based on three basic principles: one, a cause precedes an effect; two, there is a cause and effect mechanism for any outcome; three, to something happen, a cause must exist (determinism) (Morris & Brown, 2001). These principles lead to the assumptions of linear causality: cause and effect work in one direction in the order of cause preceding effect, there is a direct link between cause and effect with clear beginning and end, and there is usually one cause for one effect. In sum, linear causality implies that anything that happens in a system can be traced back to a cause in the same system suggesting that a sequence of cause and effect explains behaviors of a system.

Domino Causality

Domino causality refers to a linked sequence of events that unfold over a period of time and typically has a beginning, middle, and end. In domino pattern of causality, causes induce effects and effects turn into causes for subsequent effects. It is one directional and can have branchings; therefore, one cause can bring about multiple effects and so forth. Domino causality explains some aspects of complex systems in which a cause triggers a chain of reactions which subsequently leads to unpredicted outcomes. Climatic events that induce a cascade of challenges illustrate this pattern of causality. For instance, in 2017, Hurricane Harvey caused a widespread flooding in Houston that impeded evacuation and access to emergency services. However, it also brought about health threat and gas price inflation by, respectively, sweeping water from wastewater treatment plants and shutting down a quarter of U.S. oil production in the Gulf of Mexico (Sneed, n.d.).

Domino causality is one of the central mechanisms by which complex systems display their behavior. It explains how within complex systems a small change can bring about huge impacts and how a cause can have both direct and indirect effects. Accordingly, this practice of thinking requires individuals to consider that the impact of a cause can travel over time and space and possibly be out of their sight. The snowballing effect is another complex system behavior which exhibits itself through domino pattern. It refers to a process that starts with a small event or cause and builds upon itself and has the potential to amplify the effects along its way. Herd stampedes that can be triggered by the panic of one animal is an an example in this regard. Taking the snowball effect into consideration, domino causality emphasizes on careful attention to the events early in their patterns before they turn into an avalanche of events. Moreover, domino causality spotlights the matter of threshold effect that refers to a sudden change of behavior in a system due to accumulation of causes and effects surpassing a certain limit in a system. For instance, Earth system scientists have predicted that if Earth passes a certain threshold of warming, it can turn into a state of domino like accelerated warming that can not be stopped even after greenhouse gases are not poured into it anymore (Steffen et al., 2018).

Mutual Causality

Mutual causality is a pattern of causal relation in which two events, acts, or processes mutually or bi-directionally affect each other. Therefore, the factors or agents involved in this relationship operate as both cause and effect on each other in a way that it is usually impossible to tell which factor precedes the other. In mutual causal relationship, involved factors can both benefit, or get harmed, or one side benefit and the other side get harmed from the interaction, and the process can be simultaneous or sequential. Symbiotic relationships between two species in which at least one species benefits from the relationship illustrates a pattern of mutual causality. Some of the main features of complex systems are the abilities of self-organization and self-transformation. Mutual causality is one of the mechanisms by which scientists explain how systems and their components engage in their own organization and transformation (Morgan, 2006).

Relational Causality

In relational causality, the effect is caused by the relationship, one of balance or imbalance, between elements of a system. The variables, events, or processes involved in this causal relationship can not be a cause by themselves. Therefore, in exploring relational causality one looks for more than one variable for a cause and consequently examines the relationship between variables or sets of variables to argue for the effect. The relationship between the variables can be in balance/equivalence or imbalance/deference and the change in the relationship can influence the outcome. On the other hand, the proportional equal change in all variables in a relational causal relationship does not change the effect or outcome.

The natural world and consequently the complex systems exhibit many of their features and behaviors through the mechanism of relational causality between their components. For instance, in the osmosis process in biology, molecules of a solvent pass through cell membrane from a less concentrated area to a more concentrated one. In this process neither low nor high concentration of solution is the cause for the movement of a solvent molecules but the relationship between them determines the outcome.

Cyclic Causality

Cyclic causality refers to a pattern of relationship in which variables in an action, event, or situation are connected in a circle and typically there is no clear beginning and end to them. In cyclic causality an engaged component can be both cause and effect simultaneously. Also, there is a form of feedback loop or reciprocity in cyclic causal pattern that makes the cycle to continue. The feedback loop can feed to maintain the status quo or amplify or play down the effect over time. Cyclic causality is one of the main mechanisms that demonstrate how complex system components are interlocked to each other; thus, all components in a system are of high significance and failure of one component can disrupt the cyclic pattern and continuation. It also explains the way complex systems are sustainable and continue to maintain themselves. Natural world is full of cyclic patterns that operate through cyclic causal mechanism. As an example, carbon cycle explains how Earth sustains life on itself. Through the process of photosynthesis, carbon dioxide from air enters into the living world as carbohydrates (food). They are then consumed by animals. And eventually they return to the air through the process of respiration or decomposition of the body of plants and animals.

Methods

This study sought to examine what CM shows about students' ST and how it can improve students' ST skills. To this end, I used convergent mixed method design (Creswell & Plano Clark, 2011). This approach draws on both quantitative and qualitative data to compare and contrast their results to provide a complete understanding of a phenomenon and compare multiple levels within a system (Creswell & Plano Clark, 2011). Drawing on both quantitative and qualitative methods, this study provides a detailed insight into students' approach toward CM building to demonstrate the interrelationship among the components of biological systems. In this regard, I also present the patterns of causal mechanisms existing in students' CMs and the effect of scaffolding on their performance in showing those patterns.

Research Design and Participants

For this study, I first developed a master CM (appendix A) out of sixteen big concepts taught during an introductory biology course. The concepts addressed different levels of biological organization from sub-organismic entities (e.g., DNA, RNA, protein) to supra-organismic entities like population. Then I designed three variations of CM assignment. Providing different levels of scaffolding, the assignments asked students to demonstrate the effect of introducing a new predator species into an environment while showing the relationship between different biological concepts. The scaffoldings were practiced as follows: assignment A provided students with the concepts to build their CM; assignment B gave students the skeleton of the master CM to fill out the boxes by the given concepts and label the links; assignment C first provided students with scaffoldings for the different patterns of causal mechanisms (Appendix B) and then asked them to build their CM based on the given concepts. The CM building task was followed by three questions: First, how students evaluated their CM in regard of expressing their thoughts on the scale of 1 to 5 with five being very satisfied. Second, what aspects of their thoughts they could express satisfactorily, and third, what thoughts they could not express by their CM. The follow-up questions of the assignments served two purposes in my study. First, they provided us with students' general satisfaction in presenting their thoughts by each type of the CM assignment. This was helpful in regard of knowing students' general expectations from a CM task. Second, they worked as prompts for students to reflect on their CM building performance in regard to how CM as a tool allowed them, or not, to express their thoughts. Accordingly, students' answers to the follow-up questions provided us a rich data on how CM, as an assessment platform, favored expression of some thoughts and unfavored some others. The assignment was given to students close to the end of the semester as a take-home task. Of note is that students were taught about CM building in a 50-minute session in the first half of the semester.

Participants of this study were 173 students from an introductory biology course at a public university in the Midwest. They were randomly put into three groups and each group was assigned to a different variation of a CM assignment. I also interviewed fourteen students (five students from each group of A and C, and four students from group B). They were recruited by sending out an email to the whole class and a five-dollar gift card was offered as an incentive for interview participation. The interviews were conducted in a semi-structured format and the students were asked to elaborate on the overall structure of their CM as well as the patterns that existed in them. Students were also prompted about different causal relationships and were given the time to demonstrate them on their CM. Accordingly, the interviews lasted around 25 minutes and were audio recorded and later transcribed for detailed analysis.

My interview data was insightful in different ways. First, it revealed students' views toward CM task and their previous experiences on it. This was significant as it showed their general approach toward CM building that favored expression of some thoughts more than the others. Next, it allowed students to express their thoughts about the interaction between the given concepts and how CM enabled them, or not, in demonstrating those thoughts. Last, it revealed students' knowledge about the causal patterns. This was particularly informative because by giving students the opportunity to elaborate on their views about the causal patterns, the interviews provided us with further information in regard to whether students' demonstration of causal patterns, or lack thereof, was due to the lack of knowledge about the patterns or lack of skill in constructing interactive CM.

Data Analysis

Students' Views Expressed by CM: Qualitative Analysis

My qualitative analysis sought to examine students' overall view toward the relationship among biological components and how they could express them by CM. To this end, I conducted a qualitative inductive analysis (Thomas, 2006) on my data that entailed students' CM, their explanations regarding the expression of their thoughts by CM, and their interviews. I first carried out multiple readings and interpretations of my raw data. Then, based on my interpretations, I developed categories of thoughts and ideas students were capable and incapable to demonstrate by CM. Finally, through the lens of my theoretical framework, I analyzed my data for the patterns and reasons that enabled or impeded students' expression of thoughts through the CM instrument.

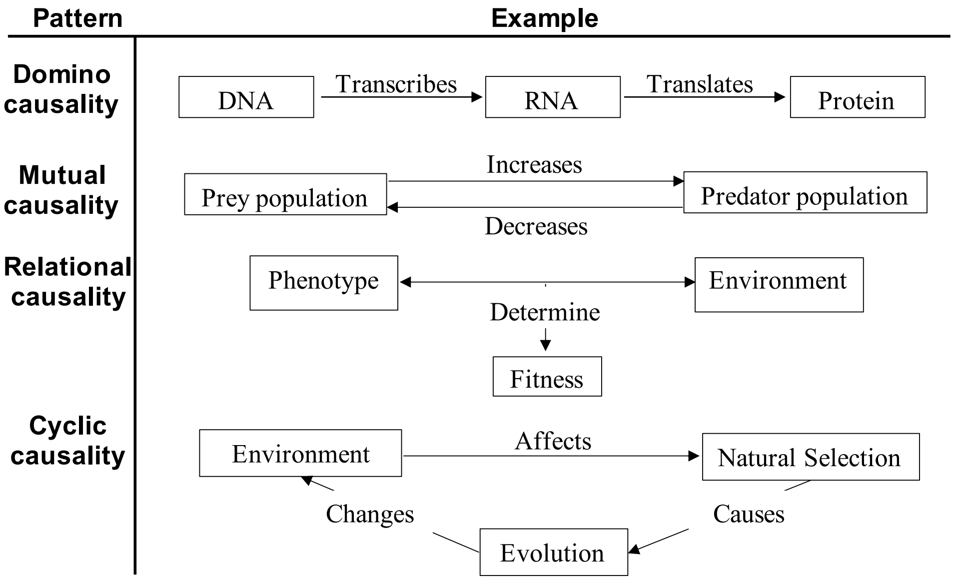
Students' CM Performance: Quantitative Analysis

To conduct my quantitative analysis, I developed a scoring scheme to examine the presence of causal patterns in students' CM. On this, I developed a list from combination of propositions that accurately demonstrated the patterns of domino, mutual, relational, and cyclic causalities. Figure 1 shows examples of proposition combinations used for scoring each causal pattern. To make the list, first, I compiled a list of all possibly accurate combination of propositions based on my own knowledge (I have a bachelor in biology and a master in biochemistry) and the repeated patterns in students' CM. Then, I had my list edited and approved by two biology experts. I used my list as a reference to score the presence of different causal patterns in the CMs. The causal patterns were scored as correct (2 points) if the concepts and describing labels were correct, partially correct (1 point) if the connected concepts were correct but without or with wrong labels, and incorrect (0 point). This pattern-based scoring method enabled us to examine students' CM at a higher organizational level than the conventional method of scoring CM does - based on single propositions. Indeed, it framed students' CM in bigger chunks of meaningful propositions, and accordingly, reduced the disorderliness of the students'

CM when it came to scoring. As a result, this approach made it easier for us to score the CM and have consensus over the results.

Figure 3.1

Examples of proposition combinations making causal patterns



Of note is that, in this study I sought for the presence of the patterns; therefore, several repetition of one pattern on one CM did not add to the score of that pattern. Moreover, considering that any proposition in CM represents a pattern of simple linear causality, I did not analyze this pattern separately as a causal mechanism in my study.

Finally, for my quantitative analysis, I calculated the percentage of scores for each pattern to determine their prevalence in students’ CM across the groups. Then, using Kruskal Wallis H Test, I compared students’ scores for each pattern between my three groups to determine how my different scaffolding approaches affected students’ performance in demonstrating causal patterns in their CM.

To validate my findings, I provided a second researcher with a science education background with 20 percent of all my data set, the scoring scheme and the findings of the study. Few discrepancies were brought up by the researcher that were discussed and addressed in a meeting with the researcher.

Results

My study, in general, investigated CM as an assessment tool to represent students' view toward biology as a complex system and in specific as a tool to examine and promote students' knowledge about underlying mechanisms in complex systems. To this end, in this section, I first provide a thematic qualitative analysis about what students were able and unable to demonstrate by CM regarding the interconnection and complexity of biological systems. Then, through the lens of my theoretical framework and the merge of my quantitative and qualitative results, I describe the patterns of causal mechanisms present in students' CM and how scaffolding affected their performance in showing those patterns.

Aspects of Complexities in Biological Systems Revealed in Students' CM

I found four major categories in my data featuring some aspects of biological complexities. These categories often were not exclusively mutual in students' CM.

Cluster of Concepts; Interconnections within Organizational Levels in Biology

Students expressed part of their views about the interconnection among biological components by creating cluster of concepts. Appendix C represents an example of a cluster of concepts CM constructed by students. The concepts of a cluster were often organized based on their association to a particular concept or their affiliation to an organizational level in biology. For example, Grace (all names are pseudonym) from group A explained that she was satisfied with her CM because the way she "organized the main thoughts and then broke the topics into subunits of each other show[ed] how they all are connected to an ecosystem's biodiversity." In her CM, she had built four clusters of concepts connecting them to the central concept of the ecosystem biodiversity. Likewise, Skylar (group C) explained in her interview that she "initially put evolution in the center […] trying to make the connections in between every individual thing." She was not satisfied with her CM (scoring her CM 2 out of 5); however, she believed that she could "explain relationship between individual parts of whole." Similar approach was adopted by group B students to fill out their pre-designed CM. Bella, in her interview, explained that "I try to put the concepts that I thought were more related … closer to each other; for example, DNA and RNA [are] very closely related as are fitness and natural selection closely related." In fact, I observed that creating cluster of concepts was an approach of CM building in which students were more focused on organizing and categorizing the concepts rather than trying to show all the meaningful interconnections among them.

Sequence of Concepts; Hierarchy and Flow among Biological Concepts

A group of students expressed their views about the relationship among the given concepts by ordering them sequentially. Appendix D represents an example of a sequence of concepts CM constructed by students. They believed that their CM showed how each concept related to the other one. For example, Molly (group A) explained that "I think I accurately and satisfactorily expressed all of the terms on my concept map by branching them off of each other. Starting with larger concepts and breaking them down to smaller parts." Molly's CM was one directional with some branches indicating that there is an order in how biological concepts are related. Similar approach was observed in group B students with pre-designed CM; Clara said that she liked “how everything flows from DNA to overall interacting evolution.” More in this regard, Kaela elaborated in her interview that “I was satisfied with that I put some kind of flow into it and the fact that I started at a more like molecular level and worked my way up to broader concepts and […] put those altogether.” I noted that organizing concepts sequentially was helpful for students in expressing some of their views about biological complexities. However, it also acted counterintuitive in showing various interconnections in biological systems as it focused on depicting the relationship among biological concepts through chain of connections.

Biological Processes; Protein Synthesis and Evolution

Biological processes were also demonstrated in students’ CM. The process of protein synthesis was one of them; the processes of DNA translation to RNA, and RNA transcription to protein were shown and mentioned by many students. Evolution and natural selection were the other processes brought up by the students as depicted well in their CM. Sadie (group A) explained that her CM showed “the evolution process and how it correlates to natural selection […] and how it changes over time due to […] adaptations and mutations.” I noted that to explain the processes, students drew on domino pattern to express their thoughts. This approach was more helpful in demonstrating the process of protein synthesis than evolution. I observed consistency and accuracy among students in presenting how DNA and RNA play role in proteins synthesis and even then how proteins attribute to an organism phenotype. But there was inconsistency and often inaccuracy in students’ patterns showing how, for example, the prey and predator population and the concepts adaptation, extinction and fitness play role in the process of evolution. In sum, students were able to express some biological processes like protein synthesis in their CM but struggled to demonstrate some other processes such as evolution.

System Dynamics; Matters of Change and Effect

Few students mentioned that their CM demonstrated the changes and effects induced by the events of mutation and the introduction of a new species to an ecosystem. For instance, Katy (group C) said that her CM clearly showed "how the ripple effect of a mutation change the original species." In her CM, she demonstrated a mutation bringing about domino of changes from DNA to protein and eventually to phenotype, and she also exhibited that phenotype affects fitness and consequently influences evolution. Similarly, Emily (group B) believed that her CM showed "how a mutation can lead to an adaptation and have a better fitness for [an] animal." Likewise, some students mentioned that their CM showed how the introduction of a new species can lead to extinction or adoption of other organisms in an ecosystem. Overall, students were able to show how an event can bring about changes and effects into a system. They did so by showing how an event unfolded sequentially to particular results.

In sum, CM as a tool allowed students to express their thoughts about both some interconnections among biological components and some dynamics in biological systems. To this end, students applied two methods; they either organized the concepts according to their biological level association or ordered them in a particular sequence of relationships. I found that these methods were helpful in presenting some aspects of biological complexities but, as will be discussed in the next section, were not proper for showing some other complex features of biological systems.

Missing Aspects of Biological Complexities in Students' CM

I found three categories in respect to thoughts students could not present in their CM based on the analysis of their CM and their dissatisfactions of it , and their interviews.

System Dynamics; Matters of Probability, Magnitude, Simultaneous Interactions and Ongoing Processes

Some dynamic aspects of biological systems were challenging for students to demonstrate by CM. They were often related to the matters that required simultaneous exhibition of multiple factors involved in a cause to bring about different effects, presentation of the causes and effects magnitude, and demonstration of ongoing processes. In this regard, showing the role of mutation in biological processes was mentioned by many students. For example, by a unidirectional arrow, Mile (group C) had shown that mutation "alter"ed fitness but did not believe such presentation expressed his view on "how a mutation can increase fitness and lead to evolution." Clara (group B) referred to a similar dissatisfaction by saying that she had difficulty to show "mutations being a mechanism of evolution." In the interview, Adeline said that she wanted to show how mutations could change organisms and elaborated that "You change something on a smaller level, it can affect all the larger tiers to like till biodiversity" but she did not know how to show a small change could bring about big effects on a CM.

The impact of a new predator on an ecosystem was another challenging issue for students to display by CM. The challenge was related to the interaction of the predator with a prey population and its overall effect on the ecosystem biodiversity and evolution. One student, who had shown on her CM that a new predator population can lead to extinction of a prey population, was dissatisfied with her presentation of the matter because she could not show "how a predator population can have a positive impact." There were students who showed the bidirectional relationship between the prey and predator population but some of them also expressed dissatisfaction about how they were unable to demonstrate the role of other factors involved in the relationship and how it could bring about different outcomes.

My analysis of students' CM aligned with their expression of discontent about not showing some system dynamics. Students struggled to show how multiple factors simultaneously affected each other and how the interactions among them could attribute to various outcomes. They also did not show aspects of complexity that required manifestation of nonlinear and probabilistic effects over a period of time.

CM Structure; Not Representative of the Whole View

The overall structure of CM was a matter of discontent for many of my participants as it did not fully reflect their views on biology. They believed that biological systems were more interrelated than what they had shown in their CM. For example, Renee (group A) had three cluster of concepts in her CM and she felt that the "sub-sections worked well but not the whole thing." She further elaborated that "I couldn't find a way to fit everything together as a comprehensive thought." Students' interviews revealed part of the reason why their CM did not represent their whole view. Sadie, for instance, said that she knew that "everything is interrelated" but she intentionally avoided drawing all the connections; because, otherwise, it would have been a "jumbled mess." A similar approach was adopted by some other interviewees as well. Tiana decided “to keep it simple” and Addison avoided showing some interactions because she did not want to have “a lot of information on [her] concept map.”

In sum, I could hardly find students mentioning that the overall structure of their CM represented their view on how the components of biological systems were interconnected. They believed that there could be more interconnections and interactions among the given concepts, but they did not show them for two reasons; either they did not know how to do so, or they avoided them so that their CM could clearly express their other points.

Some Concepts Did Not Fit Together

Students referred to the relationship between some concepts as what they could not express well in their CM. I noted that those relationships were of two types. One type was similar to what students mentioned in the cluster of concepts above; they were associated to a particular topic or an organizational level in biology with the difference that this time students did not know about them. For example, few students said that they lacked the knowledge about the evolution and so they could not express well the relationship among the concepts related to it. The other type of concepts students mentioned struggling to put together required integration of biological levels. For instance, Rylee (group A) had difficulty to show “how microbiology relates to the study of the environment and ecosystem.” Similarly, Emily (Group B) could not see “how genes influence biodiversity” and Derek (group C) was dissatisfied about the way he had tied “the lower half” of his CM, which entailed evolutionary concepts, to “the upper half,” which were about molecular biology. Overall, I observed that students found it challenging to put the concepts in a big picture and often the issue exacerbated as the two concepts were far from each other in biological levels.

In sum, I found that students struggled to express their holistic view toward biology in a CM, particularly about some aspects of complexity in biological systems. Contrary to what they had depicted in their CM, many students believed that the given concepts should have been more interconnected to each other to present a more realistic image of their view. This issue, to an extent, overlapped with the other difficulties students encountered to present about system complexities; overall their CM often failed to demonstrate dynamic aspects of biological systems and the interconnection between organizational levels in biology. In other words, students were more confident and satisfied about parts of their CM, not its whole.

Patterns of Underlying Causal Mechanisms Present in Students' CM

Drawing on both qualitative and quantitative data, in this section, I present the prevalence of various patterns in students' CM according to my theoretical framework. Then I reveal the results about the impact of scaffolding on students' CM performance in respect to showing different causal patterns.

Causal Patterns in Students' CM: Descriptive Analysis

In my quantitative analysis, I first scored the existence of domino, mutual, relational, and cyclic patterns in each student's CM. Table 1 presents the number and percent of students demonstrating each pattern. It shows that the domino pattern was the main causal mechanism that a majority of students (69 percent - correct and semi-correct scores combined) in groups A and C demonstrated in their CM. Domino causality was the second prevalent pattern (46 percent) in the CM of group B students' after mutual causality (53 percent). The table also reveals that the relational and cyclic patterns were notably absent in students' CM; on average, over 80 percent of my participants did not show those patterns.

The qualitative analysis of my data confirmed that the domino causality was the major causal mechanism employed by my participants to show the relationship among biological concepts. Group A and C students usually had a linear CM with a beginning and end with some branches, and group B students presented the relationship between most of the concepts through spotting a pattern of domino connection among them. Also, in the interviews, students used a sequential narration to explain how the concepts related to each other. For example, elaborating on her CM, Anne brought up the mice example in which a mutation "changed the DNA, RNA, proteins, genes, and then eventually changed the [mice] phenotype" and then how this process ended in creating two species. In sum, I found students more familiar with and adept in presenting the relationship between biological concepts in linear unidirectional pattern.

Table 3.1

Percentage of students showing each pattern of causality in their CMs

Pattern	**Group A (N = 62)**			**Group B (N = 57)**			**Group C (N = 54)**		
	Correct	Semi-correct	Absent	Correct	Semi-correct	Absent	Correct	Semi-correct	Absent
Domino	42%	27%	31%	32%	14%	54%	50%	19%	31%
Mutual	5%	6%	89%	14%	39%	47%	19%	20%	61%
Relational	6%	0%	94%	7%	21%	72%	7%	13%	80%
Cyclic	6%	3%	91%	0%	18%	82%	4%	7%	89%

My findings here align with the thoughts students believed they could express well by CM. In fact, it was largely through domino pattern that students connected the concepts in their organizational levels, showed the flow and hierarchy between the concepts, talked about some biological processes, and showed change and effect in their CM. On the other hand, the lack of the other patterns explains part of the students' difficulty in showing some of their thoughts by

CM. For example, students struggled to show simultaneous and ongoing processes in their CM. This problem could be eased if students were skilled in demonstrating mutual and cyclic causalities. Similarly, students wrestled to show the interrelationship among evolutionary concepts that required understanding of relational causality. Moreover, whereas students were satisfied with parts of their CM, they were discontented with its overall structure. This indicated that they were aware about the multiple and various interconnections that existed in biological systems but could not demonstrate them on their CM. This issue, to a considerable extent, was associated with students' lack of skills in showing the various causal relationships among biological concepts.

Causal Patterns in Students' CM: Comparative Analysis

I had this assumption that by providing scaffolds for various causal relationships, students would be able to demonstrate more complex relationships in their CM. To examine this assumption, I did a comparative analysis on demonstration of each causal pattern in students' CM. First, I did a Shapiro-Wilk test of normality on my data. The result was significant ($p < .05$) indicating that my data had a non-normal distribution. Then, I conducted a Kruskal-Wallis test to determine if there was any significant difference between my groups in demonstrating each causal pattern.

Table 2 shows the results of Kruskal-Wallis test on the score of domino causality. It reveals that there was a statistically significant difference ($H(2) = 6.822$, $p = .033$)

between the score of students in different groups. Post hoc comparison results revealed that the significant difference (p = .046) was between groups B and C. This result indicated that students without the pre-designed CM (i.e., groups A and C with the mean ranks of 91.60 and 95.44, respectively) had a better performance to demonstrate the pattern of domino causality than the students with the pre-designed CM (i.e., group B with the mean rank of 74.00).

My results here further confirm that students had the knowledge and skills to demonstrate the relationship among the biological concepts in a domino order. Therefore, given the pre-designed CM with limited domino patterns, group B students found it difficult to demonstrate some of their thoughts. This, indeed, turned out to be a source of dissatisfaction among Group B students as many of them "wish"ed that they were not given a pre-designed CM when talking about their dissatisfaction about their CM. In this regard, Emily mentioned in her interview that she could have had a better performance on her CM if she had built it herself from scratch. Accordingly, I also observed that students in group B evaluated their CM performance (M = 2.55, SD = 0.748) lower than the other two groups (group A: M = 3.01, SD = 0.905; group B: M = 3.08, SD = 0.908). These findings indicated that students were inclined to show the relationship among the concepts in a sequential pattern. They also explained why group C students, who got a tip about the concept of domino causality did not perform significantly better - though slightly better - than group A students. Because in any way students of both groups were going to show the relationship among the concepts through sequential orders.

Table 3.2

The results of the Kruskal–Wallis test and post hoc comparisons regarding domino causality.

Domino causality	Groups	N	Mean Rank	Chi-Square	df	P	Pairwise Comparisons of Group	P^a
	A	62	91.60	6.822	2	.033	Group A – Group B	.118
	B	57	74.00				Group A – Group C	1.000
	C	54	95.44				Group B – Group C	.046

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 3 displays the results of Kruskal-Wallis test on mutual causality. It reveals that there was a statistically significant difference (H(2) = 21.382, p = .000) between the score of students in different groups. Post hoc comparison results revealed significant difference between groups A and B (p = .000) and groups A and C (p = .004). This result indicated that scaffolds of mutual causality improved students' performance in demonstrating such a pattern in their CM. In fact, when students were scaffolded for mutual causality either through getting tips about the concept of mutual causality (group C) or having the pattern in a pre-designed CM (group B), they improved in finding such a relationship between some concepts. For example, whereas students in group A tended to show a unidirectional relationship between prey and predator populations, more students in groups B and C demonstrated that relationship as mutual. In the interviews also more students could demonstrate mutual causality when they received different levels of scaffolding. Anna (group A), for example, talked about how a new predator and environment affected each other bidirectionally when she was prompted about mutual causality. Tara (group B) had not been able to find a meaningful mutual relationship between any two concepts; however, during the interview, when she received more explanations about mutual relationship, she found the relationship between prey and predator "mutual obviously."

Table 3.3

The results of the Kruskal–Wallis test and post hoc comparisons regarding mutual causality.

Mutual causality	Groups	N	Mean Rank	Chi-Square	df	P	Pairwise Comparisons of Group	P^a
	A	62	67.98	21.382	2	.000	Group A – Group B	.000
	B	57	102.07				Group A – Group C	.004
	C	54	92.93				Group B – Group C	.746

Table 3.4

The results of the Kruskal–Wallis test and post hoc comparisons regarding relational causality.

Relational causality	Groups	N	Mean Rank	Chi-Square	df	P	Pairwise Comparisons of Group	P^a
	A	62	77.69	8.427	2	.015	Group A – Group B	.013
	B	57	95.18				Group A – Group C	.204
	C	54	89.05				Group B – Group C	1.000

Table 4 shows the results of Kruskal-Wallis test on relational causality. It shows that there was a statistically significant difference (H(2) = 8.427, p = .015) among my different groups. Post hoc comparison results indicated that the significant difference (p = .013) lied between group A and B. This shows that on a pre-designed CM significantly more students could make a meaningful relational relationship among the given concepts. My results also revealed that when students got scaffolded for the concept of relational causality (group C), they improved in showing such relationship in their CM (mean rank = 89.05). But that improvement was not statistically significant from group A with no scaffolding (mean rank = 77.69).

Although the scaffoldings improved students' demonstration of relational causality, the majority of students in all groups, found it difficult to show such relationship in their CM. This was visible in students' interviews as well. When prompted about relational causality, few students could talk and show such a relationship among some concepts. For example, prompted about the relational causality, Emily pointed out that the relationship between prey and predator affects their adaptation. Referring to the tip in the assignment, Kelsey mentioned that she struggled to show relational causality in her CM because "I kind of don't really see where two things can equally affect C (third factor)." However, after getting more explanation about the relational causality, she was able to give the example of relationship between genotype and environment determining phenotype. However, majority of interviewees were not able to give an example of relational causality even after getting prompts about it. They struggled to distinguish between the case when the interaction between two factors determined the third one (e.g., genotype and environment determine the phenotype) and the case when two factors are involved in a process to determine the third one (e.g., DNA and protein determine the phenotype). For instance, students gave examples such as DNA and the environment determine natural selection, or the mutation and the environment influence evolution that referred to the involvement of two factors in a process rather than that the interaction between the two factors determined the outcome of a process.

My quantitative analysis of cyclic patterns showed no significant difference in the score of my different groups. This indicated that my scaffoldings were not helpful in improving students' ability to exhibit cyclical patterns. Also, as mentioned above, students did not do well in demonstrating cyclic patterns according to my scoring approach. However, this finding did not align with my qualitative examination of students' CM. In general, I could observe different forms of cyclic patterns in some students' CM. Indeed, some students had attempted to show that all concepts are interrelated by making a form of loop or cycle in their CM. This indicated that they were familiar with the pattern of cyclic causality. But they lacked the knowledge and skill to show such relationship scientifically accurate as it was a multistep process; students needed to make at least three accurate or semi-accurate proportions in a cyclic form to get a score for the pattern.

On the other hand, I also noted in the interviews that students did not find it challenging to show a cyclic relationship among some of their CM. Kelsey had not made a cyclic pattern in her CM but illustrated that she knew the concept by giving the following example: "Well for example, but this could be wrong, but natural selection can lead to extinction and extinction of species can lead to change in the ecosystem biodiversity and depending on that how like how that affects the ecosystem in terms of like resources or predation or anything like that, that can also affect natural selection again and starts total." In fact, in students' interviews, I found that cyclic pattern, though much less frequent than domino causality, was one of the main approaches adopted by students to explain the interconnectivity of the biological concepts. Therefore, I assume that the low score of correct cyclic patterns in students' CM was less due to their unfamiliarity to the concept of cyclic causality and more related to the extent the task was demanding and required coherent knowledge of multiple steps in cyclic relationship in a biological system.

In summary, I found students at different levels of knowledge and skills in showing patterns of causal mechanisms to demonstrate the complex interactions in biological systems. They largely gravitated to organize concepts in a sequential order to make meaningful connections among biological concepts. Students were also somewhat familiar with the concept of mutual causality, but they needed scaffolding to display it on their CM. Relational and cyclic causality were notably absent in students' CM. I found relational causality the most abstract causal relationship for students to grasp. Despite students' improvement in showing relational causality in their CM by scaffolding, I found in the interviews that they struggled to discern the time the relationship between two factors determined the third factor from the time two factors were involved in the process of determining the third factors. In regard to cyclic causality, I found students having prior knowledge about it, but they could not show it accurately on their CM probably because the task required relatively high cognitive load and wide knowledge of concepts and their relationships.

Discussion

My study sought to examine what aspects of system complexities students can show by CM, how they do it, and how their ST skills improve by scaffolding them to demonstrate causal patterns in their CM.

My results indicated that, through CM, students were able to demonstrate some aspects of their views about biology as a complex system. To different degrees, they showed structural aspects of biological systems in regard to having different hierarchy and organizational levels and how concepts were associated with each other both within and across the organizational levels. Students also displayed some processes and dynamics of biological systems on their CM. These findings corroborate with extant literature on how CM is a helpful tool to examine students' understandings about a system components, hierarchy and behavior (Assaraf & Orion, 2005; Buckley & Boulter, 2000; Tripto et al., 2013).

My study also examined the ways students accomplished to depict their views on CM. According to my theoretical framework, students largely drew on the pattern of domino causality to organize their knowledge about biological concepts. Indeed, through a domino pattern, students showed how each concept is related to its predecessor and in this way, they built a structure of concepts that depicted biological hierarchy and processes.

I found several reasons for prevalence of domino pattern in students' CM. First, the linear and sequential expression of relationship among the concepts was probably easier for the students, as it resembled the way they learned about the concepts from the texts. In fact, I observed instances in my CM data that students attempted to make sentences to show the flow of relationship among the concepts. Second, the probability of making meaningful domino patterns was relatively higher than other patterns by the concepts in my study. Therefore, if students ordered some concepts by chance due to their lack of knowledge about them, they had higher chance of making meaningful patterns from them. Third, organizing concepts through a chain of connections and putting them in hierarchical order are the conventional approaches to construct CM. For example, aligned with constructivist view toward CM building, Reinagel and Speth (2016) helped students to make integrative gene-to-phenotype CM by first teaching them isolated relationships between pairs of molecular genetic structure and then having students construct their CM upon those pairs of relationship blocks. This approach corresponds with hierarchical CM building approach proposed by Novak and Gowin, (1984) to examine students' prior knowledge and build new knowledge upon it. Therefore, considering the mentioned reasons, I found the prevalence of domino pattern unsurprising in students' CM, as it largely aligned with both their knowledge of the concepts and their skills of CM construction.

My findings also revealed that students had difficulties to show some aspects of system complexities through CM. Part of the issue was due to their lack of knowledge about the concepts. This was the case for some of my participants on evolution and its related concepts. In this regard, CM is a proper tool to diagnose students' lack of knowledge and possible misconceptions about some aspects of complex systems. Of this, CM as an assessment and learning tool has been supported by research studies (Bergan-Roller et al., 2020; Brandstädter et al., 2012).

On the other hand, my results also indicated that students could not show certain aspects of system complexities by CM despite their knowledge about them. I found two factors attributing to this issue: students' skills of CM construction and the nature of CM itself.

Students, as a typical approach to CM construction, organized concepts. Largely, they tried to put the concepts in hierarchical orders, show a flow of relationship among them and/or categorize them in cluster of concepts associated with a topic. This approach is helpful in comprehension and retention of information by structuring and organizing concepts (Novak & Cañas, 2008). Yet, according to my findings, the overall structure of the CM built by this approach was not a true representative of students' view to the way biological concepts are interconnected; students believed in more interactions among the concepts, but avoided them as they had more emphasis on organizing and categorizing the concepts rather than showing their dynamics and interconnections. In fact, I found it counterintuitive to demonstrate system complexities by CM through its conventional approaches because the focus on organizing and categorizing concepts discouraged students to demonstrate all the interconnections they knew about biological concepts.

Moreover, I observed that some dynamic aspects of complex systems were considerably absent from my participants' CM. Tripto et al. (2013) had similar observations. They found that students could hardly show homeostasis mechanisms by CM. Drawing on literature as well as their own results, they attributed the issue to the fact that "understanding homeostasis requires several cognitive abilities, such as discerning that multiple phenomena occur simultaneously and comprehending that every process is comprised of several stages" (p. 251). Likewise, I found that students struggled to show multistage processes that presented ongoing phenomena and sustainability in systems. This challenge particularly manifested itself in students' poor performance in making meaningful cyclic causal patterns as the mechanism embodied the features of ongoing multistage processes.

Based on my findings, I attribute the students' poor performance in demonstrating certain system dynamics to their lack of knowledge and skills in depicting the different causal mechanisms. For example, through domino causality, the majority of students were able to accurately show how sub-organismic entities (e.g., Gene, DNA, RNA, Protein) were related to each other. But the same approach did not work for the evolution process. Students struggled to show how concepts such as prey and predator, environment, fitness, adaptation, etc. were related to each other to attribute to the evolution process. To be able to do so, they needed to know about the other causal mechanisms in complex systems. Because many evolutionary concepts make sense in light of understanding mutual and relational causal mechanisms; for example, fitness emerges as a result of interaction between an organism's phenotype and its environment, or adaptation and extinction emerge as a result of interaction among multiple factors such as the environment and prey-predator population. The linear presentation of these concepts did not portray an accurate image of the evolutionary process.

On the other hand, my results indicated that when students received scaffolding for the patterns of causal mechanisms, they improved in picturing more dynamic aspects of complexity on their CM. For example, getting prompts about the pattern of mutual causality, students could show the concepts of equilibrium and dynamic relationship between prey and predator population. Moreover, in the interviews, I observed that after being prompted about the cyclic pattern of connections, some students were able to demonstrate cyclic relationship among the concepts. These results further supported my stand that students' inadequacy in showing certain system dynamics by CM was due to their lack of knowledge about causal mechanisms. Consequently, I believe that informing students about the patterns of causal mechanisms can improve their ST skills through CM building practices.

Research has shown that scaffolding students' CM building improves their reasoning skills (Eggert et al., 2017). Similarly, I observed improvement in students' ST skills by scaffolding their CM building. I believe that by providing students with a pre-designed CM, I could help students to find more diverse patterns of interactions among biological concepts by reducing the cognitive load of the task. This approach, however, had some downsides as well. It limited students to express some of their thoughts. Plus, a pre-design CM provided this possibility for students to fill it out randomly without truly recognizing the causal patterns. Therefore, in my study, I found introduction and illustration of causal patterns the most effective approach to improve students' ST skills by CM. Having been introduced to the patterns and concepts of causal mechanisms, my participants in group C demonstrated more diverse and meaningful interconnections and relationships among biological concepts than students in group A with no scaffolding, and accordingly they depicted more dynamic and complex view toward biological systems. These results suggest that it is important to explicitly instruct students about the concepts of different causal mechanisms alongside scaffolding them to show such patterns in CM.

Eventually, there are some features of complex systems that I found CM not a proper tool to examine them. For example, it was impractical to show non-linear relationships with probabilistic outcomes and various intensities on a CM. I observed that, for instance, to demonstrate the matters of change because of a mutation, students were bound to provide one or two scenarios about the possible outcomes with deterministic results. Likewise, when designing this research study, the authors also found it implausible to examine and scaffold spiral causality - one of the other underlying mechanisms in complex systems - by CM as it required demonstration of interactions with outcomes of different intensities over a period of time. These limitations of CM in showing time dependent processes have been noted by other researchers as well (Tripto et al., 2013).

Conclusion

Identifying and assessing students' ST patterns is essential to "develop and facilitate a pedagogical scaffolding that allows students to engage in counterintuitive modes of thought and overcome the variety of cognitive barriers that can prevent them from fully understanding the system's complexity" (Tripto et al., 2018, p.673). Also, knowing about students' thinking patterns, educators can present biological systems in a way that develop students' meta-cognition and improve their skills in applying and adapting their mental models in new contexts (Dauer et al., 2013). My study provided insight into students' ST patterns in regard to underlying causal mechanisms in complex systems. It also revealed that students needed to know more about various causal mechanisms to be able to explain broader aspects of biological complexities and behaviors. Thus, taking my definition of ST into account, I think learning about the patterns of causal mechanisms will enable students to better coordinate their knowledge of a system to reason about its behavior and function.

Furthermore, my study showed that CM can be a powerful tool in assessing and improving students' ST skills. I found that CM could reveal students' understandings about concepts in association with other concepts and expose their knowledge about a system in regard to its structure and behavior. To show the relationship among the concepts, students largely drew on domino pattern of causality, and they did so with the purpose of organizing and categorizing the concepts. Although I acknowledge that organizing concepts through sequential and hierarchical orders is the conventional approach to CM construction, I believe that such approach provides a narrow view to students' ST skills and limits the presentation of dynamic relationships on CM. Therefore, to make CM a more powerful tool to assess and develop students' ST skills, I propose two approaches. First, like Tripto et al. (2018), I believe that CM building is a skill and needs to be taught to students prior to being used as an assessment or learning tool. However, in particular about complex systems, I insist that the emphasis of CM instruction should shift from organizing and categorizing the concepts to introducing CM as a tool to demonstrate the interconnections and interactions among concepts. Second, students should also be explicitly taught about the underlying causal mechanisms in complex systems so as to be able to implement them in their CM.

In summary, it is crucial that students understand complex systems and develop their ST skills to better navigate our contemporary world (Boersma et al., 2010; Ison & Straw, 2020; National Research Council, 2010; NGSS Lead States, 2013). In this respect, they not only need to learn about the components of systems, but also, they must know how those components through various interconnections and interactions create systems. This requires that students get introduced to the different types of interactions within systems and then practice them. In this regard, my study showed that CM is a powerful tool to both enhance and examine students' ST skills, as, on one hand, it forced students to think about the relationship between the concepts and, on the other hand, revealed their knowledge about the concepts and how they interacted with each other. My study also adds to the literature how scaffolding students' CM building can enhance their ST skills. Eventually, my study concludes that two steps should be taken to have CM building practices improve students ST competencies. First, students should be taught and scaffolded about the various causal mechanisms that run complex systems. Second, students should be trained for CM building with the focus on demonstrating the interconnection among the components of a system, rather than organizing and categorizing them.

Limitations

My study concluded that CM is a powerful tool for both improving and examining students’ ST skills, particularly in regard to causal mechanisms in complex systems. But questions remain about the relationship between students’ CM building skills and their demonstration of ST skills by CM. In this regard, my study had three limitations. First, despite having a 50-minute session of CM building, students had different approaches and skills for building a CM. Second, the CM assignment was a take-home task and the amount of time and effort students put on it varied among them. Last, students had different background knowledge about the given concepts for the CM task. These interrelated factors affected the patterns and interconnections students showed on their CM. Therefore, though my study provides insight into how in general students demonstrated causal patterns on their CM based on their CM building skills, it does not show the extent students' CM building skills were decisive on showing their ST competencies by CM.

In addition to the mentioned limitations, my scaffolding intervention results were also affected by students' lack of knowledge about causal mechanisms and how they could be demonstrated on CM. This was limiting in my study in respect to knowing the extent students' demonstration of causal patterns were meaningful to them, particularly for group B participants who had the possibility to randomly fill out their pre-designed CM. Therefore, my study indicates that scaffolding students for causal patterns and CM building improved their ST skills by CM, but it adds that the extant such performance was based on students' understandings of causal mechanisms and could be transferred to other contexts need further exploration.

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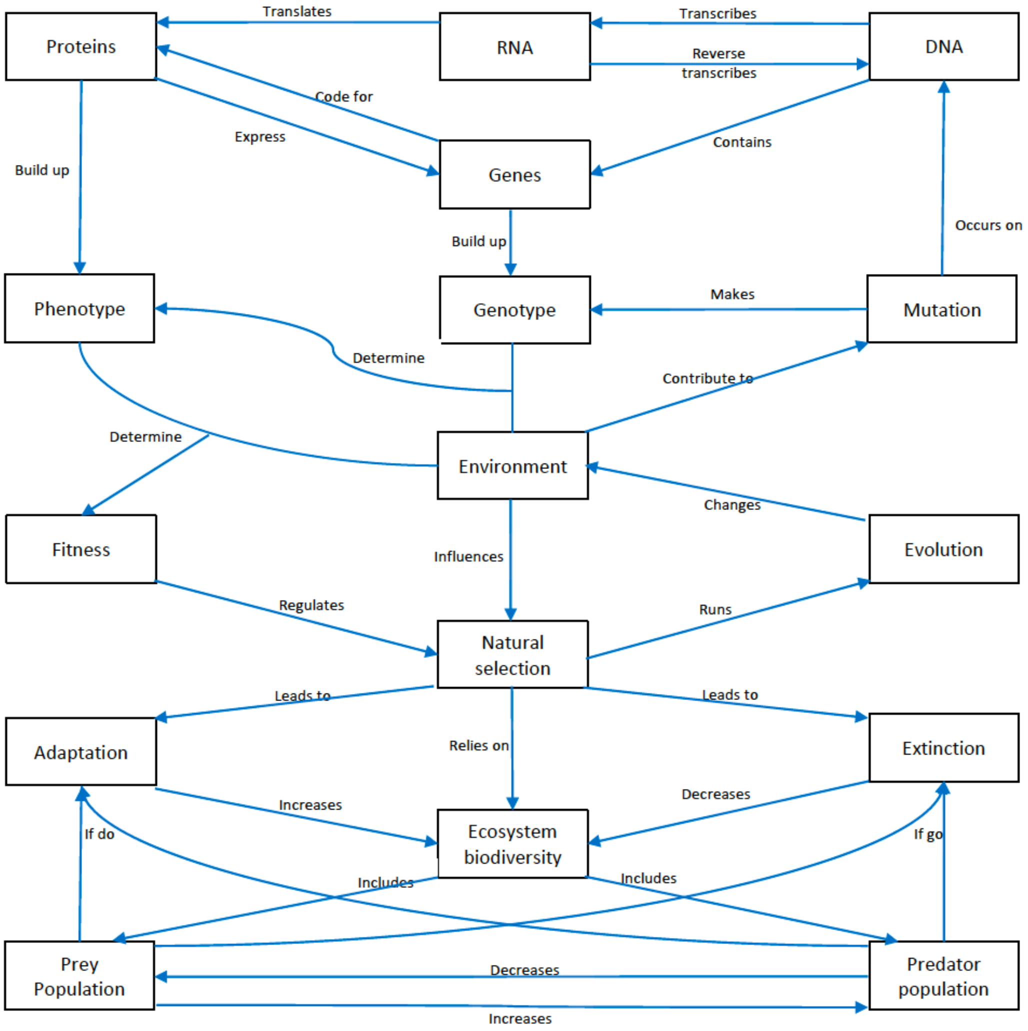
Appendix A

The Master Concept Map



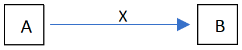
Appendix A. The master concept map developed in the preliminary stage of the study. This concept map without the concepts and the labels were given to students in group B in order to be completed.

Appendix B

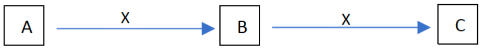
Assignment C Scaffolding

Different factors are related to each other in various ways. Below are five ways that factors can be related to each other. Try to apply these patterns in your concept map so as to make it more comprehensive. (Note: below "X" is any word or phrase that can explain the cause and effect relationship between the factors.)

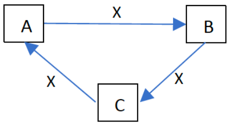
1. Simple linear relationship.
   One directional and direct effect relationship.



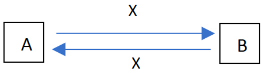
2. Domino relationship.
   One effect makes another effect, the latter effect makes another effect and so on.



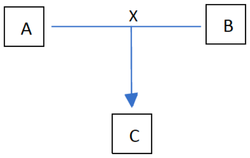
3. Cyclic relationship.
   There is no clear beginning or ending.
   Factors in a cyclic way affect each other.



4. Mutual relationship.
   Two factors affect each other simultaneously.



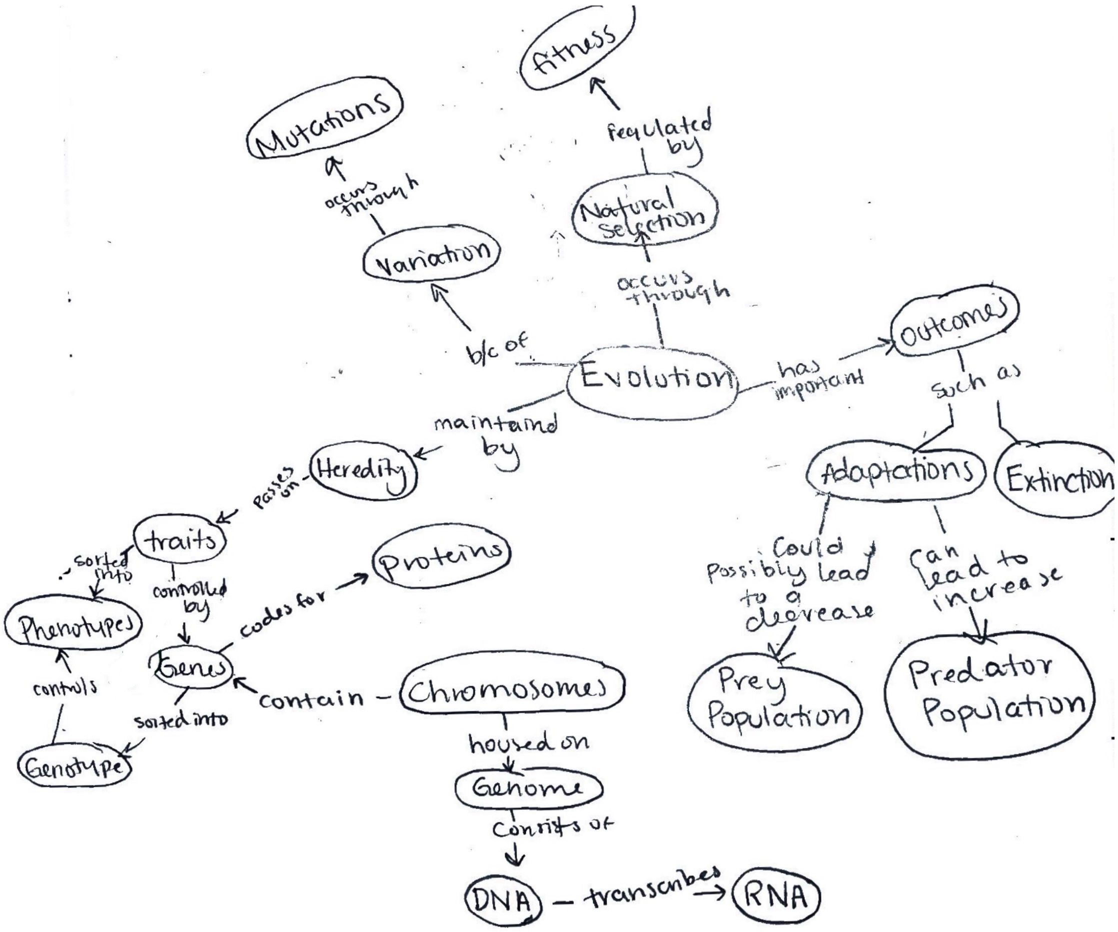
5. Relational relationship.
   The relationship between two factors determine the effect on the third factor.



Appendix B. The various causal relationships introduced to students in Group C.

Appendix C

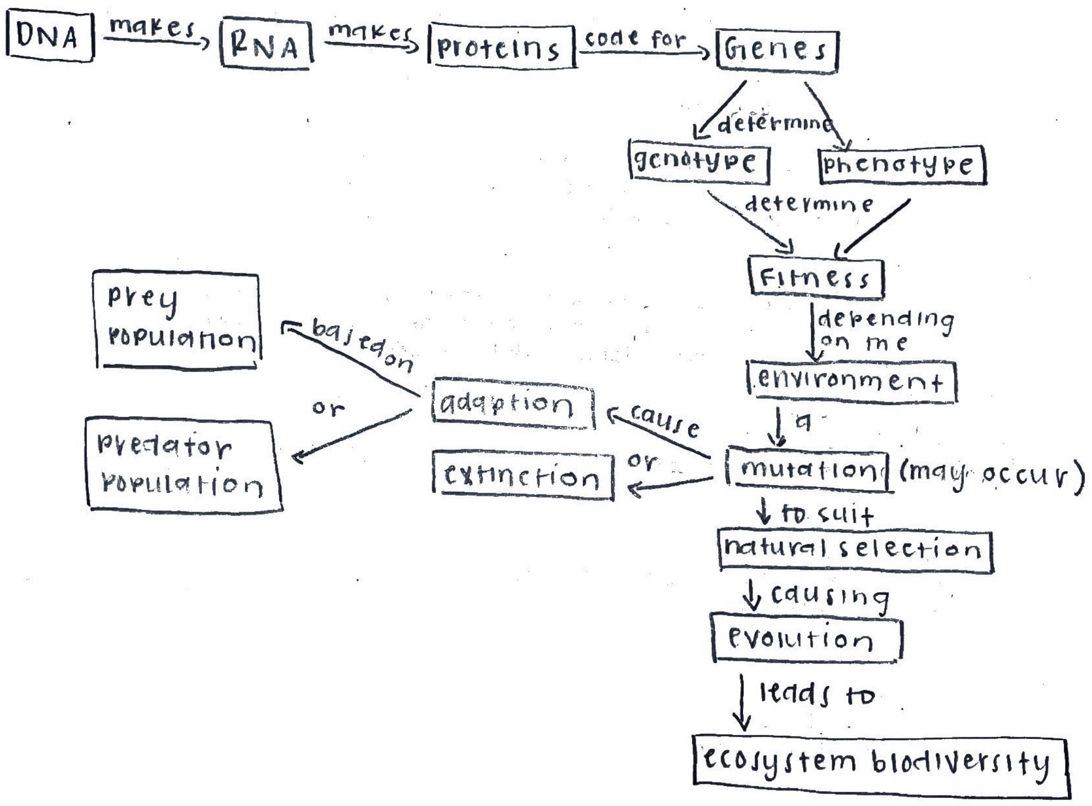
Concept Map with Cluster of Concepts



Appendix C. An example of a concept map with cluster of concepts representing one of the students' general approaches to concept map building.

Appendix D

Concept Map with Sequence of Concepts



Appendix D. An example of a concept map with sequence of concepts representing one of the students' general approaches to concept map building.

Chapter 4

A Framework for Teaching Complex Systems

Introduction

Our world is composed of complex systems. The systems that entail numerous heterogenous entities that by interacting with each other and with their environment develop various collective structures at different hierarchical levels through self-organization and without any centralized control (Baicchi, 2015). These systems manifest non-linear and emergent behaviors that make them almost unpredictable. Yet, they follow the rules of similar causal mechanisms that bring about shared characteristics among them. This, consequently, make them scientifically explorable and explainable.

However, while complex systems have been subject of study in various fields such as biology, physics, engineering, linguistics, and economics, they have not been proportionately a subject of learning in education. To better grasp the complexity of the challenges in our modern world, climate change and disease epidemics for instances, students need to develop awareness about the underlying causal mechanisms as well as the behaviors and characteristics of complex systems (Perkins, 2014). In other words, students must be system thinkers. In recent years, this need for improving students' system thinking (ST) skills has been brought up by education researchers (Yoon et al., 2018) and internationally emphasized in education documents (Boersma et al., 2010; National Research Council, 2010; NGSS Lead States, 2013).

ST is a holistic analysis approach that examines complex problems at the intersection of interactions among a system's constituent parts and its emergent behaviors over time and space (Assaraf & Orion, 2005; Meadows, 2008; Tripto et al., 2017). It has been vastly studied in K-16 education. But yet, to a great extent, ST has not been integrated into STEM education (York et al., 2019). Different factors are attributed to this lack of ST practice in science classrooms. One major issue is the fact that instruction of a natural phenomenon as a larger whole with emergent and unpredicted behaviors stands in contrast with the existing conventional methodology of science education: reductionism. Reductionism breaks a phenomenon into its constituent parts and make a linear cause and effect relationship among its components so as to make the topic easier to learn. This approach has proved to be an effective teaching strategy and has prevailed all levels of science education from curriculum design to assessing students' knowledge. Moreover, reductionism better resonates with how humans naturally tend to think about phenomena (Jacobson, 2001; Jordan et al., 2013).

My purpose in this study is to propose a general ST teaching framework that could facilitate developing ST competencies in students. This framework is not to oppose the reductionist approach, rather builds upon it. It proposes four dimensions for teaching complex systems (Table 1) through which students will have opportunities to practice ST. The dimensions are inferred from education literature as well as the author's research on developing and assessing students' ST skills in a college level introductory biology course. Likewise, the examples are also from both the extant literature and my own studies.

Table 4.1

Teaching framework for complex systems

System Dimension	Focus
Definition	Developing awareness about complex systems with a real-world case study. Defining the concept of complex system and introducing the model complex system of the course.
Structure and components	Introducing the components of a complex system with their specific roles and organizational levels in the system.
Interactions	Instructing students about causal mechanisms and having them practice the various cause and effect relationship by concept map building.
Characteristics and behavior	Introducing causal features of complex systems through comparison discussions and open-ended questions.

Teaching Framework for Complex Systems

Dimension 1: Developing Awareness about Complex Systems

Learning about complex systems is inherently challenging for people at all ages (Grotzer & Tutwiler, 2014). Considering such challenge, researchers have recommended that ST should be taught explicitly in science education (Tripto et al., 2017). In this regard, the primary focus of this dimension is to engage students with the topic of complex system and ensure that they are introduced to the concept of complex system. Accordingly, dimension 1 does not demand higher order thinking skills; instead, it emphasizes on engaging students with the topic of complex system and helping them to develop a general understanding about its concept.

Posing a real-world complex problem to students as a case to examine seems to be an appropriate first step toward teaching complex systems. For example, students in groups can discuss about a real-world health problem such as COVID-19 pandemic to examine the features of the complexity in the issue. The discussions can be guided by questions around the behavior and effects of COVID-19 and why it posed a complex problem to human health and human societies, and at the end how scientists solutions tackled the problem. In this case, the discussions around the spread of virus, its multidimensional effects, and uncertainties around it, alongside the solutions to encounter the pandemic can help students get familiar with different features of complex systems such as interdependence of system elements on each other, involvement of non-obvious factors and on-going processes in system behavior, and nonlinear and probabilistic cause and effect relationships. At the end of this activity, students can come up with a list of COVID-19 characteristics and effects and how the scientific solutions tackled the problem. This practice can help students connect complex systems to their lives and make the topic more meaningful and tangible for them. Plus, by rising a discussion about a real-world problem, we can surface students' general knowledge about complex systems and their misconceptions and possible misinterpretations of a complex problem. At the end of this activity, instructors can elaborate to students why COVID-19 pandemic is a complex system problem and what scientists mean by the term complex system. Having defined complex systems, teachers can tell students how the course or the learning unit will be about complex systems and introduce to students the complex system model they will be studying in the course.

Indeed, to improve students' ST skills, teachers need to adopt a system to work on with students. Working on a model system is actually the main approach most researchers have applied to improve and investigate students' ST skills. For example, Verhoeff (2003) used organisms' cells as models, Assarof and Orion (2005) used water cycle, and Tripto and colleagues (2016, 2017, 2018) used human body to illustrate a complex systems for students. Following a similar fashion, to improve students' ST skills, this framework requires teachers to embed a complex system into their curriculum as a model to work on.

In sum, dimension 1 requires teachers to define complex system and introduce to students a complex system model that will be studied throughout the course. This introduction can be accompanied with a set of learning goals to tell students what they will learn about the model system such as its components, the interaction among the components, and the behavior of the system as a whole.

Dimension 2: Learning about a Complex System Structure and Components

This dimension is primarily focused on helping students develop understanding about static features of a complex system. It suggests that teachers instruct students about the overall structure of a system and its components. In fact, this approach resonates with the conventional and reductionist education method in which a system is broken into its constituent parts to make it easier for students to learn. Accordingly, in this dimension students will learn about the components of the model system with their specific role in the system. They will also realize that the components are related to each other and exist at different organizational levels.

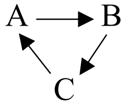
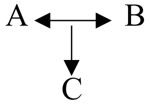
For two main reasons, learning about a system structure and components is a proper entry point to a lesson about a complex system. First, ST about a phenomenon is dependent on one's knowledge about the factors involved in the phenomenon. Therefore, students primarily need to know about the elements of a system so that then they can coordinate their knowledge to reason about it. Second, research has shown that students are more adept in thinking about a system in respect to its components and structure than its behavior and function (Assaraf & Orion, 2005; Yoon et al., 2019). This indicates that students require lesser cognitive load to think about the components and structure of a system than its interactions and behaviors. Considering the mentioned reasons and the fact that ST is a high-level thinking skill demanding high cognitive loads, in this dimension, I found it proper to guide students toward ST with cognitively less demanding features of complex systems. In sum, in dimension 1, students learn that their model system is composed of multiple components with each having a specific role at different organizational levels in the system.

Dimension 3: Learning about a System's Underlying Mechanisms

In line with explicit teaching about complex systems, the third dimension of my framework focuses on introducing students the underlying mechanisms that determine a system’s characteristics. It suggests that teachers bring into students’ attention the various type of interactions system components can have. In this regard, Table 2 shows the different patterns of cause-and-effect relationship. These casual patterns can be taught explicitly in multiple ways. For example, teachers can provide students with real life examples of domino effect or do storytelling about the way the mechanisms of a spiral causality turned a seemingly negligible incident into a full blast disaster. The goal here is to introduce the concepts of causal mechanisms to students and expand their vision on the various interactions that exist in complex systems. Further, teachers can illustrate such causal mechanisms in the model system and elaborate on the way they attribute to system characteristics. For example, by delineating the pattern of cyclic causality among the system elements, teachers can bring into students' attention how such causal mechanism can lead to the system’s sustainability.

Table 4.2

Underlying causal mechanisms in complex systems (Grotzer, 2012)

Causal pattern	**Characteristics**
Simple linear causality $A \longrightarrow B$	Cause and effect work in one direction and cause precedes effect. There is a direct link between cause and effect with clear beginning and end. There is usually one cause for one effect.
Domino causality $A \longrightarrow B \longrightarrow C$	There is a linked sequence of events with typically a beginning, middle, and end. Cause induces effect and the effect turns into a cause for subsequent effect. It is one directional and can have branches.
Cyclic causality 	It is a pattern of relationship in which variables are connected in a circle and typically there is no clear beginning and end. Component of this causality can be both cause and effect simultaneously. There is a form of feedback loop pattern that makes the cycle to continue.
Mutual causality $A \rightleftarrows B$	Two factors mutually or bi-directionally affect each other. Factors involved in this relationship operate as both cause and effect on each other in a way that it is usually impossible to tell which factor precedes the other.
Relational Causality 	The effect is caused by the relationship between elements of system. The factors (here A and B) cannot be a cause by themselves. The relationship between variables or factors cause the effect. The relationship between the variables can be in balance/equivalence or imbalance/deference and the change in the relationship can influence the outcome.
Spiral causality	It is a form of cyclic causality that has a corresponding increase or decrease in the magnitude of effect with each turn of the cycle.

To help students practice causal mechanisms and assess their understandings of such relationships, we found concept map (CM) to be a suitable pedagogical tool. CM is a diagram that entails concepts connected with labeled lines or arrows. CM building is also a way to practice modeling in science classrooms. As a form of mental model, CM has also been used to assess both people’s conceptual understandings and their ability to solve problems in complex systems (Johnson-Laird, 2001). Accordingly, it is considered a competent tool for developing and analyzing students’ ST skills (Assaraf & Orion, 2010; Sommer & Lücken, 2010). In my study, I found CM particularly helpful in promoting and assessing students’ knowledge about causal mechanisms. Specifically, with the exception of spiral causality, in my study, CM allowed students to demonstrate their knowledge about the various causal relationships among the components of a biological system. Plus, I found that by providing proper scaffoldings, CM can improve students’ performance in showing more various interconnections among a system components.

I believe after introducing the components of a system to students, the practice of CM construction is a proper next step to guide students toward ST. Because, on one hand, in order to build a CM, students have to draw on their knowledge of system components and identify the interconnection among them. Through this process, they will have the chance to think about the various causal interactions that exist among a system components. Plus, this practice will end in creation of an integrative picture of a system that can help students to better understand how variety of interactions at different organizational levels play role into creation of a system. On the other hand, researchers have shown that CM is beneficial for students' learning as it reduces the cognitive load by presenting the key features of a domain knowledge such as the relationship between the concepts and their hierarchical relationships (Amadieu et al., 2009; O'Donnell et al., 2002). I also believe that by creating a model like a CM, students will reduce the complexity of the system in regard to its dynamic. This consequently reduces the cognitive load of learning about systems and makes it easier for students to learn about both the structure of a system and its underlying mechanisms.

CM building can be done individually and collectively. Individual CM building will give students the chance to make their own big picture of the system. These CMs can also work as diagnostic assessment tools for teachers to examine students' understanding about the system components and their relationships. In collective CM building, students will generate, evaluate, and modify their CM by communicating their understandings of the concepts and their relationships. In this approach, students will have the chance to explain their ideas and analyze alternative explanations (Clement & Rea-Ramirez, 2008), and then reconstructing their maps accordingly. In any way, CM building will require students to think about the interrelationship among a system components; accordingly, it is a proper tool for students to practice their knowledge of various interactions among a system elements, and so it is a useful tool for teachers to examine students' knowledge of those interactions.

In sum, in dimension 3, students will get familiar with various causal relationships that exist in complex systems and through CM building, they will not only practice identifying causal patterns in a system but also they will create a holistic picture of the model system in the study.

Dimension 4: Learning about a System's Characteristics

To teach students about the characteristics of a complex system, this dimension emphasizes on bringing the whole system into students' attention and discussing around the behaviors of the system as a one entity. Teachers can start this dimension with re-introducing the system model to students in regard to the definition of a complex system and reviewing how the system as a one whole entails various components and interactions. Then, they can ask students to compare the system model with a simpler and a none-complex system. For example, if the system model is a cell, an organism, or an ecosystem, its characteristics can be compared with simpler systems such as a car or a computer. Students can do this comparison individually and then discuss them in pairs and groups. Throughout this activity students should be prompted about causal characteristics of complex systems (Table 3). For instance, they can be prompted to think and discuss about whether one factor is in control of the system or no-one factor can be determined to be in control and the interaction of the multiple factors run the system. Comparison is a powerful learning process that improve students' learning in various domains of knowledge (Rittle-Johnson & Star, 2011). It is known as one of the most integral components of human thought that can induce important changes in our knowledge (Goldstone et al., 2010). Considering how abstract the characteristic of a complex system might be, I believe comparing them with the characteristics of a simpler and more tangible system would create a convenient contrast for students to grasp the features of a complex system. After having students discussed around the similarities and differences between the two system, teachers can provide definitions and further elaborations on each feature of the complexity and how they exist in the system in relation to the components and the interactions within the system. For example, when elaborating about distal causality, teachers can point out the possible time and space gap between cause and effect and how domino and spiral causality play role into them.

Finally, to have students to reflect on the features of complexity in the system as well as to assess and monitor students' understandings of them, teachers can provide students with a problem about the model system and ask them to predict the systems' behavior and come up with a solution. This practice can be done individually and then in groups. Through it, students have the chance to take into account the features of complexity in their predictions of the system

Table 4.3

Features of causality in simple systems versus complex systems (Grotzer, 2012)

Features of causality in simple systems	Features of causality in complex systems
Event-based reasoning Tendency to think about events and phenomena that are distinctively recognizable from their surroundings and are usually out of routine.	*Process-based reasoning* A thinking practice that examines ongoing processes before an event disrupt the processes and lead to a possible disaster.
Sequential reasonings A causal thinking that argues things unfold to happen in a particular sequence. There is an order to the chain of cause and effect.	*Simultaneous reasonings* Causality does not necessarily require telling causes precede the effects such as in bidirectional and cyclic relationships
Obviousness-based reasoning A thinking tendency to draw on obvious causes to explain phenomena. Obvious causes get primacy over non-obvious ones and the latter is often neglected as long the former exists.	*Non-obviousness-based reasoning* A thinking tendency that takes into account the possible effects of non-obvious factors. For example, the skill to draw on existing factors and patterns to deduce a conclusion about a cause or process.
Proximal reasoning A thinking habit in which there is a relatively small gap between cause and effect. Usually examines the causalities of an event in the spatial and temporal locality of the event.	*Distal reasoning* A thinking habit that goes beyond the immediate cause and effects surrounding a phenomenon to explain it. Thus, a phenomenon can have its roots out of our attention span and have its effects far apart from the cause.
Intentional/agential reasoning A thinking habit that seeks to find an intentional agent or factor for any event.	*Unintentional/non-agential reasoning* A causal reasoning that indicates actions do not necessitate have agentic intervention and they can be random and purposeless.
Centralized causal reasoning Centralized or top-down causal reasoning refers to human thinking tendency to attribute the actions or behaviors of a system to the instructions from a higher-ranked position.	*Decentralized causal reasoning* Decentralized or distributed causal reasoning holds every member of a system accountable for the outcome of a system.
Deterministic reasoning A thinking habit that expects causes reliably lead to effects. In this sense, if we know the causes, we will know the effects.	*Probabilistic reasoning* A reasoning style that acknowledges the relationship between causes and effects can be both reliable and unreliable. Thus,

	there is uncertainty around any prediction about the outcome of an event.

For example, uncertainties around the prediction of system's behavior can guide students toward probabilistic reasoning which is due to non-linear relationship between cause and effect in complex systems. And discussions about a possible solution would require students to take into account the role of multiple factors that would be a way of practicing decentralized causality. Monitoring students' responses, teachers would also learn about students' understanding about each characteristics of the system. Finally, through a whole class discussion, teachers can sum up on the complex characteristics of the model system and describe how those characteristics cannot be attributed to any single component or group of components of the system but emerge out of the interaction among the system elements and are of their own entities.

Conclusion

Teaching systems as a whole seem to contradict with the conventional and reductionist approach of science teaching. In accordance with its reductionist methodology, science education breaks systems into their constituent parts to make them easier for students to learn (Kupers et al., 2015). This practice appears in all layers of science education from designing curricula to assessing students' knowledge and unintentionally has led students to reductionist approach toward tackling scientific problems (Kupers et al., 2015). This thinking tendency becomes problematic when students are to reason about complex problems such as disease pandemics and climate change. To address this issue, in this study, I developed a teaching framework in an attempt to guide teachers to bring complex systems and system thinking into their teaching practices by drawing on the conventional methods of teaching and using the existing reductionist science curricula.

In developing my framework, I was cognizant to different learning objectives introduced in Bloom's taxonomy (Anderson et al., 2001) and attempted to approach ST instruction from simple and concrete aspects of complex systems to complex and abstract dimensions of them. Accordingly, the dimensions 1 and 2 of the framework are more focused on engaging students with the concept of complex system and providing them with the prerequisite knowledge for ST. Dimension 3 seeks to help students to apply and organize their knowledge to create an integrative picture of their model system, and dimension 4 wants students to make evaluation and construct explanation about complex systems. However, it should be noted that my framework is not in full accordance with Bloom's Taxonomy in that each dimension still requires learning and understanding something new about complex systems.

Taking into account the general learning objectives of a learning unit about a complex system as well as the learning difficulty of each dimension of a complex system, I believe my teaching framework is interdisciplinary. I argue that this teaching framework works across the disciplines and is applicable for teaching ST to students of all level. However, I acknowledge that my proposed framework with its given examples and details seems more appropriate for college level students. But I believe that ST can be taught to students of all ages and my framework can be adapted to different age groups. Indeed, it is worth noting that this framework does not emphasize on teaching all aspects of a complex system in each dimension; rather, teachers can adapt each dimension according to the type of system they instruct and the needs of their students.

Finally, this teaching framework is based on the author's knowledge of complex systems, his understanding about the learning difficulty of each dimension of complex systems, and the author's knowledge of educational methods to approach each dimension based on his personal teaching knowledge and his research on ST. Thus, the framework might suffer from a potential narrow view of what complex systems are and what alternative teaching methodologies would better address them. Therefore, I invite teachers and educators to conduct studies by using this framework and refine it based on their results.

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Chapter 5

Conclusion

In this dissertation, I explored students' view toward biology as a complex system. In this regard, I first examined their reasoning patterns in response to complex biological problems and what those patterns tell us about the extent students see biology as a simple or complex system. Then, I investigated the potentials of concept map (CM) as a tool to assess and enhance students' system thinking (ST). Finally, based on the findings of my first two studies, I developed a teaching framework that provided guidance for instructors about the ways to embed ST into their teaching units. In this concluding chapter, I review the findings of the all three manuscripts with further questions this research has sparked for future studies.

In chapter two, having examined students' reasoning patterns, my study showed that students applied various reasoning patterns that were largely simple causality to argue about complex biological problems. The findings also revealed that students' knowledge about the topics in questions influenced their reasoning style. For example, my study showed that students were able to make both simple and complex causal reasonings while having almost the same knowledge about the topics. Therefore, according to this finding, the lack of complex causal reasoning in students' responses were more related to their skills in building such reasoning patterns rather than being related to the type of knowledge they had about them. Therefore, my study emphasized that students need to learn about the features of complexity in systems and have the opportunity to practice coordination of their pieces of knowledge so as to improve in their ST skills. On the other hand, my study also illustrated how students' domain knowledge could stop them from making complex causal reasonings. In this regard, I particularly showed how students detailed knowledge about central dogma in biology impeded them from making simultaneous reasoning by arguing for the role of environment alongside DNA in determining organisms' phenotype. On this, my study called for reconsideration of biology education in regard to the way it represents the role of DNA and its interaction with environment.

At the end, based on the results of this research as well as the findings in the literature, I developed a System Thinking Model that provided a systemic lens for examining students' ST. The model takes into account the role of education in students' reasoning approach to complex systems and problems and demonstrate how students' reasoning patterns are interconnected to each other. Accordingly, it helps the researchers and educators to examine students' ST skills within a spectrum of different reasoning types. However, acknowledging its limitation, my study also indicates that the relationship among the various causal models in my model can be different and more dynamic; therefore, it concludes that further research is required to explore how different reasoning pattern affect each other and if they render or impede each other.

Chapter three focused on concept map (CM) as a tool to assess and enhance students ST skills. Through a mixed methods approach, I examined 173 students' CM to find what aspects of system complexities they could show by them. My findings showed that students could demonstrate structural aspects of biological systems and how concepts were associated to each other within and across the organizational levels in biology. They could also show some processes and dynamics of systems by CM. Students accomplished these largely by the method of categorizing and organizing concepts through domino patterns of causality. However, my study showed that this method fell short in demonstrating many other aspects of system complexities such as showing the interrelationship among the concepts involved in evolutionary processes. In this regard, my study found that students can improve in showing many dynamic relationship among biological concepts if they receive proper scaffoldings and prompts. Accordingly, my study concluded that in order to help students to create more dynamic concept maps to show more system complexities by CM, educators need to take two key measures. First, they should teach students about concept map with the emphasis on showing the interrelationship among concepts rather than focusing on organizing and categorizing the concepts. Second, they should explicitly teach students about different causal mechanisms and how they attribute to complex systems behaviors. However, my study could not determine the relationship between students' concepts map building skills and the extent they could show causal mechanisms on their CM, thus, in this regard, my study concluded that further studies are needed.

Chapter four provided a framework for teaching complex systems. It entailed four dimensions each addressing some aspects of complexity in systems. The first dimension attempted to engage students in the topic of complex systems and introduce them the concept of complex systems. Second dimension was focused on introducing the structural aspects of systems. Third dimension focused on introducing the underlying causal mechanisms in complex systems and have students practice them by creating concept maps. The last dimension, through a comparative teaching approach, attempted to engage students to think about the features of complexity in systems and how they shape our world. This chapter was limited to the authors understanding of complex systems and his knowledge of teaching approaches. Therefore, he invited teachers and educators to conduct studies by using this framework and refine it based on their results.

In summary, my study showed that students tend to make simple causal reasonings in response to complex problems and they demonstrate the relationship among biological concepts largely through domino causal relationships. These findings were in accordance with the type of education students had received about the concepts and their relationship. Therefore, my study concludes that in order to improve students' ST skills, science education, alongside its conventional teaching approaches, needs to focus on the relationship between the concepts and consider teaching phenomena as a big whole.

VITA

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