Contributions from Biology Education Research

Orit Ben Zvi Assaraf
Marie-Christine P. J. Knippels *Editors*

Fostering Understanding of Complex Systems in Biology Education

Pedagogies, Guidelines and Insights from Classroom-based Research

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Preface

Humans today must contend with a complex set of environmental problems, including climate change, pollution, habitat destruction, and an accelerated loss of biodiversity, all of which have important implications for the well-being of all of us. Dealing with these complex challenges requires an understanding of the underlying mechanisms involving complex biological systems.

This new publication in the Contribution from Biology Education Research series synthesizes a wealth of international research on the critical topic of understanding complexity in biology education. Complex systems are prevalent in many scientific fields, and at all scales—from the micro scale of a single cell or molecule to macro complex systems such as ecosystems. Such natural systems are typically dynamic, and the interactions within and between other interdependent systems can be unpredictable. Developing a broad and logical perception of the structures in systems and of the multi-variable web of relationships between them is difficult, because these relationships are not intuitively obvious. Relationships across different levels of complex systems are also often hidden, and their causality difficult to trace. Addressing these challenges requires innovative, comprehensive approaches to teaching systems, which incorporate the full variety of scientific and social aspects that make up a complex system.

Understanding the complexity of natural systems can therefore be extremely challenging, but is nevertheless crucial for an adequate understanding of what they are and how they work. The term "systems thinking" has become synonymous with developing a coherent understanding of complex biological processes and phenomena. Attention should be paid to fostering students' internalization of systems thinking. The challenge is to let students experience systems thinking as a way to create a more coherent view of biology, and as a way to reason about biological systems in abstract terms to gain more insight in biological systems and to solve complex problems. For researchers and educators alike, understanding how students' systems thinking develops is an essential prerequisite to developing and maintaining pedagogical scaffolding that facilitates students' ability to fully understand the system's complexity.

The book opens with an introduction from Karyn Housh, Cindy Hmelo-Silver, and Susan Yoon, in which they reflect upon the theoretical perspectives that underlie research and curriculum, instruction, and technology design, in the context of learning about biological systems. The chapter discusses several conceptual frameworks regarding systems thinking and systems dynamics, structure-behavior-function and phenomenon-mechanisms-components, and then thinking in levels via complexity theory. Given the dynamic and continually changing nature of complex systems, it also addresses agent-based modeling as a strategy for teaching complex systems through computer-based models that simulate and visualize how systems behave.

At the heart of this book are ten empirical research studies that provide researchers and teachers with key insights from the current research community, introducing issues such as:

(a) How conceptual representation with models can not only promote deeper systems understanding but also make it possible to identify the development of systems thinking capacities within individual learners
(b) How different design elements of computer-based learning environments promote complex systems thinking and facilitate students' ability to regulate their learning.
(c) How students might benefit from explicit guidance in using system language, and in drawing clear connections between the various aspects of the complex system, and how such guidance can be used to help students visualize and reason about biological complex problems
(d) How pedagogical scaffolding approaches can help students draw connections between different levels of biological organization – from the full-organism level to the micro or macro level – moving back and forth between the levels to make explicit connections between concepts and phenomena at different levels

Each chapter in this book will elaborate on different theoretical and methodological frameworks pertaining to complexity in biology education.

The final chapter draws together insights from all of the book's chapters, as these reflect different approaches to fostering the understanding of complex biological phenomena. This chapter identifies a diverse range of contributions, covering different biological topics such as genetics, ecology, and physiology, testing different kind of interventions. In it, we compare and contrast the various chapters through the lens of the universal system characteristics they address, and of the pedagogical scaffolding strategies they employ, considering the insights that arise from these comparisons and their pedagogical implications.

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Contents

Chapter 1
Theoretical Perspectives on Complex Systems in Biology Education

Karyn Housh, Cindy E. Hmelo-Silver, and Susan A. Yoon

1.1 Introduction

In efforts to increase science literacy in K-12, there has been an increased focus on systems thinking (Hmelo-Silver et al., 2007; Samon & Levy, 2017; Sabelli, 2006; Wilensky & Jacobson, 2014; Yoon et al., 2018). This emphasis on systems reflects the ubiquitous and interconnected, complex nature of systems across various domains within and beyond science. Systems cut across several science domains and are critical for science literacy (Blackham et al., 2012; Checkland, 2000; NGSS, 2013; Sabelli, 2006). Furthermore, in addressing Education for Sustainable Development, the international community has recognized the importance of systems thinking to achieving this goal (Schuler et al., 2018; Riess & Mischo, 2010). However, though there is broad agreement on the importance of systems and systems models in science education, there are several theoretical perspectives that have been used to frame teaching and learning about systems.

To further add to the difficulty of understanding and teaching of these systems in STEM, is the dependence of contextual meaning of the word "complexity" across STEM fields (Cohen, 1999; Whitesides & Ismagilov, 1999). Chemistry and physics illustrate complexity in systems such as thermodynamics, through the great variations observed within a system due to the reactivity to initial conditions and the stochastic behaviour of the system (Prigogine, 1987). Whereas biology considers complexity to focus on the intricacy of levels of structure and organization in the

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presence of chaos and randomness through a series of feedback cycles (Mazzocchi, 2008; Sabelli, 2006; Verhoeff et al., 2018). For this book, we will delve further into the nature of complexity as defined within biological systems.

Systems are a central feature of biological sciences, reflecting the multiple levels of organization (Verhoeff et al., 2018). Because systems are so ubiquitous within biology, they play a prominent role in learning and research, but students face many challenges in understanding the complex nature of systems (Hmelo-Silver & Azevedo, 2006). These challenges occur for several reasons. Complex systems embody subsystems of integrated hierarchical structures which produce causal events and mechanistic outcomes resulting in outwardly visible phenomena whereas the complex dynamics and processes are often hidden to learners (Hmelo-Silver et al., 2017a, b; Jacobson & Wilensky, 2006; Yoon, 2018).

For example, the importance of oxygen in facilitating respiration is widely known to students, however the actual process through which oxygen enters the bloodstream and is utilized to produce energy, and how this system is linked to other systems such as digestion, is more challenging to understand (Housh et al., 2020). Learners are aware of the physical external process of breathing (i.e., the process of ventilation- inhalation and exhalation). However, the internal, hidden mechanisms of the movement of the diaphragm and ribcage, the action of alveoli and how their structure facilitates their role in diffusing oxygen into the bloodstream, how oxygen then enters into cells through their membrane and the chemical process of respiration in which oxygen and sugars are used to produce energy are at a micro, less visible level to students. These processes may confuse students as they occur simultaneously with the outward, observable processes of inhalation and exhalation. Furthermore, linking the sugars to the process of digestion of food, and how complex compounds are broken down to sugars and transported to cells to facilitate the chemical reaction of respiration presents another level of complexity and thus difficulty for learners to grasp these concepts.

Particularly when discussing biological systems, students must understand the importance and implications of macro-level (consuming food, breathing) and micro-level processes (oxygen molecules reacting with glucose to produce energy, oxygen molecules crossing cell membranes and entering the bloodstream) and their relationships. As shown in this example, these hidden mechanisms, the multiple planes of processes, along with the interconnected nature of systems, pose significant challenges to learners (Hmelo-Silver et al., 2017a, b; Samon & Levy, 2017; Yoon, 2008). As such, researchers have developed numerous theoretical perspectives and frameworks for understanding systems and as tools for teaching and learning about these systems.

In this chapter we will briefly discuss several conceptual frameworks such as systems thinking and systems dynamics, Structure-Behavior-Function (SBF) and Phenomenon-Mechanisms-Components (PMC), and then thinking in levels via complexity theory. Agent -based modeling is also presented here, as a strategy to enhance student learning of systems through computer simulations, which make the complexity of systems visible while allowing students to manipulate specific variables and observe the outcomes. These simulations provide a view into complex systems which otherwise would present these actions as hidden mechanisms.

Through the development of these frameworks and computer-supported simulations, we hope to engage students in systems learning to better facilitate their understanding of biological complex systems as they exist throughout the field and in the real world.

1.2 Systems Dynamics and Systems Thinking

Systems thinking involves the recognition of components within a system, the relationships between these components and the various feedback processes that occur within these interactions (Booth Sweeney & Sterman, 2007; Yoon, 2018). It tends to focus on more aggregate level processes. Building on this, but acknowledging the importance of domain specific knowledge, Ben Zvi Assaraf and Orion (2005) proposed the *Systems Thinking Hierarchical (STH) Model* This framework can help in understanding how students think about systems and suggests design principles to scaffold developing students' concepts around complex systems (Ben Zvi Assaraf et al., 2013). Through understanding systems, we observe interactions occurring across multiple elements, on various scales, through different relationships and processes, which may occur simultaneously and/or across time.

Examining the biological cardiovascular or circulatory system within this framework, primary elements or components of the system would be blood, red blood cells, the heart, lungs, veins, arteries, capillaries, oxygen and nutrients. Several relationships exist in this system. For instance, there exists a relationship between blood and red cells (i.e., red blood cells are one component of blood), the heart and blood (the heart pumps blood around the body), blood, heart, lungs and oxygen (the heart pumps blood to the lungs to facilitate gaseous exchange i.e., oxygen and carbon dioxide), the relationship between veins, arteries capillaries, blood, gases and nutrients (the structure of each type of blood vessel, facilitates their specific role in transporting blood, for example, capillaries are one cell thick to allow each diffusion of gases and nutrients both to and from cells). These interactions of elements also occur across other relationships such as the capillaries in alveoli in lungs to provide oxygenated blood to the body. Many of the aforementioned relationships within the cardiovascular system occur simultaneously and at rates that would be difficult to discern with the naked eye. Several of these actions are also at a microscopic level, further adding to the complexity of systems as the processes are unobservable to learners.

However, though this framework allows for the identification of relationships and components, the dynamic mechanisms at play within the system can easily be overlooked by students (Ben Zvi Assaraf et al., 2013). To address this issue pedagogically, the STH model suggests organizing instruction in a progression from basic skills in analyzing the system components to synthesizing of system components and then implementation of systems thinking skills. Ben Zvi Assaraf et al. (2013) analyzed high school students' understanding of the human body without this kind of explicit scaffolding and found that most students demonstrated superficial understanding.

1.3 From Structure, Behavior, Function to Phenomena-Mechanisms-Components

Though originally emerging from the field of engineering, Structure, Behavior, Function (SBF) theory has been used as a conceptual framework for systems thinking in biology (Yoon, 2018). Here researchers use this framework to denote the components (structures), the processes and/or mechanisms (behaviors) and the output (function) of a system and it is through this conceptual framework that researchers observe learners achieve deeper understanding of complex systems (Hmelo-Silver et al., 2007). Being able to discern such connections across the various levels of systems has shown to facilitate greater understanding and refinement of ideas on complex systems (Samon & Levy, 2017).

For instance, we outline a problem combining the respiratory system and the digestive system and highlight how the SBF framework may be used to think about the problem. A student is engaged in a physical exercise in which her heart rate and oxygen levels increase. She notices her hunger and energy levels also increase when consuming a carbohydrate-rich meal before the exercise when compared to consuming a protein-rich meal (Housh et al., 2020). This scenario presents the intersection of two major complex systems of the body- the respiratory and digestive systems. Some of the main structures here would be carbohydrates, protein, energy, oxygen and heart rate. Behaviors would be represented by the processes of oxygen, along with sugars (from carbohydrates or proteins), being used in respiration, increased activity leading to increased need for oxygen, the simpler structure of carbohydrates vs protein for digestion. The function, as denoted by the outputs of the system, would be the production of energy through respiration, increased heart rate due to increased requirement of oxygen due to physical activity and the more immediate digestion of carbohydrate compared to proteins to release the sugars needed for respiration.

Often novices tend to focus on structures, as these components are usually visible within systems i.e., at the macro-level such as the food consumed (carbohydrates or proteins, heart rate, oxygen and energy levels). Experts on the other hand, recognize and explain how behavior and function work interconnectedly to facilitate processes and mechanisms within the system. For example, experts would denote how the chemical structure of carbohydrates allows for easier digestion (than that of proteins), allowing carbs to produce the sugars necessary for respiration where sugars and oxygen are used to produce energy to engage in physical activity (Hmelo-Silver et al., 2007). Having students structure their thinking in the SBF framework facilitates a more robust understanding of systems as students are better able to recognize processes occurring at the micro-level. However, even within this framework of conceptualizing systems, mechanisms are not at the forefront of student understanding and may be overlooked as students focus on the structures, behaviors and functions in a system (Liu & Hmelo-Silver, 2009).

As Hmelo-Silver and colleagues continued to use SBF to design instruction, they wanted to more clearly foreground the phenomena and move away from some problematic aspects of the SBF language. Moving to Phenomena-Mechanisms-Components (PMC) avoids the linguistic confusion that some learners experienced, using behavior in the everyday definition and a misunderstanding of how we were using function (Eberbach et al., 2021). Moreover, PMC places greater emphasis on understanding mechanisms through the interaction of components within the system to produce the phenomenon, an aspect of complex systems which is often overlooked or under emphasized by learners (Hmelo-Silver et al., 2007). This focus on mechanisms serves as an attempt to address the needs of learners in gaining a deeper and fuller understanding of systems as often hidden mechanisms within systems proved to be difficult concepts for learners to grasp. This restructured format of the SBF framework directs students to specifically attend to this characteristic of complex systems.

For instance, consider a farm scenario (Cisterna et al., 2020). The phenomenon may be the observation of decreased corn yield due to the impact of an invasive species (corn rootworm). Corn rootworms feed on corn and reproduce quickly. The introduction of a predator to corn rootworm larvae (Harvestman spiders) still results in a fluctuation of corn yield and does not adequately resolve the problem experienced on the farm. The components of this scenario would be corn, corn rootworms, and the Harvestman spiders, whereas the mechanisms would be the consumption of corn due to the rootworms, Harvestman spiders preying on the corn rootworm larvae, and the hidden mechanism would be that though the spiders may prey on the corn rootworm larvae, their capacity to control the invasive species is very limited due to the low number of spiders introduced to the ecosystem compared to that of the corn rootworms, thus still resulting in reduced corn yield.

The recognition of mechanisms, those visible as well as hidden, are crucial in the understanding of systems. Structuring the system around components which interact through mechanisms to produce phenomena, students can better frame their thinking of the complex system, discerning a deeper, more developed understanding of the complex concepts within the system (Hmelo-Silver et al., 2015). Through the use of this framework to understand systems within simulations, researchers have observed students' increased ability to organize their ideas and make connections between the various elements of the system, leading to a more accurate representation of the system (Hmelo-Silver et al., 2017a). Hmelo-Silver and colleagues have used the SBF and CMP frameworks to examine expertise in biological systems (Hmelo-Silver et al., 2007), identify learning trajectories (Eberbach et al., 2021), and design instruction (Hmelo-Silver et al., 2017a, b).

1.4 Agent-Based Modeling

As a means through which learners can better represent and visualize their thinking about systems, modeling has become an important tool used in systems learning (Hung, 2008; Perkins & Grotzer, 2005). Agent-based models represent a dynamic, visual, learning environment in which students can navigate specific contextual domains while they interact with the various elements within the system. Here, the various components, mechanisms and phenomena within a system can be impacted by the decisions made by students and the subsequent impacts this may have on the other elements within the systems (Yoon, 2018). The combination of conceptual frameworks with visual representation serves to enhance learner understanding of the complex nature of systems as the processes at both the macro and micro levels may be observed by students as well as the nonlinear impact that one variable may have on the system at large (Hmelo-Silver et al., 2017a, b).

Though several modeling platforms have been developed, Star Logo and NetLogo represent two of the popular agent-based modeling platforms used in the study of biological systems (Yoon, 2018). Using these tools for simulations allows students to observe and model some of the hidden mechanisms occurring in systems (e.g. Wilensky & Resnick, 1999; Yoon et al., 2016). Learners have the freedom to select and apply various settings or conditions and then observe the impact of their decisions in real time. Researchers over the years have observed an increase in student understanding through the implementation of agent-based modeling as learners engage with these dynamic models (Danish, 2014; Hmelo-Silver et al., 2011, 2015; Yoon et al., 2016).

To better describe how agent-based modeling may be useful to learners, we will now examine an existing example on one of these platforms. One model in NetLogo illustrates the impact of an invasive species in an ecosystem over a number of years. Here, the simple ecological system of rabbits and grass are presented, and participants have the ability to select (through sliders) the population of rabbits and the population of grass or weeds in the given scenario. Students can also determine aspects of the ecosystems, such as lifespan of the rabbits. Rabbits feed off the grass and weeds, and thus gain energy. This energy may be used to reproduce, hence increasing the population of rabbits which would now require a greater food source (i.e., more grass or weeds to consume). Participants can observe the fluctuations of the ecosystem based on the choices selected for the various conditions and the unexpected consequences of some actions. This may be observed if too short of a lifespan is selected which could result in the eradication of the species, or too long of a lifespan could lead to overpopulation and a decimation of grass and weeds, which could then in turn lead to a high death rate in the rabbit population due to starvation (i.e., no food leads to no energy which results in death, also, there is no energy available so rabbits can no longer procreate and continue the species).

This technology also makes student understanding visible as users can construct models based on what they believe is occurring within the system as each model is altered with the manipulation of conditions. This dynamic and visual nature of agent-based modeling allows students to better discern patterns in systems which may emerge over time and or through the manipulation of settings. Furthermore, users have the benefit of observing these changes in real time (for actions which would take years to observe), at multiple planes (both macro and micro levels) and in the safety of an environment in which students could adjust their actions and undo past actions as needed, as the dynamics in the system are altered as the student opts to adjust the variables at play.

1.5 Thinking in Levels

Complexity theory describes an approach to systems through the understanding of the interconnected, interacting nature of systems and how this results in the dynamically evolving complexity of systems (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006; Yoon et al., 2019). This approach has been particularly useful in supporting students learning to differentiate between mechanisms occurring at the micro- and macro-levels of systems (Samon & Levy, 2017). Within the research on systems learning, students have often expressed difficulty in grasping the nuances and differences of phenomena occurring simultaneously at different scales in systems (Chi, 2005; Hmelo-Silver & Pfeffer, 2004; Levy & Wilensky, 2008, Yoon et al., 2018). This idea of thinking across levels can also be noted in the study of genetics in which students often face difficulty in understanding the relationship between genotypes and phenotypes and how this results in evolution through natural selection (Jördens et al., 2018).

Agent-based modeling encapsulates many aspects of complexity theory which places great importance on emergent phenomena. *Emergence* within systems is described as the macro, global or group behaviour or observation, which results from the micro, specific or individual interaction, which often takes place through hidden mechanisms of a system (Samon & Levy, 2017; Yoon, 2008, 2018; Yoon et al., 2018; Knippels & Waarlo, 2018). Several researchers have described students' difficulty in understanding such emergent phenomena (Chi et al., 2012; Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Schneeweiß & Gropengießer, 2019; Wilensky & Resnick, 1999). This concept of emergent phenomena poses challenges for learners as they try to comprehend the various simultaneous interactions occurring at the micro- and macro-levels within a system (Wilensky & Resnick, 1999). Some have argued that these concepts may prove to be beyond the scope of students' cognitive ability when taught together (Chi, 2005) but others have shown that students at early ages are able to grasp these concepts with appropriate support (Danish et al., 2015; Hmelo-Silver & Azevedo, 2006; Penner, 2000). Gilissen et al. (2020b) suggest that the concept of emergence may prove to be too difficult for learners to grasp if they first do not possess the foundational understanding of systems. Nevertheless, with emergence playing such an important role in understanding complex systems, researchers have sought to develop tools to make these ideas visible.

From the complexity perspective, another key characteristic is the element of *randomness*, which plays a vital role in complex systems. *Randomness* disrupts students' more common ways of thinking about systems, which is they anticipate linear interactions and simple one-on-one cause and effect relationships (Chi et al., 2012; Hung, 2008). Complex systems however, more often than not, display stochastic processes and dynamics within and across micro- and macro-levels of interactions and the behaviors of these systems may not follow a pre-determined or anticipated path (Hmelo-Silver et al., 2007). Furthermore, these unpredictable interactions may occur across varying spatial and temporal settings, thus increasing the complexity of understanding systems (Perkins & Grotzer, 2005). The authors Schneeweiß and Gropengießer (2019), highlight through their review, that learners often focus on components, rather than the interactions occurring within and between levels of systems. These interactions, however, are crucial to understanding how systems function and why outcomes may be presented as they do (Düsing et al., 2019). Recognizing and understanding these interactions allow students to better grasp and explain the complex and random nature of systems (Düsing et al., 2019; Jördens et al., 2016)

Canonically if we consider the Darwinian theory of Natural Selection comprised of the basic processes of variation, transmission, and selection, the notion of variability in, for example, a gene pool, is critical in understanding how systems evolve. Variation must exist in order to ensure that systems are continually adapting to changing environments and one source of this variation enters systems through random mutations. It is often that this randomness causes systems to bifurcate or shift in their emergent macro-scale patterns despite the existence of the same initial conditions. Students all along the K-16 educational continuum have demonstrated misconceptions about systems that are related to their lack of understanding of randomness (Jacobson, 2001; Yoon, 2008).

An additional affordance of agent-based modeling is that these computational simulations can provide multiple dynamic representations of systems phenomena that enable students to grasp the concept of randomness or random variation among other challenging systems processes. Students can run the simulations multiple times with the same initial variable settings (e.g., predator-prey population levels) and find that the outcomes may differ slightly each time. They can glean this from both qualitative interactions emerging on the screen as well as visualizing the population fluctuations over time showing how random variation in the system can affect outcomes. A third representation of the phenomenon found in the computer code that students can access can reveal how these stochastic processes are initialized. As a field, we have found that offering students the ability to investigate these multiple representations for meaning making has immensely supported the development of complex systems understanding. (Eberbach et al., 2021; Hmelo-Silver et al., 2017a; Hmelo-Silver et al., 2017b)

In an attempt to further analyze how students think about complex systems, Levy and Wilensky (2008), suggest some students, when dealing with naturally occurring systems, develop a “mid-level construction” of their understanding of systems, which they term the *meso-level*. They found that learners who adopted a mid-level to bottom-up framework of thinking of systems tend to be more successful in understanding systems dynamics and the hidden mechanisms of systems (Jacobson, 2001). The construction of a meso-level appears to be one method through which learners develop their understanding of complex systems and the mechanisms which occur on various scales, i.e., micro-level and macro-level. Organizing systems thinking in this manner aids in making hidden processes more visible to learners, as the leap from understanding macro-level observations to micro-level observations is supported by the establishment of a meso-level of interaction between components and associated observations (Levy & Wilensky, 2008).

One example utilizing this concept of the meso-level is in the description of the system of the aggregation of slime molds through an agent-based model in StarLogo. Under favorable conditions, slime molds are independent from each other and feed, move and reproduce independently as amoebas. However, when conditions change and food sources become scarce, slime molds react to this change in environment by ceasing reproduction and aggregating. Many students often assume that the mold clusters formed would be fewer in number but larger, however, by forming smaller clusters, this improves the stability of clusters facilitating faster movement towards more favourable environmental conditions thus increasing the chances of survival. The hidden mechanism of the interaction of the pheromone with the individual cells, which results in this aggregation of smaller and more numerous clusters to enhance stability of the clusters, is at the micro-level of interaction which is often lost to students. However, through this agent-based modeling tool, students can observe the action of this hidden mechanism. Still the behavior of the mold clusters may prove difficult for learners to comprehend even with this tool (See Wilensky & Resnick, 1999).

Students often observe the behavior of one component and attribute it to the global system, however, as within the simulation, there is randomness at play in systems, and the behavior and movement of one individual mold does not predict the actions of the entire mold population. However, should students form a meso-level in their thinking in an attempt to understand this system, learners would observe the behavior of individual smaller clusters (i.e., clusters consisting of two slime mold cells or single molds), and recognize that not all molds move in the same direction or are able to follow the pheromone gradient as effectively, nor do all molds stay in their clusters, nor are all cells positioned to interact with the pheromone. This level of unpredictability is common in systems; however, it is often overlooked by learners (Chi et al., 2012; Yoon et al., 2019). However, through observation and organization of thoughts at the meso-level, students can better observe the contributing factors which would yield success for the molds and the factors and uncertainty which could also contribute to overall fluctuations of observations within the system.

This form of conceptual organization is thought to naturally occur when learners try to describe and analyze everyday occurring systems. Learners are better able to develop their thinking of systems by viewing interactions at the micro scale, then conceptually forming small groups in which to analyze the system, which is thought to better structure their thinking to understand how the system and its interactions can be understood at the macro-level (Levy & Wilensky, 2008). Implementing a form of conceptual framing that students already utilize is hoped to enhance students' efficacy in understanding complex systems.

1.6 Conclusion

Several theoretical perspectives on complex systems have been developed throughout the years that are applicable to learning about biological systems. We began with Systems Dynamics, discussed SBF and the development of PMC, agent-based modeling, and ended by considering complexity and thinking in levels. However, what do these various versions of conceptualizing systems mean for learners and educators today? With the vast array of biological systems and their varying degrees of complexity, we propose that each theoretical perspective presents a useful addition to the scope and repertoire of conceptual framing and tools used in unravelling the intricacy of systems (Riess & Mischo, 2010)

For instance, complexity theory differs from Systems Dynamics in many ways. Systems Dynamics serves to identify the elements of a system and the interactions which occur between them, it also implies a more global approach, whereas complexity theory is based on the possibility of chaos and randomness within systems suggesting nonlinear dynamics and stochastic interactions and outcomes. Both theories embody the complex nature of systems, however, Systems Dynamics could potentially lead learners to expect a more simple, aggregate level of interactions and observations, whereas complexity encourages students to conceptualize systems as a more messy, nuanced and unordered entity than Systems Dynamics would suggest. It is our belief that both of these theories play a significant role in how students build mental models and perceive complex systems, the usage differs in both the targeted audience and the content.

Not every system in biology requires students to apply the complexity perspective frame of thinking. In teaching fifth grade learners about ecosystems, it may be more useful to teach students about basic food chains, food webs, trophic levels and the interactions between the components of the ecosystem. However, at the high-school level, students would be expected to understand the cascading effects of an ecosystem with changed environmental conditions such as climate change resulting in loss of a water resource.

The PMC framework affords another approach to help learners acknowledge, discern and emphasize the hidden mechanisms of complex systems which account for observable phenomena. This framework helps students dig deeper on concepts which embody systems thinking through foregrounding mechanisms, thus allowing students to move from more surface level thinking to deeper, more enriched levels of understanding. This can be observed in the scenario of an ecosystem within an aquarium, where an increase in the size of the fish population results in the water becoming cloudy and this also results in the death of some fish. The micro levels of interactions for this scenario might involve the hidden mechanism of the failure of the aquarium's biological filter. The filter serves to regulate the nitrifying and denitrifying bacteria which maintain the levels of nitrates in the water. Without a functioning filtration system, this could lead to a build-up of fish waste, thus increasing the levels of ammonia within the tank, resulting in fish death. Furthermore, the hidden mechanisms at macro-level of interaction can be described as the increase of fish in tank generating waste. This addition of fish within the ecosystem may have surpassed the carrying capacity of the ecosystem, disrupting its stability, which may have overwhelmed the filtration system of the aquarium, resulting in fish death. By having students apply the PMC framework, they may be more inclined to think deeper, to surface hidden mechanisms at play, at both the micro and macro levels of interaction.

Another way in which these various theoretical perspectives shape our teaching and learning of complex systems is through their application to learning progressions. Learning progressions (LPs) can be described as sequential descriptions of learning trajectories which define how learners may move from more novice ways of knowing to more sophisticated or expert level ways of thinking (Duschl et al., 2007). This approach can serve to structure curriculum, assessments and classroom activities to better inform educators and researchers on where student misconceptions of systems exist and where intervention may be required for our learners to achieve and develop sophisticated ways of understanding complex systems.

In the United States, the Next Generation Science Standards (NGSS), has designated Systems and Systems Models as a cross-cutting concept (CCC) as it spans across science domains, however, their description of standards lacks a full view of the complexity of systems and the terminology used is vague making educators face difficulty in implementing and utilizing this approach (Yoon et al., 2019). Similarly, the U.N. proposed the Education for Sustainable Development, which also cited Systems Thinking as a key component across and beyond science domains, however, progress towards this was hampered by the ambiguity of terms used and the lack of direction and guidance given to educators to begin addressing this concept effectively in schools (McKeown et al., 2002).

In an attempt to address these shortfalls, the authors of this chapter have embarked upon the journey of designing and validating LPs for complex systems in hopes of providing a more detailed and clearly outlined pathway to both tailor and assess students' competency and progress towards the complex concepts within Systems thinking. To effectively illustrate this, the authors designed and described each LP along the trajectory towards sophisticated ways of knowing, beginning with the most novice form of thinking about systems, while emphasizing the importance of mechanisms to systems understanding (see Yoon et al., 2019; Liu et al., 2020; Housh et al., 2020). Through the provision of these LPs, educators and researchers using qualitative descriptions should be able to more effectively discern where student understandings and misconceptions may lie and, as such, instruction, intervention and assessments may be designed to address students' needs.

To further address the lack of clarity of instruction and strategies used in the teaching of complex systems researchers suggest that teacher preparedness with the intentional focus on systems thinking, can be viewed as a crucial component towards our learners' success in grasping these concepts (Gilissen et al., 2020a; Boersma et al., 2011; Yoon, 2018). Effective professional development (PD) can support teachers in flexibly applying appropriate conceptual framework(s) for instruction. This PD should integrate Systems and Systems Models which may be more suitable to be applied to the biological system of focus within the classroom at the given point in time, and thus develop more effective teaching and learning strategies for complex systems. It is hoped that with increased effective PD for our teachers in the realm of systems thinking, teachers would better illustrate their ability to accurately apply and utilize the various frameworks and tools. In doing so, we believe that more of our biology learners would begin to express deeper understanding of complex systems and have an understanding of how to flexibly shift perspectives as appropriate.

To enhance research in biology education, the authors propose that the frameworks and tools discussed in this chapter be used to inform instructional strategies and interventions for future work in various biological contexts. Much of the current research in biology on systems has focused on the study of ecosystems, and genetics to some extent, however there is a need to diversify research on systems teaching and learning across a broader range of systems within biology (Yoon, 2018). Also, as highlighted by Gilissen et al. (2020a), teachers often have difficulty in grasping the concept of systems thinking. Thus, professional development specific to biological systems can use the frameworks and tools discussed here to help teachers understand and support teaching and learning about biological systems in ways that allow them to use appropriate frameworks in their pedagogical practices. Moreover, without adequate, foundational understanding of systems, teachers themselves may not fully comprehend some of the more conceptually challenging concepts such as emergence or randomness of systems, and as such, this might then be difficult to address in their own instruction (Yoon, 2018).

Furthermore, with the development and implementation of complex systems LPs in biology education research, this could provide insight into student learning and where interventions may be needed to confront misconceptions. For example, the LPs designed using the PMC framework emphasize student recognition and understanding of the phenomena, mechanisms and components of the system and how the hidden, interrelated interactions result in the outward visible phenomenon (Housh et al., 2020; Liu et al., 2020). We proposed that these might be applicable to any complex system being investigated by biology education researchers.

We agree with the works of Schneeweiß & Gropengießer (2019) and call for an increase in the implementation of interventions which emphasize the study of systems through the organization of levels and the interactions across micro and macro levels of complex systems. Thinking across levels may prove fruitful for biology education researchers especially when combined with agent-based modeling and PMC frameworks for instructional strategies, interventions and professional development for teachers. PMC provides one framework for scaffolding thinking across levels. Agent-based models can be useful in providing opportunities to visualize many systems ideas (such as emergent properties and relationships across macro and micro levels of systems).

This chapter provides an overview of theoretical perspectives in the study of biological complex systems. We hope that these theoretical perspectives described here help guide biology education researchers in their continued progress towards the development of productive understanding of teaching and learning about systems as well as the design of effective learning environments.

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Chapter 2

Long Term Ecological Research as a Learning Environment: Evaluating Its Impact in Developing the Understanding of Ecological Systems Thinking – A Case Study

Shayli Dor-Haim and Orit Ben Zvi Assaraf

2.1 Introduction

In the modern world we are exposed to a variety of complex problems, such as climate change, ozone depletion and rising carbon dioxide levels, which are characterized by a complex web of interactions. This complexity cannot be solved with the disciplinary tools or methodology we commonly use, in which each variable is isolated and tested separately, but rather requires the development of an appropriate approach. The system approach and system thinking suggest addressing these issues through understanding the interactions and dynamics created in the system (Barry, 1993). In the 1980s, the ecological community recognized that long-term research could help unravel the principles of ecological science, which frequently involves long-lived species, legacy influences and rare events. In order to cope with those complex problems, they developed the Long-Term Ecological Research (LTER) approach.

The LTER program was designed to help researchers understand long-term patterns and processes of ecological systems at multiple spatial scales (Hobbie et al., 2003; Kratz et al., 2003; Magnuson, 1990; Swanson & Sparks, 1990). Today, there are multiple LTER stations working in cooperation at dozens of sites around the world. Researchers at each site gather scientific data using a single, standardized methodology over long periods of time, and upload that data to a single hub, making it available to fellow researchers around the world. This approach makes it possible to conduct comparisons at a large temporal and spatial scale, based on the understanding that observing large-scale, long-term change is critical to our ability to

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understand and predict the ecological response to both slow changes and rare ecological events.

In addition to gathering data, LTER sites are also meant to be a source of education. One of the program's stated goals is "To promote training, teaching, and learning about long-term ecological research and the Earth's ecosystems, and to educate a new generation of scientists" (LTER Europe, https://www.lter-europe.net/). Many LTER sites therefore also incorporate educational projects in which students visit the stations, learn from the scientists who work there and even experience engaging in that work for themselves. Working with scientists has been suggested as one of the most productive activities for helping students to learn science and experience the diverse aspects of science practice in problem-solving contexts with a high degree of complexity (Hsu & Espinoza, 2018; Lee & Butler, 2003). Programs in which students work with scientists have been suggested as one of the most productive activities for helping students to engage in open-inquiry activities (Houseal et al., 2014; National Research Council, 2010) and to experience diverse aspects of science practice in problem-solving contexts with a high degree of complexity (Lee & Butler, 2003). The LTER sites also constitute an authentic outdoor learning environment which provides opportunities for scientific observation and inquiry learning. Authentic engagement in science has been shown to help students better acquire and apply scientific concepts and skills in a practical and meaningful context (Robinson et al., 2008; Sorensen et al., 2018).

The study presented in this chapter followed an 8th grade science education program that was designed around the educational activities at an LTER site in Israel – combining activities at the LTER site with complementary educational activities in and around the students' school. The program's goal was to develop the students' in-depth understanding of complex ecological systems and of the scientific practices associated with advanced ecological research. The results presented here are part of a larger study that addressed multiple aspects of this program. Here, we will address the specific question of how the students' participation in the program may have advanced the development of their system thinking.

2.2 Literature Review

2.2.1 The Ecosystem as Complex System

The ecosystem is a fundamental ecological concept that is not as simple as it first appears (Pickett & Cadenasso, 2002). Rather, it is a subtle and complex concept that can be challenging for both scientists and students. Tansley (1935) defined the ecosystem as a biotic community or assemblage and its associated physical environment in a specific place. Ecosystems can therefore be as small as a patch of soil supporting plants and microbes, or as large as the entire biosphere of the Earth (Odum, 1989). Whatever their size, all ecosystems meet the definition of a "complex system." Their complexity is characterized by numerous interrelated components spanning multiple spatial and temporal scales, interacting in ways that result in emergent properties that cannot be predicted solely on the basis of the components themselves (Lesh, 2006; Long et al., 2014). Emergence is a central concept associated with complexity and is the process by which the actions and interactions of the system's entities transform into global patterns. Ecological complexity emerges from the interactions between organisms and their biotic and abiotic environments (Anand et al., 2010). The study of any ecosystem therefore requires an understanding of the processes, feedbacks, interactions, structure and function of that system, *and* how these are related to the interactions between the four Earth systems: ecosphere, hydrosphere, geosphere and atmosphere. The key challenges in the field of ecological complexity include: (1) the development of appropriate descriptive measures to quantify the structural, spatial, and temporal complexity of ecosystems; and, (2) the identification of the mechanisms that generate this complexity, through modelling and field studies (Anand et al., 2010).

2.2.2 The Difficulties Associated with Understanding Complex Ecological Systems

The complexity and dynamism of the relationships within them makes complex systems such as ecosystems difficult to understand (Fanta et al., 2020; Mambrey et al., 2020), since understanding these interdependent relationships requires systemic reasoning (Hokayem & Gotwals, 2016). Various studies have shown the difficulties students have with the topic of complex systems (see for example, Ben Zvi Assaraf & Orion, 2005; Tripto et al., 2018). They describe a number of obstacles to understanding the different aspects of the system, among them difficulties drawing connections between the systems' different levels and navigating to the mechanisms, functions/phenomena of the system (Hmelo-Silver et al., 2007). Specific difficulties have been found in studies examining students' understanding of complex ecological systems as a whole (Jordan et al., 2009) and of aspects of the system, such as food chains (Hogan, 2000), nutrient cycles and energy flow (Hogan & Fisherkeller, 1996; Leach et al., 1996).

Those studies revealed that students have difficulty thinking beyond linear flow, single causality, and visible structure, in order to grasp the dynamic, emergent and hidden aspects of complex systems. As a result, students understand the concept of ecosystem partially, and although they are aware of the elements of ecosystem individually, they have limited cognition regarding the functions of these elements as well as their interactions with one another (Özkan et al., 2004). For example, Eilam (2012) conducted a study in which ninth grade students studied a live ecosystem and manipulated variables in a lab, and found that students seldom connected individual processes of matter transformation and energy transformation at a molecular level with patterns of matter cycle and energy flow processes at the ecosystem level. Also, multiple studies have shown that students are not aware of the flow of energy among the living beings in the ecosystem and fail to understand the true flow of energy in the food chain (Arkwright, 2016; Hogan, 2000; Özkan et al., 2004).

Empirical studies suggest that identifying system-level patterns in ecosystems is very challenging for students (Hokayem & Gotwals, 2016). As discussed before, complex systems have a hierarchical structure, with multiple components that interact dynamically, nonlinearly, and simultaneously, within or across levels. Such interactions, moreover, are often implicit, occurring over time, at varying microscopic and macroscopic levels, and with indirect causality that is difficult for students to trace and grasp (Eilam, 2012; Hmelo-Silver & Azevedo, 2006). Students have difficulty in comprehending those interactions which specifically involve the transformation of matter (molecules) within the system. These relationships are termed ‘dynamic’. For example, in relation to understanding of the food web, a dynamic relationship refers to energy transfers between the plant and animal. Those dynamic relationships that occur at the molecular or cellular level are termed invisible dynamic processes (Duncan & Reiser, 2007; Hmelo-Silver & Pfeffer, 2004; Verhoeff et al., 2008).

Despite the difficulties, ecology constitutes an inherent part of most western countries’ curriculum, because it provides opportunities to study systemic phenomena and plays a crucial role in human decision making (Sabelli, 2006). Researchers suggest that providing students with opportunities to learn about systems with multiple and interrelated components can help provide a context for students to develop an understanding of complex systems (Hmelo-Silver et al., 2007; Hogan, 2000; Jordan et al., 2009). These opportunities, however, must be accompanied by the development of higher-order thinking skills such as “system thinking” (Tripto et al., 2018).

2.2.3 Developing and Assessing System Thinking

Systems thinking is the ability to understand and interpret complex systems. For example, Knippels and Waarlo (2018) suggested that thinking to-and-fro between the levels of biological organization is part of systems thinking in biology and of biological reasoning. The National Research Council (NRC) defined system thinking as, “the ability to understand how an entire system works; how an action, change, or malfunction in one part of the system affects the rest of the system” (NRC, 2010, p. 3). Gilissen et al. (2020) defined systems thinking in terms of eight system characteristics (Boundary, Hierarchy, Components, Interactions, Input output, Feedback, Dynamics, and Emergence).

System thinking is expressed by the identification of relationships between system components and/or between systems, including hidden parts of the system, and is perceived as a high-level thinking skill (Ben Zvi Assaraf & Orion, 2005). Moreover, in order to understand whole systems, a separate understanding of each of the parts will not suffice. The system must be viewed holistically, as an entity unto itself, with both temporal and spatial characteristics, in which interactions occur between the system’s parts as continuous and dynamic activity, and where any disturbances in one part of the system may induce changes throughout the system as whole (Ben Zvi Assaraf & Orion, 2005).

An exploration of learners' system thinking capacities should be based on a theoretical framework that enables identification of differences in the extent of individuals' system thinking capacity, as well as of the development of these capacities within each learner. One idea for such a framework is the Systems Thinking Hierarchy (STH) model developed by Ben Zvi Assaraf & Orion (2005). They suggested that thinking about and understanding a system can be categorized according to eight hierarchical characteristics or abilities, which are evinced by students in an ascending order. These eight characteristics compose the STH model, which was developed following a study of junior high school students in the context of Earth Systems (Ben Zvi Assaraf & Orion, 2005). The model's characteristics are arranged in ascending order of advancement into three sequential levels: (A) analyzing the system components (characteristic 1); (B) synthesizing system components (2, 3, 4, 5); and (C) implementation (6, 7, 8). Each lower level is the basis for developing the next level's thinking skills. Students' implementation thinking skills of the system enable them to maintain a systems level view while moving between the levels of analysis, and synthesis, thinking skills.

The characteristics are as follows: (1) Identifying the components and processes of a system (level A). (2) Identifying simple relationships among a system's components (level B). (3) Identifying dynamic relationships within the system (level B). (4) Organizing the systems' components, processes and their interactions within a framework of relationships (level B). (5) Identifying matter and energy cycles within the system (level B). (6) Recognizing hidden dimensions of the system (understanding phenomena through patterns and interrelationships not readily seen) (level C). (7) Generalizing about a system and identifying patterns (level C). (8) Thinking temporally (employing retrospection and prediction) (level C).

2.3 Methods

2.3.1 Setting and Population

The results presented in this paper are drawn from a larger research project that tested multiple aspects of the development of a new ecological curriculum based on the LTER approach, and of the LTER site as a learning environment. The curriculum was based on a series of outdoor activities in which students, under the guidance of scientists from a local LTER station, engaged in scientific inquiry – both at the LTER research site and in designated areas near their schools. Over a period of one school year, the students participated in four field trips, during which they set up experiments, performed biotic and abiotic monitoring and learned about special studies being conducted at the station, such as the impact of wild boars on the ecosystem and a project to restore the endangered local vulture population.

The study sample for the data presented here included 31 high-achieving students, all from one eighth grade class. The school is located in an affluent neighborhood in central Israel. Near the school is an archeological site that has been preserved as a green area in the heart of the city. In this area, we established for the students an LTER site of their own, where they conducted experiments and observations and learned about their local ecosystem. A breakdown of the curriculum's topics and activities is provided in Table 2.1.

Between October and April, the students participated in three hours a week of class discussions and knowledge integration activities. These included topics such as "Earth systems: Hydro-Geo-Atmo-Biosphere," in which the students received tasks on each system and examined the various connections between them (for example, infiltration and its role in soil fertilization; influence of soil humidity on plant biodiversity). The students also learned about biogeochemical cycles like the water cycle, the carbon cycle, the nitrogen cycle, about the system's hidden dimension, microorganisms, and processes such as decomposition. In addition, they saw a film that emphasized the role of the vulture in nature, and human influence on its survival.

Table 2.1 Program activities and their contribution to developing ecological system thinking

	Preparation for the field trip	Outdoor activity	Lab
Field trip 1- Late September	Introduction to LTER – What is it and why is it important? Emphasis on the two main components of LTER: expanding the scope of research in both the spatial and temporal dimension. For example: Long-term monitoring of the common oak (*Quercus calliprinos*) population in response to drought conditions. Field trip preparation – where they will go, what activities they will do, what kind of variables they will be collecting data on.	Field trip 1 was to LTER station to work with the scientists. In the outdoor activity the students collected data on a-biotic components: phenology, arthropods, plant litter. Collecting bags of litter in the field with scientists that work at the site.	LTER Lab – The students measured the plant litter (separated and weighed it), and uploaded the data to the LTER station's computers.
Field trip 2 – October	Learning about the vegetation in the ecosystem and the importance of conserving such an ecosystem in an urban area. Discussing the comparison of ecosystem characteristics between the beginning of winter and spring.	Similar to field trip 1, the students collected data at the designated ecological areas near their school, monitoring the same biotic components, collecting bags of litter from the field.	School Lab – weighing, writing up the results. Practicing Excel-based data analysis.
Field trip 3 – April	The students performed several experiments, such as microorganism identification and examining matter in various states of decomposition through microscopes and binoculars.	Similar to field trip 1 and 2, the students collected data at the designated areas near their school, monitoring the same biotic components, collecting bags of litter from the field.	

(continued)

Table 2.1 (continued)

	Preparation for the field trip	Outdoor activity	Lab
Field trip 4 – May	Discussions with scientists emphasizing two examples of LTER research's role in understanding the complexity of ecological phenomena: a) A study of wild boars as omnivorous seed dispersal agents, showing how they serve as effective dispersal vectors of exotic plant species from agricultural and urban areas into protected natural ecosystems. b) Goat farming and landscape management – A project designed to identify the breed that will consume tannin-rich plants, and to develop a sustainable goat farm combining shrub control, and fire prevention.	Outdoor activity – The students collected data on a-biotic components: phenology, arthropods, plant litter. Collecting bags of litter in the field with scientists that work at the site. They also joined a scientist researching butterflies, learning about the process of monitoring butterfly migration.	LTER Lab – Working with scientists, the students performed a timeline meta-analysis and saw the changes in the ecosystem from the late summer to the spring.
Field trip 5: summary – June	A concluding event, which gathered together all of the students who had participated in the program. In mixed groups, they compared notes, analyzing the data they had collected during the year from all the field trips and examining the differences in both time (seasons) and space (between sites).	Observation of vultures at the LTER station rehabilitation site, where wounded vultures are kept prior to being returned to their natural environment. Moreover, the students compared their data with those of students from other schools, and with data collected in previous years in LTER stations both in Israel and USA.	

2.3.2 *Research Tools and Data Analysis*

The data collection was based on a series of four quantitative and qualitative research tools: (1) The Matter Transfer in the System questionnaire; (2) A drawing task; (3) Concept maps; (4) The LTER Questionnaire.

The Matter Transfer in the System Questionnaire This questionnaire was designed to assess students' ability to identify relationships among the components. It measures students' perceptions of matter transfer between Earth systems and their perceptions regarding matter transfer and energy in the ecosystem. In constructing the questionnaire, we used statements from the different versions of this questionnaire that have been employed variously by Ben Zvi Assaraf and Orion (2005), and Batzri et al. (2015). The questionnaire included 22 statements (see Tables 2.4 and

2.5). The students were asked to indicate their level of agreement with each statement on a scale of 1 to 5 (rated from 1 – “don’t agree at all” to 5 – “strongly agree”) and to explain their choice. The students completed the questionnaire both before and after the program.

The Drawing Task Drawings have been shown to be a useful tool for probing the level of students’ understanding of natural phenomena (Ainsworth et al., 2011). We employed a drawing task that was developed by Ben Zvi Assaraf & Orion (2005): “What did the painter forget to paint?” (Fig. 2.1). This task allowed us to collect information about how the students perceive the ecosystem and to determine the students’ level of system thinking before and after the learning process.

Each student was given a picture describing an ecosystem. It was explained to the students that the painter had “forgotten” to paint some of the existing components in the system, and they were asked to add as many items as possible that they think are missing in the picture and to write why they added those items. (Fig. 2.1).

Concept Maps In teaching complex systems, one basic principle is to explicitly represent the conceptual framework to the students, and help them to represent their mental models explicitly. One way to do this is to use concept maps as a visual means of externalizing and examining students' internal mental models (Kinchin, 2020). A concept map is a graph consisting of nodes and labelled connecting lines,

Fig. 2.1 The picture of an ecosystem: “What did the painter forget to paint?”

which explicitly organize and represent the mapmaker's knowledge of concepts and the relationships between them (Novak et al., 1984). The concept map is also a powerful research tool that allows examination of the way learners restructure their knowledge. It does so by identifying misconceptions, and recognizing different learning styles (Martin et al., 2000; Novak et al., 1984). Moreover, concept maps focus on the structure and the links that the student perceives. Mapping is a means of eliciting the relationships that each student perceives among the concepts.

The students created concept maps at the beginning and the end of the learning process (Fig. 2.2). Making the concept maps involved the following three stages: (1) the students were asked to write 15 concepts that, in their opinion, are associated with the ecosystem; (2) the students were asked to write down ten sentences that

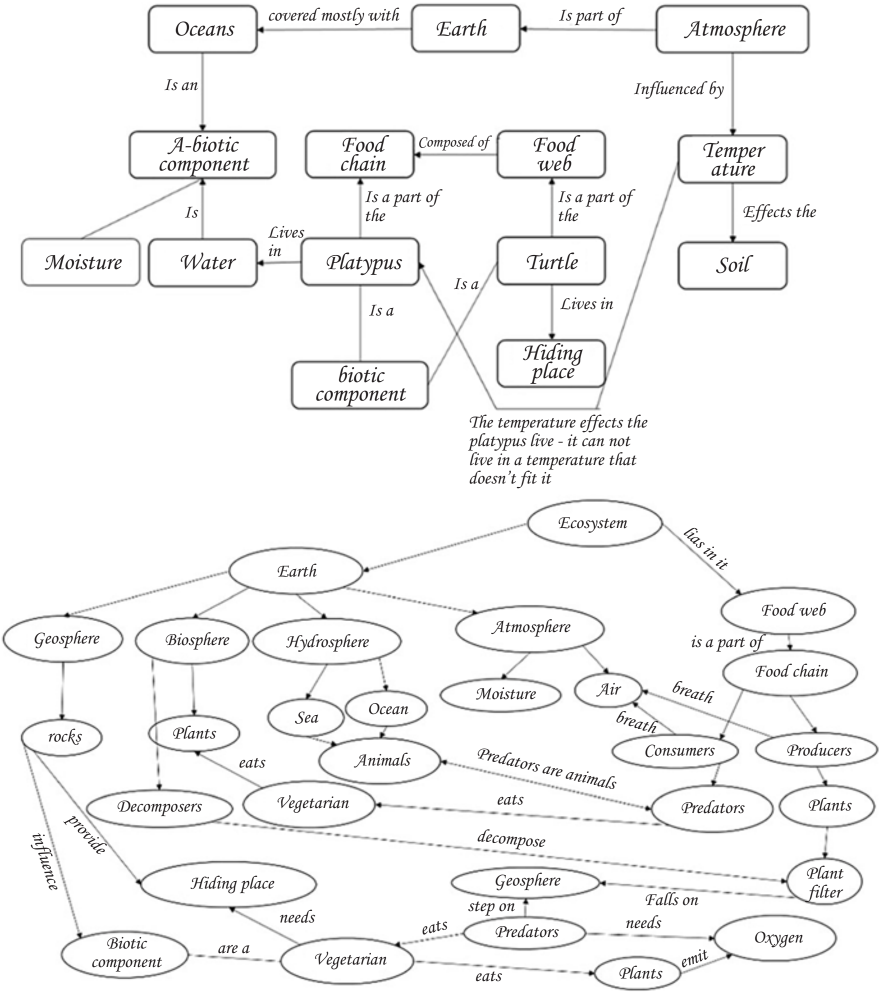

Fig. 2.2 Example of concept maps – Comparison between Idan's pre and post concept maps, before learning (top); after learning (bottom)

connect any two of these concepts. They could use the same concept more than once; (3) students were given a blank page and asked to create a new concept map concerning the ecosystem (Note: they were not required to use any or all of the concepts and sentences from stages 1 and 2).

We used the analysis of the students' concept maps to look for the following system thinking components: the ability to identify the system's components and processes (reflected by the number of concepts in the map; The ability to identify relationships within the system (reflected in the number of linkages); the ability to organize components and place them within a framework of relationships (reflected in the number of represented generalized concepts, which reflect a more holistic perception of the system using a concept map); the number of macro-level elements represented; the number of micro-level elements represented; the representation of retrospection and prediction. Our analysis was validated by the judgment of two additional experts in the field of science education. The tool analyses conducted by the STH model principles and a detailed explanation can be found in Tripto et al. (2018).

LTER Questionnaire This questionnaire was developed specifically for this study, in collaboration with ecology experts, in order to determine how well the students understood the LTER components (time and space) and the importance of research in LTER sites, after learning the program. The questionnaire was based on Müller et al.'s list of requirements for long-term ecological research (2010). The questionnaire was given to the students after the learning process. It included 25 statements and the students were asked to indicate their level of agreement with each on a scale of 1 to 5, and to explain their choice. The questionnaire's statements were designed to reflect the LTER components that had been emphasized and learned during the program, for example: "tracking countrywide annual precipitation over the years will help us more accurately predict areas of drought and desertification"; "Ecosystems such as coral reefs are constantly changing – in order to understand processes and events in the system it is enough to collect data for only two years"; "Bees are very important for agriculture – long-term research on disturbances in the ecosystems (such as epidemics) where the bees live, will help us protect them from harm".

2.4 Results

We have chosen to present in the results a case study of one class (out of five) that studied this program in the unique LTER environment. The results, which incorporate data from all four research tools, are divided according to the three levels of the STH model – analysis, synthesis and implementation, emphasizing the development of the students in each level before and after the learning.

2.4.1 Analysis Level

The analysis level gives expression to students' ability to identify ecosystem components and processes within the Earth systems. We found that the students arrived with a high level of analysis even before they started learning the program. This can be explained by the fact that those students are all high academic achievers and arrived with relatively broad knowledge and high learning skills. These results were reflected in the expression the students gave to Earth system components before learning, using terms from the Biosphere (for example, plant, bird, tree, apex predator, herbivore, decomposers), Hydrosphere (water source, rainfall), Atmosphere (air) and Geosphere (soil) (see, for instance, the drawing task in Fig. 2.3a). They were also reflected in the students' ability to identify processes in the ecosystem, such as food web, water cycle and photosynthesis. Analysis of the students' concept maps showed a high analytical level and a wide range of concepts even before the learning process.

We also found, however, that the students presented an even higher analytical understanding after the program. For example, while no change was found in the average number of concepts added by the students to the drawing before vs. after the learning process, we *did* find that after the program, the students addressed the geosphere and biosphere components in the ecosystem more prominently (Fig. 2.3b). Thus, for instance, in the drawing tool (Fig. 2.3), the students added references to plant litter and the vulture's role in the ecosystem to the drawing after the learning process, explaining: "plant litter will decompose and will become a fertilizer that will help to a better growth of the plants"; "plant litter – food for the decomposers, very conductive"; "vulture – so that carcasses break down and materials return to the soil"; "vulture eats carrion and cleans the system." We also found an increase in the number of connections in the students' concept maps that refer to processes in the system (Table 2.2), such as: "Plants provide food and air for humans"; "water

Fig. 2.3 "What did the painter forget to paint?": (**a**) Pre learning; (**b**) Post learning

Table 2.2 Concept map analysis comparing pre vs. post in terms of no. of concepts, no. of junctions, no. of connections and content of connections

	Concepts		Junctions		Connections (total)		Connections (descriptive)		Connections (processes)		Connections (biotic)		Connections (a-biotic)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Mean	17.94	17.06	6.12	8.76	12.24	17.41	5.47	8.12	6.82	10.0	8.65	7.18	3.47	6.47
Std.	1.13	1.59	0.64	0.79	2.01	2.33	1.08	1.73	1.54	1.85	0.90	1.89	0.64	0.48
T test	0.29		0.015		0.02		0.12		0.02		0.22		0.01	

Note: Each connection could be attributed to more than one content category irrigates the plants"; "we find plant litter in the ecosystem that decomposes into the soil".

In this study the students visit the ecosystem near the school once before the pre-test.

At the beginning of the learning process (A) we see a description of the system components (level A) such as clouds, grass, flowers, and spiders. In the explanations the student wrote: "I saw those components in the ecosystem around the school." The student did not describe processes or interactions. At the end of the learning process (B) we see higher complexity in the painting. The components added to the system (level A) are: Lentisk, Phillyrea Latifolia, lake (water source), goat, decomposers, clouds and plant litter. These are components that the students saw during the field trips. The student describes processes in the system, such as feeding and decomposition: "the mouse feeds from the wheat"; "the bird eats the Lentisk fruits". In addition, the student describes the interactions in the system (level B) as "the clouds bring down rain that provides water for the plants and fills the lake so that animals can drink (linking Hydro and biosphere)". Describing the interactions as a web- "Without the sun the plants will not be able to do photosynthesis and they will die and the animals will have no food". The student has developed a good understanding of ecological system thinking using examples that include reference to Earth systems.

2.4.2 Synthesis Level

The synthesis level gives expression to the students' ability to identify interactions, matter transfer and cycles in the system before and after learning. Analysis of the research tools showed that the students had a good understanding of interactions and matter transfer before beginning the program. Even so, after learning the program, the students demonstrated much higher synthesis thinking about the ecosystem, addressing matter transfer and cycles, especially in all the parameters that relate to the plant litter component (for example, its role in the food web, decomposition, ecosystem function). This is expressed, for instance, in the increase of connection statements in their concept maps that address relationships between systems and matter transfer (Table 2.3).

Table 2.3 Analysis of connection statements in the concept maps tool: Students' perceptions of the identification of relationships and matter transfer in the system

	Relationship between components		Relationship between systems		Matter transfer	
	Pre	Post	Pre	Post	Pre	Post
Mean	3.94	5.24	1.4	2.24	2	2.76
Std.	0.57	0.66	0.21	0.68	0.39	0.5
T test	0.06		0.009		0.06	

Table 2.4 The Matter Transfer in the System Questionnaire: Items pertaining to synthesis level

		Std.		Mean		T test
	Phrase	Pre	Post	Pre	Post	
1	When the number of species drops under certain value, the entire ecosystem may collapse.	0.74	0.74	4.45	4.45	1
2	The web-food represents the transfer of matter and energy in the ecosystem.	1.34	1	3.23	3.85	0.054*
5	The total number of species on Earth is decreasing.	1.08	0.63	4.2	4.45	0.32
7[a]	An invasive species has no effect on the local population’s size because it has no chance of taking hold in the ecosystem.	0.84	1.04	4.28	4.08	0.23
8	Raptors contribute to the balance of the ecosystem in the area in which they live.	0.79	0.90	3.96	4.18	0.31
10[a]	The ecosystem can exist without plant litter.	0.94	1	3.9	4	0.67
11	Without interaction (predation, reciprocity, parasitism) there will be no life in nature.	1.09	0.82	4.45	4.42	0.83
12[a]	Carbon cycle in nature – begins with the carbon emitted from animals’ breath, and ends with the plants that absorb the carbon in the process of photosynthesis.	0.9	1.44	2.71	3.07	0.24
14[a]	The amount of water in the oceans increases over time as a result of rainfall and rivers entering them.	1.44	1.33	3.69	4.07	0.16
19	The lower the amount of water that the plant receives, the smaller the amount of organic matter it produces.	0.83	0.95	3.46	3.87	0.16
17[a]	The food web in nature begins with plants and ends with super predators.	1.19	1.54	4.14	3.66	0.11
19	The lower the amount of water that the plant receives, the smaller the amount of organic matter it produces.	0.83	0.95	3.46	3.87	0.16
22[a]	Water cycle – starts in the cloud and the ends in the tap.	1.4	1.39	3.25	4.00	0.03
24[a]	Abiotic conditions do not affect biotic conditions in the ecosystem.	0.91	1.56	3.6	3.52	0.80

[a] Reversed negative phrases; *$p \leq 0.05$

The students presented a variety of interactions to explain ecosystem processes. For example, in the drawing tool they added elements such as: prey, drinking and place to live (niche – here we have a misconception about what is ecological niche). In another example, their understanding of the influence of invasive species on the ecosystem was reflected in their explanations for item 7 in the “Matter Transfer in the System Questionnaire” (Table 2.4), where they noted that invasive species “affect the population and interrupt the balance,” and that “if the species is strong or a predator species it may take food from other species”. Other explanations in this questionnaire reflected a significant improvement in the students’ understanding of interactions, as students expressed and explained the important role of the food web and decomposition in the ecosystem, noting that: “The food web represents the transfer of materials and energy in the ecosystem”; “There is matter transfer from the prey to the predators and this matter transfer expresses the energy transfer (chemical)”; “In the predator-prey interactions matter and energy transfers”; “the plants produce energy for themselves and other species eat them and the energy transfers to them".

One aspect with which the students seemed to have more difficulty is understanding the carbon cycle. In the biosphere, cyclic thinking means understanding the recycling of substances in biota within the carbon cycle (see statement 12 in Table 2.4). We found that in the post test, most of the students still struggled to understand that cyclicality in Earth systems is present in all of Earth's processes. In their explanations, most students argued that "the carbon cycle ends when the plants deposit the carbon in the ground," rather than claiming that "It's a cycle, how can you say where it starts and where it ends?" Moreover, very few students' explanations referred to the carbon cycle and related concepts as biological, geological, and chemical mechanisms. Instead, most related the carbon cycle to high concentrations of CO_2 that caused global warming and desertification, while others perceived it as an example of interactions between Earth's systems at the macro level only.

2.4.3 Implementation Level

This level gives expression to the students' ability to present the generalization and identification of patterns in the system, the description of the hidden dimension and the ability to think in time and space dimensions before and after learning. The results revealed that the students had a good generalization understanding even before they started the program, but after the program the students discovered higher thinking skills in all three components of the implementation level of the STH model (generalization/patterns, hidden dimension and temporal thinking). As can be seen in Table 2.5, the students' post-program answers to the questionnaire scored very high, reflecting a good perception of the system as a whole. This is further supported by explanations like: "The biosphere cannot exist without the hydrosphere, atmosphere and geosphere"; "System factors are interdependent"; "Climate change in a particular place also affects remote places on Earth".

After the learning the students showed a significant change in regards to the hidden dimension. In addressing statement 9 ("the plant litter is related to the vulture"), for instance, they noted that "the plant litter affects the plants and the plants affect the animals from which the vulture eventually feeds," referencing the role of hidden processes of decomposition (Table 2.5). This is further supported by the analysis of the concept maps tool, in which significant improvement was found in the representation that the students give to microscopic creatures (Pre Mean 0.29; Post – Mean 0.824 $p < 0.053$) in the system. This finding can be directly related to learning the program during which the students become familiar with the mesofauna in the soil and are taught about their important role in the energy and matter cycle. The students' understanding of the temporal dimension is elaborated below, in the section devoted to the LTER questionnaire.

Table 2.5 The Matter Transfer in the System Questionnaire: Items pertaining to implementation level

		Std.		Mean		T test
	Phrase	Pre	Post	Pre	Post	
6	Climate change in one area can affect other, faraway places elsewhere on Earth.	1.06	0.94	3.9	3.66	0.35
13	Studying the ecosystem of a desert in Africa can teach us about the ecosystem of a desert in Israel.	1.26	1.27	3	3.14	0.68
15	The biosphere (life) cannot exist without the hydrosphere (water), the atmosphere (air) and the geosphere (rocks).	0.85	0.7	4.4	4.56	0.59
16	The stability of an ecosystem is measured by its resilience to disruptions such as: storms, fires, invasive species.	1	0.85	3.6	3.68	0.86
18	The more processes take place in an ecosystem, the better it will function.	0.73	0.97	3.1	3.24	0.65
4[a]	The destruction of nitrogen-fixing bacteria in a particular habitat will not affect the animals in that habitat.	0.97	1.52	3.6	3	0.12
9	The plant litter on the ground is connected to the vulture in the sky.	1.15	1.26	1.6	4.15	0.0001***
20[a]	Photosynthesis in the ecosystem is not important for human existence.	1.14	1.5	4.4	3.96	0.125
21	Decomposition of the plant litter is a process in which the litter breaks down into simple components that are released into the ground and absorbed by the plants.	0.85	1.22	3.5	3.87	0.26

[a]Reversed negative phrases; ***$p<0.01$

2.4.4 Students' Understanding of the Content and the Value of LTER

The data analysis of the LTER questionnaire suggests that following the learning process, the students improved their ability to comprehend the spatial-temporal scales that are of great importance for understanding the ecosystem and its complexity. Their understanding of spatial scale, for example, can be seen in the response to statements like "Studies in Park Ramat-Hanadiv have found that herbaceous plants take over the landscapes. Since the park is so large, there is no need to conduct further research elsewhere" (Mean 4.071; Std.–0.616*negative statement – been reversed). Similar results were revealed in the statement: "Tracking countrywide annual precipitation over the years will help us more accurately predict areas of drought and desertification" (Mean 4; Std.–0.67). One student emphasized the breadth of the phenomenon by explaining, "vegetation is influenced by rainfall, which is related to both the water cycle and the rocks in the desert."

In the temporal dimension, the students' answer to the LTER questionnaire reflected their understanding that short-term research cannot accurately capture the changes that take place in the ecological system. This was evident in the students' responses to the negative statement, "to understand the effect of grazing on plants in Mount Carmel, two years' research is enough" (Mean 3.786; Std.−0.85). As one student explained, "The basic idea is that you can't, in two years of research in an ecosystem, you can't understand the system, what the primary factors are that affect the system's biodiversity.

The temporal dimension was also demonstrated when the students elaborated on various ecosystems, in which species became extinct and as a result the ecosystem was completely changed. They presented a good understanding of the importance of predicting various effects on the ecosystem in order to maintain and rehabilitate it, as shown in the LTER questionnaire statement "Global warming is expected to cause thawing glaciers and extinction of the polar bears. Therefore, humans need to conduct long-term studies that will examine the causes of warming" (Mean 4.50; Std.−0.65). One student suggested that: "Polar bears have a right to exist, one must investigate to prevent their extinction – a comprehensive set of abiotic variables is needed to identify a variety of biodiversity changes."

The students' responses to other items in the questionnaire reflect their understanding of a key point in LTER that combines the spatial *and* the temporal, namely that understanding multiple aspects of global change requires long-term observation over large spatial scales, multiple experiments, and comparative studies. This point was reflected in the students' responses to statements like, "data gathered from different studies on different topics must be recorded in the same manner so that comparisons between studies can be made to cover a larger scale" (Mean 4.333; Std.−0.724); "It is important that researchers conducting a study of butterfly migration in Israel uses the same monitoring and measuring methods as those used by butterfly researchers in England" (Mean 4.133; Std.−0.834). As one student explained, "this is important so that comparisons can be made between the results of different studies, and it's important to study this because butterflies drink pollen from flowers and pollinate them by transferring pollen." The students' responses express their understanding that LTER infrastructures provide the continuity necessary for addressing long-term change, and are important for the assessment of the effects of global change on landscapes and ecosystems.

2.5 Discussion

The Long-Term Ecosystem Research (LTER) project was established in order to investigate ecological processes over long temporal and broad spatial scales, with the involvement of scientists from multiple disciplines, in many sites around the world. Scientists around the world believe that dealing with these spatial-temporal scales is of great importance for understanding the ecosystem and its complexity (Knapp et al., 2012; Stoll et al., 2011). As demonstrated by Müller et al. (2010), we need long-term research to understand ecosystem complexity, ecosystem self-organization, the role of hierarchies and scales, and the dynamics of large-scale variables that could function as strong constraints in the future. In addition, long-term ecological studies are extremely valuable for providing consistent data records (Müller et al., 2010).

The curriculum employed in our study was designed to address the six main objectives of long-term research, as defined by Müller et al. (2010). Thus, for instance, to address objective (i), "understanding large-scale variabilities," our students underwent a lesson in which they learned about similar studies conducted at LTER sites located in different ecosystems around the world. This emphasized the importance of research at large scale. For objective (ii), "understanding the interactions of short-term and long-term fluctuations," the students became familiar with different ecosystem phenomena (for example, the decomposition of plant litter in various ecosystems, the vulture's role in the ecosystem), and with their short- and long-term effect on the ecosystem. Objective (iii) "understanding self-organization," was addressed by the activities in which the students explored the matter cycling involved in litter decomposition. For objective (iv), "understanding rare events and disturbances," the students participated in two activities that emphasized the impact of disturbances on the ecosystem: learning about the causes and effects of repeated forest fires, and about the influence of climate change on butterfly migration. The human impact on the ecosystem was woven throughout the program to address objective (v), "better understanding the impacts of anthropogenic use of landscape resources on ecosystem functions." For example, the students studied the human influence on wild boar and on vultures, and learned about the ecosystem in the Easter Islands. For the final objective, (vi) "generation of knowledge and data for the development and evaluation of new generations of ecosystem models for resource management," the students were taught how to write a data description and how to use and create a database using their data and others'. These examples illustrate the complexity of ecosystems as a topic of study, and the extensive effort involved in comprehending phenomena that take place on such massive temporal and spatial scales.

In our study, the main assumption was that the LTER environment, as a complex ecosystem that emphasizes the importance of long-term research and combines temporal-spatial dimensions, would help students to develop ecological system thinking. The need to understand spatial-temporal dimensions in order to develop complex systems understanding has been emphasized in many studies (Ben Zvi Assaraf & Orion, 2005; Eilam, 2012; Hmelo-Silver & Pfeffer, 2004). Analysis of the students' constructs through the lens of the STH model provided us with insight into the conceptual understanding of systems that the students brought with them into – and attained from – the learning process. Even before studying the program, analysis of the pre-questionnaires showed that students have a good understanding of the analysis and synthesis levels of the ecosystem. However, post-learning, the students gave greater expression to patterns, as well as the temporal and hidden dimensions (restricted to students investigated in this research). The students explained changes that occur in the ecosystem while referring to the hidden dimension in the system and referred to processes that occur over time and that affect the functioning of the system as a whole. For example, the students referred to the decomposition process as a process that involves plant litter that decomposes via microorganisms and matter transfer into the soil; they also noted the impact of human activities and disturbances in the system (such as intensive construction, fires and drought).

Magntorn & Helldén (2005) describe the ability to recognize organisms and relate them to matter cycling and energy flow in the specific habitat as the ability to 'read nature'. 'Reading nature' requires the ability to create links between the macro and micro levels. Lee and Bednarz (2009) supported the idea of spatial thinking as a constructive amalgam that requires knowledge about three mutually reinforcing components: the nature of space, the methods of representing spatial information, and the processes of spatial reasoning. They noted that spatial relations include the ability to recognize spatial distributions and spatial patterns, to connect locations, to associate and correlate spatially distributed phenomena.

The one major obstacle that our study identified in the students' system thinking development related to their comprehension of the carbon cycle. The students had difficulty understanding the cyclic nature of its processes (namely, that there is no start or end point), and identifying carbon as a component of matter transport at the system's micro level. They also largely failed to associate the carbon cycle with biological mechanisms (such as respiration, photosynthesis, decomposition), connecting it primarily with geological phenomena like global warming and desertification.

Further research is needed to explore – how this conclusion generalizes to all biogeochemical cycles or is the difficulty specific to the carbon cycle.

This finding supports those of multiple previous researchers. Zangori et al. (2017), for instance, found that, within secondary and undergraduate classrooms, students struggle to understand key carbon cycle processes such as photosynthesis and cellular respiration, and visualize carbon cycling at a global scale. Similarly, Nguyen, and Santagata (2021) noted that being able to express the idea that "decomposers return the carbon in organisms to the atmosphere, continuing the carbon cycle" was a sign of "more elaborate systems thinking" (p. 2). They concluded that students' difficulty in understanding decomposition was based on their inability to identify invisible causes and effects that are distant in time and space, such as the activity of microorganisms.

In their work, Mohan et al. (2009) have realized that a notable limitation for students is that they cannot consistently follow carbon through key processes, nor can they fluidly move through the hierarchy of systems to explain large-scale change using atomic-molecular accounts, both of which are essential for making sense of environmental issues involving global carbon cycling. Düsing et al. (2019) described the potential problems that can arise if students do not understand the role of CO_2 in photosynthesis, showing that students might "switch atoms" shifting their focus from carbon atoms to oxygen molecules rather than consistently tracing the movement of carbon atoms in carbon compounds – even when specifically instructed to do so.

Energy flow and matter cycling constitute one of the ideal topics that demonstrate the hierarchical and complex nature of the living world. At the level of organisms, energy flow and matter cycling can be depicted in the ecological conceptions of the food chain and its three main participants (producers, consumers, and decomposers) (Lin & Hu, 2003). Re-entrant causality involves recognizing feedback loops and simple cyclic patterns such as in the process of decomposition. Decomposition involves the process of matter recycling and the related understanding that matter is conserved (Grotzer & Bell Basca, 2003). And yet, very few students understand the concept of decay as organic matter turning into mineral matter (Hogan & Fisherkeller, 1996).

Recently, Asshoff, et al. (2020) demonstrated that after explicit teaching using Jigsaw cooperative instruction of carbon flows and related concepts, grade 12 students were able to better identify flows as well as related concepts, resulting in a better ability to interrelate the different levels of biological organization within the carbon cycle. Moreover, they found that students switched atoms less often when explaining carbon flows and were more proficient in naming the correct state of carbon (organic or inorganic). The findings of Gnidovec et al. (2020) research also speaks in favor of explicit instruction suggested by Hmelo-Silver et al. (2007).

In order to explain how the students in our study developed the ecological system thinking skills, it is necessary to analyze their learning environment – the LTER environment. There are three main characteristics of the learning environment that we assume could have significantly influenced the learning process and the development of ecological system thinking in students. First of these is the availability of the LTER station itself as a physical inquiry space. During the field trips the students collected data (biotic and abiotic components), conducted the plant litter experiment in the field after learning about it at school, and at the end of the experiment took the plant litter to the lab and analyzed the results and worked with the station scientists as scientists. Those activities enabled the students to contrast a wide variety of processes in the ecosystem and to understand its comprehensive components. The second influence is the LTER environment's use as a platform for data sharing and interaction between students. The students compared their data with those of students from other schools, and with data collected in previous years. This way they could observe the changes in the ecosystem over the years and gain a better understanding of the importance of long-term data collection. In addition, they analyzed a long-term database that was collected in an LTER station in the USA. This activity emphasized the importance of the long-term study, in which they observed trends and changes in the ecosystem after analyzing the data. The third influence is the use of a dual environment – the LTER site and a school site. During one year of study, the students learned in two different environments, documented their findings in each environment and compared them. This allowed the students to observe the changes that took place in each environment throughout the year in two ways: (1) The seasonal change in each ecosystem (emphasizing the temporal dimension); (2) the differences between the two ecosystems (emphasizing the spatial dimension). Moreover, the main experiment that the students performed (the plant litter experiment) highlighted the temporal dimension by exposing the students to various rates of plant litter decomposition.

In conclusion, this study emphasizes the important role of combining formal learning with the LTER environment, taking advantage of the LTER approach. Its goal was to engage the students with the complexity of the ecosystem and encourage them to develop ecological system thinking. This learning environment needed to include access to a natural ecosystem, and to the work of ‘real’ scientists and labs. The use of an authentic environment, which offers learners direct experience with concrete natural phenomena and materials in a real, authentic scientific context, allows students to draw upon that experience in order to construct and integrate their knowledge of abstract concepts. Our research thus shows that combining formal learning with an approach that provides students with a conceptual framework like LTER enables them to reach a high level of understanding of system complexity and develop ecological system thinking.

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Chapter 3

Involving Teachers in the Design Process of a Teaching and Learning Trajectory to Foster Students' Systems Thinking

Melde G. R. Gilissen, Marie-Christine P. J. Knippels, and Wouter R. van Joolingen

3.1 Introduction

Systems thinking is important in science education to help students make sense of complexity in (biological) systems (Verhoeff et al., 2018). Researchers agree that this higher-order thinking skill can assist students to create a more coherent understanding of biology by seeing the universal principles that apply to biological systems at different biological levels of organization (Hmelo-Silver et al., 2007; Knippels & Waarlo, 2018; Raved & Yarden, 2014; Verhoeff et al., 2008). Nowadays, many curricula include systems thinking (American Association for the Advancement of Science, 1993; Yoon et al., 2018). For example, the American Next Generation Science Standards (NGSS) include the crosscutting concept 'systems and system models' which focuses on defining systems, specifying their boundaries and using models (NRC, 2012). In the Netherlands, systems thinking has been part of the end terms for secondary biology education since 2010 (Boersma et al., 2010). It is described as '*the ability to differentiate between different levels of biological organization, elaborate relationships within and between different levels of biological organization and explain how biological units maintain and develop themselves on different levels of biological organization*' (Boersma et al., 2010, p. 33).

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3.1.1 Definitions of Systems Thinking

While systems thinking has been part of many curricula for some time now, multiple definitions of systems thinking can be found in the science education literature. Ben Zvi Assaraf and Orion (2005) use the Systems Thinking Hierarchical (STH) model to describe the skills systems thinking includes, that is the ability to: (1) identify the system components and processes; (2) identify relationships between separate components and processes; (3) understand the cyclic nature of systems and organize components and place them within a network of relationships and make generalizations; (4) understand the hidden components of the system and the system evolution in time (prediction and retrospection). The National Research Council (NRC, 2012, pp. 63–64) defines systems thinking as '*the ability to understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a 'big picture' perspective on work. It includes judgment and decision-making; system analysis; and systems evaluation as well as abstract reasoning about how the different elements of a work process interact.*' Hmelo-Silver et al. (2017) describe systems thinking in terms of the Components-Mechanisms-Phenomena (CMP) conceptual representation. This representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon.

According to Boersma et al. (2011), differences in the definitions of systems thinking can be attributed to the implicit or explicit reference to three systems theories that systems thinking originates from, that is General Systems Theory (GST), Cybernetics and Dynamical Systems Theories (DST). Each systems theory has its own focus and corresponding systems key concepts. GST focuses on the hierarchical structure of open systems and the key concepts are: identity, system boundary, level of biological organization, components and in- and output (Von Bertalanffy, 1968). Cybernetics focuses on self-regulating networks and the key concepts are feedback, self-regulation and equilibrium (Wiener, 1948). DST focuses on the self-organizing component of biological systems and the key concepts are self-organization, emergence, nonlinearity and equilibrium states (Prigogine & Stengers, 1984; Thelen & Smith, 1994). The results of the study of Boersma et al. (2011) showed that most science education studies focused on only some systems concepts in their definition, while they and Verhoeff et al. (2018) recommend to focus on the systems concepts of all three systems theories. The systems concepts can be used as a perspective to explore and analyze complex biological phenomena as biological systems and make predictions about future behavior of a system.

In a previous study (Gilissen et al., 2020a), we investigated how Dutch upper-secondary biology teachers (n = 8) and teacher educators (n = 9) define systems thinking and how they pay attention to systems thinking in their teaching practice. We studied how their definitions and teaching relate to the three systems theories (GST, Cybernetics and DST) and the perspective of current experts, that is systems biologists (n = 7). The following five systems thinking aspects were extracted from the conducted interviews and implicitly refer to one or more systems theories (Table 3.1):

Table 3.1 Overview of the different systems thinking aspects that were extracted from the interviews and related to one or more systems theories, that is General Systems Theory (GST), Cybernetics (C) and Dynamical Systems Theories (DST)

	Systems theories			Indicated aspect as important	
Systems thinking aspects	GST	C	DST	Teacher educators	Teachers
1. Identify the system	x			5/9	7/7
2. Input and output	x	x		8/9	7/7
3. Emergence	x		x	9/9	6/7
4. Development			x	8/9	4/7
5. Modelling	x	x	x	8/9	5/7

This table also gives an overview of the number of participants who indicated a specific aspect as important in the questionnaire. This table is based on Table 2 and 3 of Gilissen et al. (2020a)

1. *Identify the system:* Biological entities can be seen as systems: they can be distinguished from their environment with a boundary and they consist of different interacting components.
2. *Input and output:* Biological systems are open systems; they interact with their environment. Matter, energy and/or information enter the system (input), then the system itself can be seen as a black box where all sorts of processes take place and after that, matter, energy and/or information comes out (output). Dynamic behaviour arises when the input and output of a system changes over time. Moreover, systems are self-regulating. Some of the system components form a control loop. Negative feedback loops tend to reduce disturbances, for example, change in input and positive feedback loops increase the effect of a disturbance in a system. Systems at the level of the cell and the organism converge to a steady state with the aid of negative feedback loops, which is called homeostasis.
3. *Emergence:* The interactions between the components of a (sub)system can lead to appearing of new qualities at a higher organizational level. This phenomenon is called emergence.
4. *Development:* A system develops over time, for example, in terms of developmental biology (how does an individual develop during his life) or in terms of evolution.
5. *Modelling:* Biological systems can be visualized in a quantitative computational or qualitative model to study the system of interest more in detail, for example, to make predictions about the systems behaviour.

All systems biologists indicated the importance of the five systems thinking aspects related to the three systems theories in the questionnaire, which is in line with Boersma et al. (2011) and Verhoeff et al. (2018) who argue that systems thinking comprises the systems concepts of all three systems theories. The teacher educators indicated most of the aspects that are included in the three systems theories as important, while the teachers mostly emphasized the systems concepts of the GST and Cybernetics (Table 3.1). Thus, it seems that the perspectives of teachers and educators are mostly in line with the experts and the systems theories. Despite the teachers and educators emphasizing the importance of systems thinking for biology education, the results showed that systems thinking could receive more attention in Dutch teaching practice. The teacher educators indicated that they paid limited attention to systems thinking in their practice because ‘there is not enough time to extensively elaborate on something complex like systems thinking’. The teachers seem to include systems thinking rarely or only implicitly in their teaching practice because they do not know how to do it. This is a pity because systems thinking can play an important role in creating a coherent overview of biology for students. Systems thinking allows for changing the focus in biology education from an overload of concepts, which are presented in the school textbooks, to a number of key concepts (that is system characteristics) which can be applied and are useful in a wide variety of biological contexts (Verhoeff, 2003). This would even make it possible to save time, because the focus is on understanding the key concepts which are needed to understand biological phenomena in general, instead of on teaching all the different chapters in the school textbooks.

3.1.2 Teaching Systems Thinking

Literature gives several recommendations regarding teaching systems thinking, but there is no ready-to-use pedagogy for teachers to implement systems thinking in biology education yet.

According to Verhoeff et al. (2018), systems thinking can be implemented in education as a metacognitive strategy to understand biology. Systems can be identified in all biological phenomena around us and share universal system characteristics. Based on the systems theoretical concepts of three systems theories described by Boersma et al. (2011) and the systems thinking aspects that are emphasized as important by current systems biologists, seven system characteristics can be identified: systems have a *boundary*, consist of different *interacting components*, have an *input and output*, are regulated by *feedback loops*, are *dynamic* and are *hierarchical* (involve different levels of biological organization) (Gilissen et al., 2020a). Moreover, an overarching characteristic can be identified, that is *emergence*. Systems have emergent properties which are new qualities that emerge from the interactions between the components of the system. For example, collaboration of different organs, for example, muscles and nerves, at the organism level leads to the emergent property of walking.

Taking a systems’ perspective to biology means an understanding of the causes of the *interactions* between the *components* among different *levels of biological organization* that result in *emergent properties*. Students have to be assisted to learn to reason across these different levels when explaining complex biological phenomena (Asshoff et al., 2019; Knippels & Waarlo, 2018). The yo-yo learning and teaching strategy focuses, among others, on the system characteristics *hierarchy* and *interactions* and can be used to foster students thinking between and within these levels (Knippels, 2002; Knippels & Waarlo, 2018). This strategy includes a guided learning dialogue starting with a central question/problem. Causal explanations can be found by moving down to lower levels of biological organization and functional explanations by moving up to higher levels (Knippels & Waarlo, 2018).

Awareness of the universal system characteristics can be helpful to understand biological systems in various contexts: the system characteristics can be used as a perspective or lens to see biology in a more coherent way (Verhoeff et al., 2018). Experts seem to make significantly more explicit references to system characteristics, i.e., apply systems language (Jacobson, 2001) and integrate more dynamic structures, behaviours and functions in their reasoning (Hmelo-Silver et al., 2007). Novices naturally seem to focus more on the perceptually available, static structures of involved subsystems. Therefore, researchers recommend stimulating students' explicit use of the system characteristics during their reasoning (Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016; Tripto et al., 2018; Westra, 2008; Verhoeff et al., 2008; Verhoeff et al., 2018). Results from the study of Tripto et al. (2016) showed that the use of explicit systems language by teachers encouraged students to make more use of systems language themselves in comparison to a control group.

The National Research Council (2012) emphasizes to teach students to make an explicit model (for example, a schematic drawing) of the system of interest in which the main system *components* and their *interactions* are made visual. A visualization of a system provides a way to understand the system under study and test hypotheses. Modelling qualitatively or quantitatively provides a way to make the invisible visible (Hmelo-Silver et al., 2007). Qualitative modelling approaches focus on representation of systems in a more abstract way showing some system characteristics (Verhoeff et al., 2008) and quantitative modelling approaches focus on the (mathematical) prediction of the system's behaviour (Wilensky & Reisman, 2006). In both modelling approaches, the focus is on identifying the system *components* ('agents') and their *interactions* ('actions'). Verhoeff et al. (2018) recommend qualitative modelling to develop an initial systems concept.

3.1.3 Focus of the Research

The overarching aim of our study is to implement systems thinking in Dutch upper-secondary biology education in a sustainable manner. To bridge the gap between research and educational practice, we involved teachers in our study as *co-designers*. The interplay between researchers, teachers and students makes it possible to go from the intended level (theory about (teaching) systems thinking brought in by the researchers), to the implemented level (design and enactment of the lessons by the teachers), to the attained level (student products and observations provide information about student learning) (Van den Akker, 2006). Another advantage of teachers as co-designers is the chance of good *implementation fidelity* (Sandoval, 2014); because the teachers participate in the design process, they know how the lesson should be taught because they are aware of the underlying principles of the lesson.

In this chapter, we focus on the contributions of teachers during the design process of a learning and teaching strategy on systems thinking and their (learning) experiences.

Lesson Study (LS) was used to design and evaluate lessons on systems thinking in collaboration with teachers. LS is an approach in which a team of teachers collaboratively designs, performs, observes and evaluates a lesson in different steps, the so-called *research lessons* (Fernandez & Yoshida, 2004; Hart et al., 2011; de Vries et al., 2016). These lessons consist of several learning and teaching activities, the so-called *key activities*. An LS team is assisted by a knowledgeable other (in our case *the researchers*) who chairs, prepares and summarizes the meetings of the LS team (Takahashi, 2014). Although, LS originally is known as a teacher professional development approach (Lewis et al., 2006), it is also used nowadays for research purposes (Bakker, 2018, p. 16). While the role of teachers as co-designers has been emphasized by several studies (Cober et al., 2015; Westbroek et al., 2019; Penuel, 2019), it seems that there are no studies that report about the contributions and learning experiences of teachers as co-designers in a research purposed LS approach. Therefore, the following research questions are addressed:

1. *What is the contribution of teachers in the design of a teaching and learning approach in the context of Lesson Study to foster students' systems thinking?*
2. *What do teachers report to have learned from their participation in a Lesson Study trajectory on teaching systems thinking?*

3.2 Method

This chapter reports about two Lesson Study (LS) cycles. Both case studies have been analysed in a qualitative way. Each LS cycle consists of various steps:

- *Design of the lesson*: determine student learning goals, corresponding key activities to achieve these goals and expected behaviour for different types of students that will be observed, the so-called *case students*;
- *Enactment of the designed lesson*: one teacher teaches the lesson, while the other team members observe specific case students to determine students' learning caused by the key activities;
- *Evaluation, improvement and re-enactment of the lesson* in a second class by another teacher. After enactment of the lessons, the observers conducted a short interview (maximum 5 min) with the case students in which they asked what the students think they have learned, what they valued in the lesson and how they think the lesson could be improved. These interviews, the observation notes of the lesson and the student materials are used as input for the evaluation meetings.

The different LS meetings and the enactment of the designed lesson give the opportunity to investigate the contributions and learning experiences of the teachers during the whole process.

3.2.1 Participants

The lessons were designed and evaluated in close collaboration with the three authors of this chapter (from now on called *researchers*) and two secondary biology teachers. The three researchers functioned as *knowledgeable other* (Takahashi, 2014) in the LS team which means that they explained the LS approach to the teachers, introduced the main recommendations from literature, chaired the meetings, worked out the lesson plans in more detail and summarized the meetings. The first researcher has 5 years of experience as a secondary biology teacher and is a colleague of the involved teachers. She was present during the whole LS trajectory, while the second and third author attended a couple of the meetings. Julia (pseudonym) is female, has a background in physiotherapy and has 8 years of experience as a secondary biology teacher. Frans (pseudonym) is male, has a background in tropical forestry and has 10 years of experience as a secondary biology teacher. The school belongs to a school community in the eastern part of the Netherlands and offers senior general secondary education and pre-university education. During the lessons and the evaluation meetings, the LS team was accompanied by an extra observer, which is the second or third author or a staff member of the school. The two lessons were performed in two senior general secondary biology education classes (n = 26, n = 29, 15–16 years old students), lasted 60 min and were performed during school year 2018–2019. For each lesson, three case-students (and three back-up students) were selected to observe in detail. The selection of students for lesson 1 was based on motivation because the teachers did not have test scores yet: case student A represents an obviously motivated and hard-working student, student B represents a quiet but hard-working student, student C represents a passive student. The selection of students for lesson 2 was based on their average scores on a regular biology test: case student A scored especially well on the insight and application questions, student B on the application questions and student C scored high on the factual questions.

3.2.2 LS Meetings

LS 1 consisted of four preparation meetings, the enactment of the first version (1α) and second version (1ß) of the lesson in classroom practice, two meetings in which the taught lessons were discussed and improved and one evaluation meeting. LS 2 consisted of two preparation meetings, the enactment of the first version (2α) and second version (2ß) of the lesson in classroom practice, two meetings in which the taught lessons were discussed and improved and one evaluation meeting. All meetings lasted between 1 and 2 hours, were audio-recorded and summarized. Design choices and challenges (decision points) were highlighted and categorized into the following emerging categories, “teachers’ knowledge of student capabilities”, “teachers’ didactical knowledge”, “teachers’ motives”, “practical concerns of the teachers”, “literature provided by the researchers” and “student observations and products” (Tables 3.2 and 3.3).

Table 3.2 Illustration of the decision points the teachers faced during the development of lesson 1

Decision point	Elucidation	Decision based on
1. Specifying the learning goal of the lesson	At the first meeting, the first researcher introduced the concept of systems thinking to the teachers including the seven system characteristics that students should be made aware of. The teachers discussed what the students exactly should learn about the system characteristics in the first lesson: Frans: "*In short, students must be able to name the seven system characteristics. Should they also be able to describe them? That is the question: to name, describe or explain.*" Julia: "*I think that it would be a nice goal if students are able to recognize and name the different system characteristics of a system after lesson 1.*" Frans: "*I am not sure if that is not too little.*" Julia: "*Description of the system characteristics should be achieved in the upcoming lessons, but for lesson 1 it seems too much.*" Frans: "*For these students formulating is very difficult, while recognizing and learning by heart is easier for them.*"	Teachers' knowledge of student capabilities
2. Way to introduce the system characteristics	The teachers decided to introduce the characteristics explicitly to students because this is recommended by the literature (Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018; Westra, 2008).	Literature provided by the researchers
	The teachers think that this group of students will experience difficulties to come up with abstract system characteristics by comparing different biological phenomena (inductive approach), so they choose a deductive approach: Julia: "*Only give the example of the cell, the topic we just taught. First introduce the seven system characteristics in the context of the cell. In follow-up lessons, other examples can be given in which students should find out whether the system characteristics can be applied. I guess that is more in line with the students' level. If I just ask them about the levels of biological organization [hierarchy], they do not know what I'm talking about. […] It would probably be better to start with a system that is more in line with their experience, a mobile phone or the school for example.*"	Teachers' knowledge of student capabilities
	The teachers discussed icons to visualize the different system characteristics. They came up with a tangram as a metaphor for a system (Fig. 3.1a). Moreover, the teachers formulated guiding questions related to each of the system characteristics (Fig. 3.1b). By answering the questions, the students can create an overview of a biological system in terms of the system characteristics. Julia: "*We have to bring the system characteristics into the classroom as a reminder for the students, but also for ourselves [teachers] so we can easily refer to the characteristics.*"	Teachers' didactical knowledge and practical concerns

3. Context in which the system characteristics are introduced	The teachers determined that the system characteristics will be introduced in the context of the school as a system, because this is a simple example and close to the experience world of the students which will possibly lead to more enthusiasm. In the second activity, the students have to apply the characteristics to the cell as a system, because "*at the moment the students are taught about this chapter so it is also more in line with the previous lessons and their prior knowledge. In addition, it immediately let the students experience this topic from a systems perspective.*"	Teachers' knowledge of student capabilities and practical concerns
4. Effectivity of the lesson	During the evaluation of lesson 1, the teachers indicated that they observed that most students were passive during key activity 1 and therefore the teachers decided to explain the system characteristics in the context of the school by themselves, so it is possible to shorten this activity from 25 to 10 min. The remaining time could be used to add an extra activity to the lesson in which students gave feedback on the answers of other students. The feedback activity did not work out as the team hypothesized. Based on the observations, it appeared that students need more specific guidance to give feedback to each other. It also seemed that students are used to there being only one right answer, which does not have to be the case when applying the system characteristics because different examples can be given for each of the characteristics, for example, the cell consists of various feedback loops.	Students observations and student products

Table 3.3 Illustration of the decision points the teachers faced during the development of lesson 2

Decision point	Elucidation	Decision based on
1. Specifying the learning goal of the lesson	The teachers concluded that students are aware of the presence of systems (in biology) and the corresponding system characteristics, but need to practice more. Frans: "*Students need to see more examples of systems to be able to get a deeper understanding of systems*." Moreover, student learning results showed that students often described the characteristics hierarchy, feedback and dynamics from their daily life perspective instead of from a systems perspective, so these characteristics should receive more attention.	Teachers' knowledge of student capabilities (based on student products of lesson 1)
2. Topic/context	Lesson 2 will be enacted in the period when the topic human blood glucose regulation (homeostasis) will be taught. This topic gives good opportunities to pay specific attention to the characteristics feedback and dynamics.	Practical concerns
3. Way to improve student understanding of the characteristics feedback and dynamics	Due to the abstract nature of these characteristics, a modelling activity is embedded, which is recommended by Hmelo-Silver et al. (2007). The teachers came up with a simulation of blood glucose regulation in a role play.	Literature provided by the researchers
4. Way to visualize student thinking	The teachers would like to get a more detailed view on student thinking; therefore, they incorporated teaching and learning activities in which students have to visualize the glucose and hormone levels in a graph and have to explain to each other what happens in the graph. In this way the teachers are able to follow the students' thoughts.	Teachers' didactical knowledge
5. Evaluation of the lesson	After lesson 2α, the team concluded that students' representations of the fluctuations of glucose were not detailed enough, due to the format of the graph on the worksheet. Therefore, they changed the format of the x-axis of the graph in lesson 2ß. Moreover, students seemed to find it difficult to explain the cause of a glucose fluctuation. Therefore, the teachers introduced four different coloured pens in lesson 2ß which represented different causes: intake of food, activity, glucagon and insulin, and which could be used by the students to explain the glucose fluctuations. The results of student products of key activity 3 suggest that most students were able to recognize and describe the characteristics feedback and dynamics in the context of glucose regulation (learning goal 1). The student products of results of key activity 5 showed that students formulated questions which show implicit or explicit references with the system characteristics and mostly related to the characteristics components and input and output (learning goal 2).	Student observations and student products

3.2.3 Designed Lessons

3.2.3.1 Lesson 1

The four different preparation meetings in the LS team led to the design of lesson 1 with the following learning goal: students are able to name, apply and describe the eight system characteristics, that is boundary, components, interactions, input output, feedback, dynamics, hierarchy and emergence. Lesson 1α consisted of three key learning and teaching activities:

1. **Introduction of the system characteristics in a teacher-student conversation in a well-known non-biological context.** After a short general explanation of the characteristics by the teacher with the aid of the tangram and guiding questions (Fig. 3.1), the students applied the system characteristics to the school as a system in a teacher-student conversation. Duration: 25 min.
2. **Application of the system characteristics to a biological context.** Students, in groups of 3 or 4, had to answer the guiding questions related to the different system characteristics in the context of the cell as a system. Duration: 20 min.
3. **Naming and describing the system characteristics.** To determine whether the students achieved the learning goal, the students had to name and describe the characteristics in their own words. Duration: 15 min.

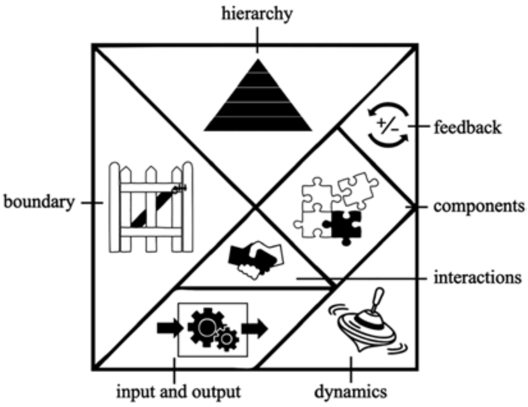
In lesson 1ß key activity 1, the teachers explained the system characteristics in the context of the school themselves (and did not ask the students to do this) which led to a shortening of this activity from 25 to 10 min. In this case, it was possible to add an extra step to activity 2. After answering the guiding questions, the student groups exchanged their answers and gave feedback on the answers of the other group.

3.2.3.2 Lesson 2

Two preparation meetings in the LS team led to the design of lesson 2 with the following learning goals: (1) Students are able to recognize and describe the system characteristics in a new biological context; (2) Students are able to formulate questions related to the system characteristics to identify and unravel an unknown system. Lesson 2α consisted of three key learning and teaching activities:

1. **Visualization of the blood glucose regulation.** In groups of 3 or 4, students had to visualize the glucose regulation of a person over one day with a seesaw in a roleplay. The case student had to draw the fluctuating glucose level in a graph. The other students had to play the role of control centre and the alpha and beta cells in the pancreas. Duration: 20 min.
2. **Explanation of the glucose fluctuations.** The students had to explain why there is an increase or decrease in the glucose level they have drawn in the graph. Duration: 10 min.

A – Tangram



B – Guiding questions

Boundary – Where can you draw a systems boundary? What belongs to the system and what belongs to the environment?

Components –Which components does the system consist of? What is the function of the individual components within the system?

Interactions –What are the relations between the different system components?

Input and output – What (energy, information or matter) enters the system? And what leaves the system?

Feedback – Which feedback loop(s) can be made with the system components?

Does the feedback lead to opposing changes within the system?→negative feedback

Does the feedback lead to enhancing changes within the system?→positive feedback

Dynamics – Which regular changes occur in the input and output? In what way do changes take place within the system over time (hours, days, months, years)?

Hierarchy – In which subsystems (and to which larger system) can you divide the system? And, to which levels of organization does these (sub)systems belong?

Emergence – Which behaviour or properties arise on the systems level caused by the interactions of the system components?

Fig. 3.1 (**a**) presents the tangram which has been used as a metaphor for the different system characteristics that are symbolized with icons. The individual pieces (with different shapes) represent specific system characteristics and together they illustrate the concept of emergence: the different pieces together form a new shape, for example, a bigger square. (**b**) presents the guiding questions related to the different system characteristics which can be used to investigate a specific biological system from a systems perspective

3. **Description of feedback and dynamics.** The students had to describe the system characteristics feedback and dynamics for the context of glucose regulation. Duration: 10 min.
4. **Recognition of dynamics.** The teacher evaluated the different causes of fluctuations in the graph and asked the students: Can you think of another (biological) system which shows dynamic behaviour? Duration: 10 min.
5. **Formulation of questions to unravel system X.** Students had to formulate questions to unravel what system X is and how it works. Duration: 10 min.

In lesson 2ß, the second enactment of the lesson, small adjustments were made to key activity 1 and 2. The format of the graph was adapted: the previous graph represented different moments during the day on the x-axis (for example, breakfast, lunch and so on) and the new graph represented time in hours of the day. Moreover, the students received four different coloured pens which represented different variables: intake of food, activity, glucagon and insulin. The students could make use of the different colours to indicate the cause of an increase or decrease of glucose in the graph.

3.2.4 Pre- and Post-interviews

Before and after the LS trajectory individual semi-structured interviews (approximately 60 min) were conducted with the two teachers. The interviews were audio-recorded and transcribed verbatim by the first researcher. The aim of the interviews was to determine teachers' reported learning progression regarding (teaching) systems thinking and their experiences of the LS trajectory. The transcripts of the pre- and post-interviews were analysed with a qualitative bottom-up approach in which the following emerging codes were used to summarize the interviews: "understanding of systems thinking", "teaching systems thinking" and "(expected) (learning) experiences of the LS trajectory" (Table 3.4).

3.3 Results

3.3.1 RQ1: Contributions of the Teachers

During the design and evaluation phase of lesson 1, the teachers encountered four main *decision points*: specifying the learning goal of the lesson, the way to introduce the system characteristics, the context in which the system characteristics can be introduced and the effectivity of the lesson (Table 3.2). Teachers used their knowledge of student capabilities to align the learning goal of the lesson to students' initial knowledge situation and to determine possible difficulties to achieve the student learning goal. Teachers used their didactical knowledge to think of a

Table 3.4 Reported learning experiences of the teachers related to (teaching) systems thinking the LS trajectory

Teacher	Pre-interview	Post-interview
Understanding of systems thinking		
Julia	Did not know about systems thinking. She saw systems thinking as the ability to see coherence between different systems: "*It is a skill. When students are trying to answer a question, they stay mostly within one system, but they have to learn that different (sub)systems are working together and they need to involve these systems to answer the question. See the bigger picture.*"	Systems thinking has made her think differently about biology: *"I myself gained more insight into systems thinking and also see how this could help the students to think about biology." […] If I approach this from a systems thinking perspective, what is the boundary and what is the input and output, I try to put myself in the student perspective."*
Frans	Knew already about systems thinking from his background in tropical forestry. He described systems thinking as: "*The awareness of systems and their collaboration and how they are organized. The emergent properties are the result of the organization of such a system. […] Each system is born, develops and dies and you find this on each level of biological organization.*"	In retrospection, he thinks that more coherence can be created between the system characteristics. Feedback for example, is already an example of an interaction. The interactions between different components can be a feedback loop. There is also a relation between the boundary and the input and output. The boundary is the place where selection of the input and output takes place.
Teaching systems thinking		
Julia	In her daily classroom practice she paid attention to concept mapping to create conditions for students to learn to connect various systems to see the bigger whole and she paid attention to the different levels of biological organization. She does not use the term 'system'.	Indicated that she thought beforehand it would be easier that students were familiar with the system characteristics. "*For myself, it [the system characteristics] makes so much sense now, so I expected the students to be able to think about them in the same way, but for students it appears less logical and normal.*" She thinks it would be better to introduce the system characteristics already at the start of lower secondary biology education and teach students to look at biology from a systems perspective. Moreover, she experienced students first need to see various examples of systems in biology to which the different characteristics can be applied. She indicates a future LS trajectory could focus on developing a way to let students experience more the utility of the characteristics to understand biology. In her regular lessons she now always tries to pay attention to the system characteristics, for example by asking students which subsystems are involved in a specific question, or what the input and output are.

Frans	In his daily classroom practice he paid attention to the hierarchy of biological systems, the relation between different subsystems, the concept of emergence and the visualization of biological phenomena.	Indicated that he learned that students found it difficult to recognize the system characteristics. He thinks this is due to the abstract nature of the different system characteristics: “*Visualization of the system characteristics, just as simulating the glucose level in a role play, can make it more concrete for students*.” He experienced that visualization can improve student understanding, but also can assist them to recognize the applicability of the characteristics more easily in new contexts. In his regular lessons he now pays attention to the system characteristics by trying to motivate students to approach a question from a systems perspective, for example, Which components are involved? How are they interrelated? On which level of biological level of organization are you now reasoning?
(Expected) (learning) experiences LS trajectory		
Julia	Julia expected that involvement in LS will give her more insight into the learning progress of the students during each lesson. She thinks that this will lead to more effective lessons. Moreover, she hopes that the lessons that will be developed around systems thinking will give her enough knowledge/input to integrate it in her own regular lessons as well.	Indicated the LS trajectory as very intensive, but also very informative: “*Lesson Study stimulates to think more deeply about a lesson*.” It requires a description of the different student learning goals, the key activities to achieve these goals and expected behaviour of the different case students, which in total led to well thought out lessons. Julia: “*I have never actually looked so much in detail at a lesson*.” She indicated that she is proud of the developed lessons. She also indicated that she was a bit scared to perform the lesson “*because you know you are part of a research project, so you want to do it as we discussed it in the meetings*.” She indicated that she sometimes felt a bit passive because the first researcher worked out all the details that were discussed in the meetings which led to detailed lesson plans, but she also indicated that she felt very involved in the process.

(continued)

Table 3.4 (continued)

Teacher	Pre-interview	Post-interview
Frans	He expected that LS will give him better insights into how students learn and develop systems thinking. He would like to use this developing knowledge around the use of LS to improve his future lessons.	Frans indicated that he learned a lot from the LS trajectory. “*I did not think there are so many things you would like to discuss in more detail.*” He also indicated that he liked the enthusiasm and the involvement of the first researcher. *“It was nice to see that the expectations we had did come true.*” He emphasized the importance of communication between the members of the LS team: *“Does everyone mean the same?”* He thinks this is especially the case for key activities that have an open character, for example, which scaffolds can be given to students when they are working on the key activities. During the meetings it is important to discuss how much and what type of guidance can be given to the students. He ended the interview stating that: “*Participating in this trajectory was very fun and informative, I am glad I participated.*”

way to achieve the learning goal supported with recommendations from the literature provided by the researchers. Practical concerns also influenced the final design of the lesson, for example, connection of the lesson to the regular lessons by using the same biological topic. The teachers seemed to evaluate the lessons based on the student observations and products.

During the design and evaluation phase of lesson 2, the teachers encountered five main decision points: specifying the learning goal of the lesson, the topic/context, the way to improve student understanding of the characteristics feedback and dynamics, the way to visualize student thinking and the effectivity of the lesson (Table 3). Based on student products of lesson 1, teachers developed 'new' knowledge of student capabilities in relation to systems thinking which they used to specify the learning goal of lesson 2. The choice of the topic/context for the lesson was based on practical concerns: how does it fit in the regular lessons? The teachers designed the teaching activities with the use of input from the literature and their own didactical knowledge, and the lesson was evaluated with the use of student observations and products.

3.3.2 RQ2: Learning Experiences

Teachers' answers in the pre- and post-interviews were used to determine what they have learned about (teaching) systems thinking and how they experienced the LS trajectory (Table 3.4). Both teachers reported a more sophisticated understanding of systems thinking and biology in general. Moreover, they both indicated they did not expect it should be so difficult to foster students' systems thinking, but they also mentioned new insights and possible ways to achieve students' systems thinking in their future teaching, which new acquired knowledge of student capabilities and didactical knowledge. Based on the interviews, it seemed that the intensive LS trajectory encouraged the teachers to think more in detail about a lesson.

3.4 Conclusion

The first aim of this chapter was to give insight into teachers' contributions during the design process of two lessons to foster students' systems thinking. Analyses of the meetings of the two Lesson Study (LS) cycles (Tables 3.2 and 3.3) show that in both lessons the LS team made decisions about the same major issues, for example, specifying the learning goals, the choice of the key learning and teaching activities and the determination of the effectivity of the lessons (Fig. 3.2). The learning goals of both lessons were specified with the use of teachers' knowledge of student capabilities. The choices for the various key learning and teaching activities were based on recommendations from the literature (which was provided by the researchers), teachers' didactical knowledge and practical concerns, for example, which topic is

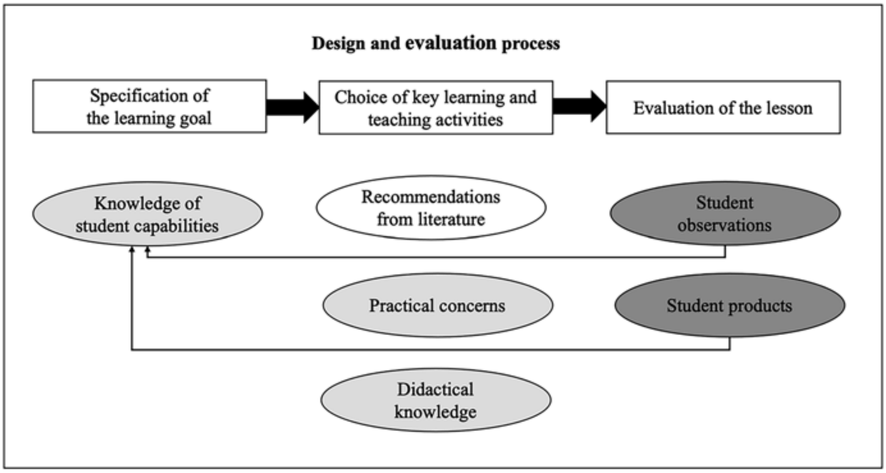


Fig. 3.2 Overview of the different steps in the design and evaluation process. The light grey circles represent the input from the teachers, the white circle the input from literature (provided by the researchers) and the dark grey circles are output of the lessons which gave input to the team to evaluate the effectivity of the lessons

now taught in the regular lessons and how could this be combined in a lesson focused on systems thinking. The evaluation of the lessons, in terms of student learning, was performed with the aid of student products and the observations of the students. Overall, the contributions of the teachers seem to be in terms of their knowledge of student capabilities, didactical knowledge and practical applicability. The main advantage of the involvement of teachers is that the designed lessons are more connected to students' capabilities and daily classroom practice.

The second aim of this chapter was to give insight into the reported learning experiences of the teachers. As the teachers indicated in the post-interview, they learned a lot from the LS trajectory. This was due to the fact that a lesson is discussed in a lot of detail, which is (unfortunately due to time constraints) often not possible for their regular lessons. They indicated LS stimulates them to think more deeply about a lesson in terms of student goals, key learning and teaching activities and expected student behaviour, which led to well thought out lessons. Moreover, this trajectory gave them insight into ways to foster students' systems thinking, but also let them experience the difficulty of fostering such a higher-order thinking skill as systems thinking by students. Both teachers indicate they now have a clear idea on how they would foster students' systems thinking in their regular lessons in the future, for example, early introduction of the system characteristics (for example already in lower secondary biology education) in a well-known biological context and regular repetition of these characteristics and guiding questions in different biological contexts. The question remains how they can let students experience the value of the use of the system characteristics to understand biology in a more coherent way. Frans already suggested to use the system characteristics to solve a complex biological problem. Whether this motivates students to use a systems thinking perspective could be investigated in a future LS trajectory.

Both teachers are very positive about their participation: they learned a lot, felt engaged and are proud about the developed lessons. There are only two points that require some attention. The teachers sometimes felt insecure about their teaching actions. They did not know what to do or say when students were working on an assignment, because they were afraid of influencing the research. A similar result is found by Jansen et al. (2021), which showed that teachers can have the feeling that they have to perform well, because they would otherwise hinder the research. In future studies, it is important to talk about this possible anxiety of teachers and to think of ways to avoid it. In retrospect on our study, it would be of great importance to discuss in detail how much assistance teachers could give to individual students during the activities, for example, which scaffolds can be given. The second point is that teacher 'Julia' indicated that she sometimes felt a bit passive because the first researcher worked out all the details. The researchers opted for this in order to relieve the teachers' workload and thereby prevent their dropping out of the study. Participation in an LS trajectory is time-consuming; all meetings together took approximately 30 hours and teachers in the Netherlands already have a high workload.

LS is known as a teacher professional development approach (Lewis et al., 2006). The results show that the teachers in our study learned to think more in-depth about a lesson design, but also learned how they can implement systems thinking in their daily classroom practice, which is development of 'new' knowledge regarding student capabilities and didactical knowledge. Originally, an LS trajectory starts from questions that teachers struggle with. In this specific case study, we involved teachers to solve a question from the research team: how can we foster students' systems thinking? Fortunately, the pre-interviews showed that the teachers were motivated to participate in this study. They indicated seeing the importance of systems thinking for biology students, but also declared that they did not pay explicit attention to systems thinking in their daily classroom practice. The teachers also indicated that they were proud of the lessons they developed themselves, which shows ownership. We think that enthusiasm at the beginning and ensuring teachers' sense of ownership are important prerequisites for a successful designing process.

Overall, this case study is an example in which teachers and researchers closely collaborated on the design and evaluation of lessons to get insight into how students can be fostered to develop systems thinking. It illustrates how expertise from educational practice can be combined with expertise from educational research and so bridge the gap between education and research. The close involvement of teachers in designing an approach to systems thinking proved to be of great value in leveraging students' capability of dealing with complexity in biology.

When interpreting the conclusions of this chapter, it is important to take into account that this is a qualitative case study in which only two teachers were involved. Despite the small scale of the study, it has shown that LS can be utilised as a useful instrument to bridge the gap between theory-driven research and educational practice. With LS, teachers' knowledge of student capabilities, didactical knowledge and practical applicability can be integrated with theoretical knowledge from the educational research community, but can also lead to the construction of new theoretical knowledge. For example, the LS trajectory also led to heuristics regarding teaching systems thinking in biology education (Gilissen et al., 2020b). These heuristics will form the basis for follow-up studies in which they will be given in the hands of in- and pre-service teachers in the context of professional development activities. The main goal will be to investigate how the LS results can act as a germ for further dissemination of systems thinking in biology education by embedding the resulting heuristics into new teaching activities.

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Chapter 4
Supporting University Student Learning of Complex Systems: An Example of Teaching the Interactive Processes That Constitute Photosynthesis

Joseph Dauer, Jenny Dauer, Lyrica Lucas, Tomáš Helikar, and Tammy Long

4.1 Introduction

The expert blind spot phenomenon describes the inability of instructors to recall how they learned and developed expertise in a subject area (Nathan et al., 2001). We forget ‘why’ it was hard to learn, make assumptions about our students’ knowledge and skills, and fail to acknowledge the barriers we encountered as novice learners. Science instructors’ blind spots related to complex systems consist of two types of understanding: “what makes systems complex” and “how students learn complexity” (Jacobson & Wilensky, 2006; Nathan et al., 2001). The former has been debated in biology for decades (or longer), while the latter is profoundly complicated. We suggest that in the context of teaching complex biological systems at the college level, experts’ knowledge of systems developed both implicitly and explicitly through years of disciplinary training. However, as university instructors, Ph.D. scientists rarely receive formal pedagogical training that would make them aware of the necessity to help students bridge gaps in their conceptual knowledge. Together, these factors influence instructors’ blind spots in creating opportunities for students to learn what makes systems complex. By virtue of the uneven training, understanding complexity becomes automatic in their disciplinary practice, but requires effort to recognize and address in teaching practice.

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In this paper, we propose instructional design elements that teachers may use to develop instruction that purposefully supports students' understanding of complexity. We describe student reasoning about photosynthesis during a modeling activity as a manifestation of our thinking that: (1) complexity is inherent to biological systems and we must therefore consider it when designing instruction to support biology learning, (2) systems thinking is a skill set that enables reasoning with biological complexity, and (3) modeling is simultaneously a tool that fosters reasoning about complex systems for students and an outcome that makes students' reasoning visible to instructors. This chapter will describe why photosynthesis is a complex system, how students vary in their understanding of interactive processes within photosynthesis, and how computational modeling of dynamic processes supports sensemaking in this system.

4.1.1 What Makes Biological Systems Complex?

While experts are likely to be acquainted with complexity in the systems of the discipline they teach, they are unlikely to have given much thought as to why the system is complex and how they personally gained an understanding of the system. As a result, they will likely repeat the same learning experience for their students without addressing the challenges associated with it (that is, perpetuating the blind spot). To support students in their conceptual change, higher education instructors must clearly understand the ontology of a system's complexity in the same way they understand the ontology of complexity within their disciplinary research.

Emergent and dynamic processes are fundamental to life and arise from the integration of processes ranging from molecular to ecosystem levels. Recent innovations in life sciences research (for example, high-throughput technologies) have resulted in the generation of tremendous amounts of data. These innovations have also led to the identification of complex, nonlinear network systems that underlie biological phenomena. These network systems span multiple layers of biological organization, ranging from molecular to ecosystem levels. Computational and systems modeling has become an integral part of life sciences research to deal with complexity within and between levels. Computational models enable scientists to synthesize knowledge into more concrete representations. Additionally, scientists use computational models and their simulations to better understand the system's underlying dynamic mechanisms, including emergent properties (Azeloglu & Iyengar, 2015; Helikar et al., 2008) through simulated experiments that can be performed to interrogate the dynamics of the processes involved. This inherent connection between modeling and complex life systems is important as context for biology instructors who want to support students' learning of complexity.

The connection between modeling and complexity is fundamental and inextricable. As such, one's selection of models defines the nature and extent of complexity for a given system. Across disciplines, 'complex systems' are regarded as 'complex' when their properties and outputs cannot be predicted from merely modeling the system components (Goldstone, 2006; Northrop, 2014). In contrast, simple systems are highly predictable and can be modeled mathematically with knowledge of system components. Systems become complex, however, when properties and phenomena *emerge* as a result of nonlinear and random interactions among components. Such interactions frequently transcend multiple scales of space and/or time and exhibit regulatory and feedback properties that modulate system behaviors, further characterizing a system as 'complex'.

In biology, simple systems are rare (or non-existent). For example, food chains are simple systems that exist in theory, and can enable students to reason about basic ecological interactions, such as predation or competition. A student may be asked how the introduction of a top predator affects a food chain, allowing the student to apply simple top-down reasoning that suggests one species controls the system. In reality, the system is far more complex. Population densities of the predator, as well as all other species in the system, emerge from interactions among *all* the organisms in the system. Therefore, prey density is not merely a function of predator density but a consequence of myriad other interactions with competitors, mutualists, conspecifics, and abiotic factors in its environment. These relationships are best understood using models that incorporate multiple factors to reveal adaptive behaviors and consider variation in space and time. These models would allow students to move from simple theoretical or conceptual understanding to a perspective of the multiple processes and emergent properties of a system. Computational modeling supports students in transitioning from static and siloed parts-lists to more realistic dynamic system representations. Computational modeling and simulations can also support instructors as they transition toward more active learning approaches in their classrooms. In this context, students can learn about biological processes by constructing, simulating, interpreting, and revising computational models (King et al., 2019; Lucas et al., In Review). In addition to providing a more effective way to learn about biological systems, modeling and simulation are more representative of how scientists study living organisms and provide scientific authenticity to learning (Helikar, 2020).

4.1.2 How Students Learn About Complexity

More than 30 years ago, Spiro et al. (1988) proposed cognitive flexibility theory to explain how experts have learned to reason about complex systems. The theory states that experts have learned over time to minimize their own tendencies toward reductive biases, defined as the general tendency to reduce important aspects of complexity and make them more simple than they are. Reductive tendencies are a consequence of how we learn since we initially have incomplete knowledge (Feldman, 2003). At any point in time, our understanding of any complex system is bound to involve simplifications. "Many concepts are formed by combining simpler concepts, and the meanings of complex concepts are derived in systematic ways from the meanings of their constituents" (Goodman et al., 2008). University students begin their studies with overly simplistic reasoning tendencies about complex systems (Hmelo-Silver & Pfeffer, 2004) that can lead to misconceptions which are resistant to change. Students "… may need to go through 'strong' or 'radical' conceptual change" (Jacobson & Wilensky, 2006, p. 15) as they organize and apply their new biological knowledge.

In order to articulate these reductive biases that cause cognitive difficulties related to understanding complex systems, Feltovich et al. (2004) proposed eleven dimensions of complexity that require mental effort because the learning and performance tasks associated with systems are difficult. Feltovich et al., coupled these dimensions of complexity with the reductive biases of engineering university students that inhibit their abilities to reason about complex systems. These eleven dimensions describe the inherent nature of complex systems by comparing the simple (linear, separate, and sequential processes) to the complex (non-linear, interactive, and sequential processes, for example). Because learners have a tendency toward interpreting systems using the simpler alternative, careful instruction is needed to support cognition. Two of this chapter's authors re-framed these into ten dimensions that make biological systems complex and suggested ways that biology instructors can integrate these ideas into higher education biology instruction (Dauer & Dauer, 2016). This chapter applies understanding of student learning about complexity taken from Spiro et al.' (1988) cognitive flexibility theory and Feltovich et al.' (2004) eleven dimensions of complexity and applies them to a specific context (photosynthesis). We report on an implementation focused on improving student reasoning of a single dimension of complexity – interactive processes and to propose general ideas and frameworks for how instructors could make explicit decisions about how to reduce complexity in order to teach a particular concept or principle.

4.1.3 How Instruction Can Support Student Learning of Complex Systems

In Spiro et al.'s (1988) Cognitive Flexibility theory, the authors proposed general themes on how to minimize reductionist tendencies that mirror strategies used by individuals with advanced knowledge. These themes we find to be useful in thinking about how biology instruction can be shaped to help students engage in conceptual change that would move them toward a more expert understanding of complex systems. Below we reframe these themes in the context of student learning:

- **Avoiding oversimplification.** To an expert, a complex system can be easily simplified, given they are aware of how the system works. While this is a necessary step for teaching students, it must be done purposefully. Oversimplification can inhibit students' understanding by promoting misconceptions (Feltovich et al., 2004; Spiro et al., 1988) and memorization instead of understanding (Jimenez-Aleixandre et al., 2000) that can limit students' abilities to generalize principles

of the simplified system. One approach to avoid oversimplification is to relate the study system to the biological levels of organization above and below (Hmelo-Silver et al., 2007; Knippels & Waarlo, 2018). Another approach is to limit the dimensions of complexity such that students can identify what it is about the system that is complex and therefore analogous to another system.
- **Providing multiple representations** allows students to revisit the same "sites" in crisscrossing directions across a "conceptual landscape" (Spiro et al., 1988). By repeating the presentation of the same concepts in new contexts, additional multifaceted aspects are brought out, allowing students to more nimbly navigate the system and identify gaps in a representation of a system (Ainsworth, 1999). Multiple representations also allow the student to constrain their interpretation and construct deeper understanding (Ainsworth, 1999), so long as instructors are conscious of the potential to overwhelm student reasoning.
- **Relating the complexity to a clear example context.** The context that is used to illustrate general principles must be carefully chosen because each example case will have variability and different ways of relating to the general principles being taught. When multiple examples are used, the rationale for the order of each example should be deliberate to build key and nuanced understanding. Additionally, for students, establishing a purpose for the learning and importance of the context to their experiences will allow motivation and interest that fosters knowledge construction. Careful attention should be paid to students' prior knowledge, which can help and hinder learning (Lobato, 2012). The context plays an important role in forming a mental model for the complex system while the instructor sets the bounds of the complexity that are necessary for the context.
- **De-compartmentalizing concepts by explicitly connecting them across a curriculum**. Students can't know the system holistically all at once. However, if instructors teach a complex system only as compartmentalized into separate "chapters," students will miss the connections across concepts. Educators can help students negotiate a complex conceptual system by explicitly creating more relationships among components within a system. There must be classroom time spent on connecting concepts to bolster students' ability to understand biology, not as a series of disconnected concepts but to apply biology as a lens for understanding phenomena.

We demonstrate how these themes could be applied in learning exercises related to photosynthesis in the context of a university introductory biology classroom.

4.1.4 Teaching and Learning the Complexity of Photosynthesis

Photosynthesis is a complex biological system that evolved over millions of years and acted as an essential process for bacteria, algae, and plants (Antal et al., 2013) to obtain inorganic carbon from the atmosphere and convert into usable organic forms. Photosynthesis can be written in a simple formula:

$$CO_2 + H_2O \rightarrow CH_2O + O_2 \left(\text{in the presence of sunlight}\right)$$

that belies the complexity of the system. By the end of primary school, students will have likely characterized photosynthesis as taking in carbon dioxide, forming sugar, and releasing oxygen. By the end of secondary school, students will likely have added conceptual understanding of energy to this equation, may be familiar with different cycles within photosynthesis, and coupled photosynthesis with cellular respiration (NGSS Lead States, 2013). In universities, photosynthesis is commonly included as a topic within the cell and molecular portion of introductory biology. It may be revisited in more advanced courses in biochemistry, plant physiology (related to matter and energy flow), or ecology (related to ecosystem primary production).

In higher education contexts, students learn about the transformation of molecules within the light-dependent reactions (LDR) and the Calvin cycle (CC), leading to the production of O_2 and fixed carbon molecules. Textbook representations typically show the LDR and CC as separate processes connected with energy-rich molecules of ATP and NADPH and the energy-depleted molecules of ADP + inorganic phosphate and NADP+. Instructional materials tend to show these processes as compartmentalized and not integrated with physiological processes like gas exchange, transport, cellular respiration, or biosynthesis. In one commonly used text, an image of a leaf appears only on the introductory page of an entire chapter on photosynthesis. The blind spot assumption is that students learn the interactivity of the LDR and CC processes and connection with other physiological processes, through these static diagrams (Fig. 4.1).

In form and function and ecology, most or all molecular interactions are black-boxed (that is, compartmentalized into a box called photosynthesis) based on the assumption that students stored knowledge of the cellular and molecular processes and are prepared to build on the foundational knowledge. The pedagogical focus shifts to plant physiology like transport, biosynthesis, and respiration. University students struggle to notice the interconnections between other simultaneous plant processes such as photosynthesis and cellular respiration and struggle to see how biochemical processes are nested within larger organismal and ecological systems (Akçay, 2017; Brown & Schwartz, 2009). In our courses, students can confidently recite the photosynthesis equation but are far less likely to accurately explain how the photosynthesis system interacts with other plant processes. In particular, the oversimplification of photosynthesis results in an inability to reason about effects of input variation (for example, insufficient water, reduced CO_2 from closed stomata) to determine how a plant survives and grows in its environment.

There is a paucity of information about students' misunderstandings of photosynthesis in terms of the interaction between CC and LDR. Some science education researchers have documented that difficult concepts related to LDR and CC include the idea of energy transfer, the role of chemical energy produced in LDR, and the role of water or the idea of energy storage (Hazel & Prosser, 1994). There is a misconception prevalent among secondary and post-secondary students that the "dark

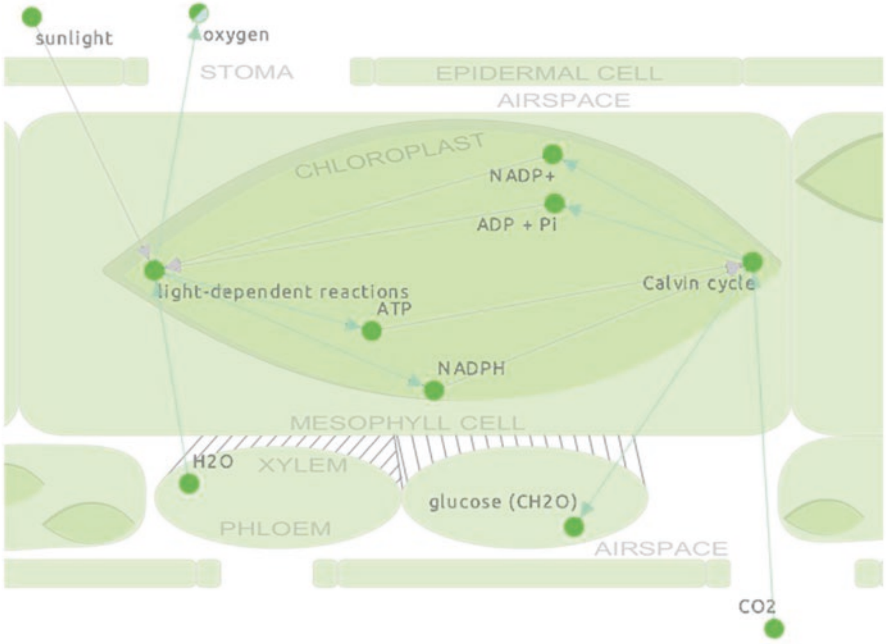


Fig. 4.1 Screen shot of photosynthesis model used by students to learn interactive Light-dependent reactions and Calvin cycles

reactions" of the CC occur in the dark (Lonergan, 2000; Storey, 1989). This idea may have arisen due to historic holdovers that called the CC "dark reactions." Reductive tendencies also favor the notion that LDR happens in the light, and the CC, therefore, must occur in the dark. However, in actuality, these two processes are connected in more nuanced ways. Because LDR yields ATP and NADPH for the creation of sugars in subsequent CC reactions, photosynthesis requires these processes to operate interactively. Additionally, the CC actually operates maximally in the light, through the direct and indirect activation of enzymes that are regulated by the presence of light (Lonergan, 2000; Peretó, 1996).

We set out to develop and implement a computational modeling activity to specifically address students' reductive tendency of treating processes as separate instead of interactive within the context of photosynthesis. To achieve this goal, we leaned on the themes from Spiro's Cognitive Flexibility Theory to create a particular set of instructional design elements that are articulated in the context of the photosynthesis activity in Table 4.1.

We addressed a single dimension of complexity – interactive processes, in one activity to support student learning of a complex phenomenon (Table 4.2). We designed this activity to overcome students' tendency to reduce interactive processes to their separate, disconnected processes. To assist in knowledge construction, we built upon Cognitive Flexibility theory through these aspects (Spiro et al.,

Table 4.1 Design elements of the photosynthesis modeling activity that emerge from application of the Cognitive flexibility theory

Cognitive flexibility theory (Spiro et al., 1988)	Photosynthesis computational modeling lesson
Avoiding oversimplification Establishing a clear example context	Set the system's boundaries around the photosynthetic processes of LDR and CC reactions occurring within the chloroplasts of plant cells.
	Determined that the activity will focus on the complexity dimension of interactivity to address the common misconception that the Calvin Cycle's dark reactions continue in the absence of light (Lonergan, 2000; Storey, 1989).
Multiple representations	Designed a computational modeling activity that allowed students to manipulate inputs and determine how the inputs relate to the system function. Designed checkpoints to assess student understanding of key concepts centered on the interactive nature of LDR and CC reactions.
Decompartmentalizing by connecting the complexity	Focused on LDR and CC reactions at the subcellular level; however, we recognized that the inputs and outputs of these processes involve more nuanced processes at the organismal level. We considered the outputs of CC as "glucose" in order to mentally connect the molecular processes to the larger photosynthesis context, although we recognize that the direct result of CC is two glyceraldehyde-3-phosphate molecules (3-carbon) precursors to glucose. We focused on the interactive nature of LDR and CC while keeping in mind that these processes also occur simultaneously.
	Guided students to think like a systems biologist by experiencing how computational models can inform inquiry into the function of photosynthesis. Connected molecular processes to the organismal process of an individual plant survival during drought.

Table 4.2 Target dimension of complexity addressed in the photosynthesis modeling activity

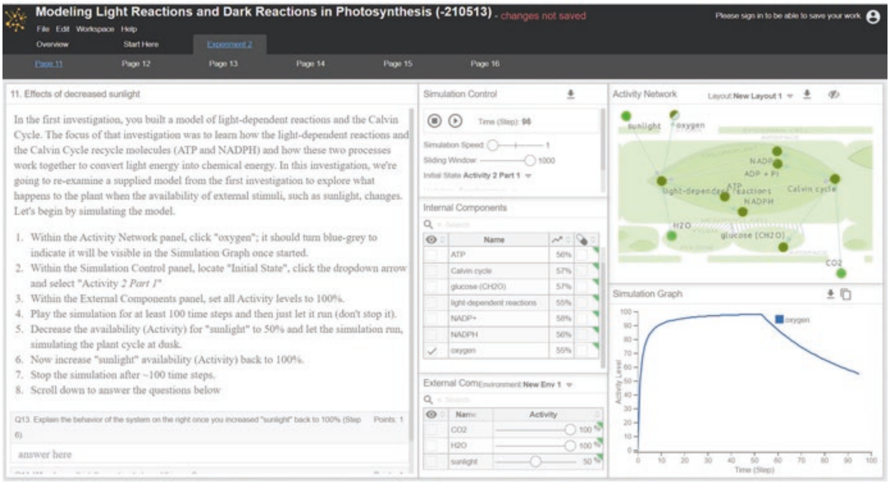
	Reductive tendency that affects learners' abilities to reason about a complex biological system	Reasoning about complex systems
Generally	Separable: processes occur in isolation.	Interactive: Processes have strong interactions and are interdependent.
Specific to this context	Outputs of LDR and CC can be determined without considering the other cycle.	Outputs of the LDR and CC can only be explained after reasoning about energy-rich and energy-depleted molecules recycled between them.

1988). We purposefully developed the activity to teach the interactive processes separately (simple) then connected (but not too simple), relating them to organismal level processes, relying on multiple types of representations, all centered on photosynthesis phenomena. The purpose of this chapter is to describe student reasoning related to a complex system during an activity designed to address students' reductive tendency, to lend perspective for instructors working to integrate complex systems into their undergraduate classrooms.

4.2 Classroom Context and Methods

The photosynthesis computational modeling activity was implemented in an introductory life science course for biology majors as a week-long assignment to be completed at home. Fifty-four students were instructed to use a simulation freely available in the Cell Collective platform (http://cellcollective.org) to perform investigations on a plant's oxygen and glucose production with varying availability of sunlight, water, and carbon dioxide. The activity included 20 tasks that required students to separately discover the interactivity of the LDR and CC, manipulate computational models of the interaction between LDR and CC, interpret the resulting simulation graph, and apply knowledge of photosynthesis across levels of organization in context-rich problems focusing on observed plant physiology and conditions in their environment (Fig. 4.2). Thirty-eight (*n* = 38) students consented to participate in research, and their responses to the computational modeling tasks were downloaded from the Cell Collective software. This was an assignment and we assume many students were working independently although some students mentioned meeting with peers to work together. All students submitted their individual responses.

In the activity, students first familiarize themselves with the model and software. All students in this course had previously completed an introductory biology course that included three Cell Collective modeling activities and therefore the software



11. Effects of decreased sunlight

In the first investigation, you built a model of light-dependent reactions and the Calvin Cycle. The focus of that investigation was to learn how the light-dependent reactions and the Calvin Cycle recycle molecules (ATP and NADPH) and how these two processes work together to convert light energy into chemical energy. In this investigation, we're going to re-examine a supplied model from the first investigation to explore what happens to the plant when the availability of external stimuli, such as sunlight, changes. Let's begin by simulating the model.

1. Within the Activity Network panel, click "oxygen"; it should turn blue-grey to indicate it will be visible in the Simulation Graph once started.
2. Within the Simulation Control panel, locate "Initial State", click the dropdown arrow and select "Activity *2 Part 1*"
3. Within the External Components panel, set all Activity levels to 100%.
4. Play the simulation for at least 100 time steps and then just let it run (don't stop it).
5. Decrease the availability (Activity) for "sunlight" to 50% and let the simulation run, simulating the plant cycle at dusk.
6. Now increase "sunlight" availability (Activity) back to 100%.
7. Stop the simulation after ~100 time steps.
8. Scroll down to answer the questions below

Q13. Explain the behavior of the system on the right once you increased "sunlight" back to 100% (Step 6) Points: 1

answer here

	Name		
	ATP	56%	
	Calvin cycle	57%	
	glucose (CH2O)	57%	
	light dependent reactions	55%	
	NADP+	58%	
	NADPH	56%	
✓	oxygen	55%	

	Name	Activity
	CO2	100 %
	H2O	100 %
	sunlight	50 %

Fig. 4.2 LDR simulation panel that shows the student prompts, simulation controls, and the simulation output

and general approach to the activity were well understood. Students' baseline knowledge of cellular-level photosynthesis processes was assessed (Table 4.3, first example prompt) and allowed students to describe the two key cycles in photosynthesis. No feedback was provided on this, or any of the prompts during the assignment.

The computational model's use was intended to amplify the interactivity of the LDR and CC and reinforce the key concept that levels of chemical and energy inputs determine functional outcomes like the production of oxygen and sugar molecules. Student learning was scaffolded by asking how each output was affected by the availability of the inputs – water, carbon dioxide, and sunlight. Because of the cycles' interactivity, lack of input availability (for example, stomata were closed and carbon dioxide was unavailable) inhibited one of the cycles (Table 4.3, second example prompt). While students could easily observe outputs (for example, that oxygen or sugar was not generated, see Fig. 4.2 Simulation Graph), the intention was to prompt student mechanistic explanations about why these molecules were not generated and how the photosynthesis system has stopped.

Lastly, we wanted to situate this complex interactive system within the context of the whole plant. Students completed a question designed to apply their knowledge to water and carbon molecule transport and biosynthesis (Table 4.3, third example prompt). This prompt relied less on computational model outcomes and more on reasoning about the system and applying their knowledge at the organismal level. These concepts also allowed the instructor to segue from this activity to teaching plant physiology and growth.

We used a thematic analysis to examine the content of student responses for each prompt by starting with concept-driven categories derived from the target

Table 4.3 Example prompts from the photosynthesis modeling activity

Computational modeling activity	Example prompts (3 out of 20 tasks)
Separately explore LDR and CC	Describe the energy molecules that are generated by the light-dependent reactions and the energy molecules that are generated by the Calvin Cycle.
Manipulate computational models of the interaction between LDR and CC and interpret the resulting simulation graph	What happens to glucose production in the Simulation Graph when you stop the simulation, keep "CO2" availability (Activity) at 100%, and set "H2O" and "Sunlight" to "0%" availability, and then restart the simulation? NOTE: you must stop the simulation then restart it in order to get the correct results.
Apply knowledge of photosynthesis across levels of organization in context-rich problems focusing on observed plant properties and conditions in their environment.	Your friend gave you her green philodendron (a common house plant) to take care of while she is on vacation, but your roommate's cat keeps knocking it over, and so your roommate insists you keep it in your bedroom. However, your bedroom doesn't have a window, and there is no sunlight during the day. Explain, in terms of the light-dependent reactions and Calvin cycle, what would happen to glucose production in the plant if you kept it in your dark bedroom for a week. [Hint: use your model and understanding of the inputs and outputs of these photosynthetic processes]

dimension of complexity addressed in the activity. The main categories – separable and interactive – are described in Table 4.2. Although student responses varied in length, each response was considered a unit of analysis. Some responses could not be categorized and were left unmarked, suggesting not enough evidence to show reductive or systems thinking. We compiled text passages corresponding to the main categories and determined subcategories that pertained to manifestations of separable and interactive interpretation of photosynthetic activities. For example, in the LDR exploration, a subcategory determined for the interactive code is the observation that oxygen production went to zero with a lag.

4.3 Results from Implementation

The initial task for students was to describe the energy molecules generated by LDR and CC. Although simple, this task was meant to prepare students to focus on system structures that they should observe when specific conditions are implemented in the simulation of photosynthesis. Students' responses revealed mental models that are more indicative of a separable view of LDR and CC. Although most students were able to identify ATP, NADPH, ADP+Pi, NADP+, they did not describe that these molecules are recycled between LDR and CC, "The molecules generated by light dependent reactions are made from H_2O and release oxygen *while* the molecules from the Calvin Cycle are made from glucose and release CO_2 (Student 6)." Thus, at the start of the activity, students' mental models of photosynthesis in terms of the processes of LDR and CC lacked details on how these cycles interacted in order to function.

In the LDR exploration, students first simulated oxygen production with all necessary inputs (sunlight, water, carbon dioxide), generating the result that oxygen production was maximized. Then students were asked to reduce water and carbon dioxide to 0% availability, resulting in no production of oxygen. The majority of the students (69%) determined that the lack of water and carbon dioxide would result in a decline in oxygen production, saying, "oxygen production declines over time before eventually stopping completely (Student 19)." Then students were asked to increase water to 100% available while keeping carbon dioxide at 0% availability, simulating what may occur if stomata were closed to gas exchange. Here, most students correctly observed that oxygen production went to zero, despite availability of water, "The oxygen production still dropped significantly. The graphs look relatively the same (Student 17)." Carbon dioxide is an input to CC and is not directly necessary for LDR to function and produce oxygen. However, it is indirectly necessary to produce oxygen. Interestingly, seven students made a key observation in timing: the oxygen production went to zero, with a lag (see Fig. 4.2). These students showed emerging reasoning by recognizing the lag caused by the interactivity between the LDR and CC.

> Oxygen production drops to zero, but this time more slowly (Student 25).
> Eventually everything's activity level drops down to 0%, but it takes a few more time steps and doesn't happen all at once. First, the Calvin Cycle drops to 0%, then glucose's activity level falls, then light-dependent reactions and, finally, oxygen (Student 22).

Many students missed the nuance inherent to this prompt that would have pointed them towards the mechanism behind the observation that oxygen production is inhibited indirectly.

In the CC exploration, students first simulated glucose production with all necessary inputs (sunlight, water, carbon dioxide), generating the result where glucose production was maximized. Students were then asked to keep carbon dioxide present and move sunlight and water to 0%. In this scenario, the LDR and CC processes were both stopped, LDR, because of lack of key inputs of sunlight and water and CC because of lack of energy inputs from LDR. More than half of the students (62%) determined that the lack of sunlight and water would result in a decline in glucose production despite the availability of carbon dioxide to be used in CC. "When H_2O and sunlight are not available, glucose production initially is fully active (level 100). Shortly after, however, glucose production begins to decline and become less and less produced (Student 34)." This could suggest that students were beginning to make sense of the interaction between LDR and CC, that is, understanding that the absence of sunlight and water (inputs to LDR) inhibited the generation of energy-rich molecules necessary for the processes involved in CC. Three students noticed the similarity to the LDR prompts, "Like oxygen in the previous activity, it starts out at 100% and then gradually drops to 0% before stopping completely (Student 19)." However, no students specifically mentioned the energy-rich molecules of ATP and NADH transferred from LDR to CC. Lastly, students were prompted to make carbon dioxide and sunlight present and water absent. In this scenario, the LDR was inhibited because there was a lack of matter (hydrogen) that was essential to the generation of energy-rich molecules. All of the students observed that glucose production eventually went to zero, "After a few steps the Calvin cycle activity level drops to 0, and then glucose's activity level drops to 0 (Student 22)." Unlike in the LDR exploration, no students (not even the seven students who recognized the interactivity in the LDR exploration) explicitly mentioned the interactive cycles.

As an application of their reasoning about interactive cycles, students were prompted to explain glucose production when a plant was placed in a dark room. In this scenario, students were asked to consider the matter output (glucose) when the energy input (sunlight) was removed. The prompt did include additional hints to direct student attention towards the model: "Explain, in terms of the light-dependent reactions and Calvin cycle, what would happen to glucose production in the plant if you kept it in your dark bedroom for a week. [Hint: use your model and understanding of the inputs and outputs of these photosynthetic processes]." Of the 29 students who responded to this prompt, 13 included energy-rich molecules of ATP and NADPH in their responses, and 16 did not include them. For the students who included them, there was clear evidence of reasoning about the interactivity of the cycles.

> After a week the plant would not be able to produce the glucose as the light-dependent reaction would not be started without light. Therefore, it would be unable to charge the energy-poor ADP+Pi and NADP+. Without those molecules recharged into ATP and NADPH the Calvin cycle could not use the energy from those molecules in order to produce glucose (Student 8).

Others described the mechanism generally, suggesting they were making progress towards understanding the interactivity even if they weren't able to accurately include the energy-rich and energy-depleted molecules. This may show the emergence of a more cohesive mental model that still must be strengthened for this context and transferred to other interactive processes.

> The plant would eventually die. This is because there is not sufficient sunlight available to the plant, and it is not able to go through the process of the Calvin cycle. This would then stop the production of glucose which then prohibits oxygen from being released (Student 24).

Conversely, the 16 students who excluded mention of recycling energy-rich molecules described their observations with little explanation of the mechanisms.

> The glucose production of the plant would almost cease to happen due to the fact that there is insufficient sunlight within the environment that it's in (Student 12).

Or, they presented their reasoning so generally that we were unable to determine their abilities.

> Keeping the plant in a dark room will bring production of glucose to a halt. Without sufficient sunlight, the plant will not be able to renew its resources needed for glucose production (Student 46).

These students likely retained a separable schema of photosynthesis processes, unable to reason through the cellular mechanisms that underlie their observation of reduced glucose production when sunlight was absent.

For students who were able to reason about the interactive processes in photosynthesis, the conceptually similar prompts (oxygen production when carbon dioxide was absent, glucose production with varying sunlight and water absent, glucose production in the plant without sunlight) appeared to support reasoning about the complexity inherent to photosynthesis. Responses from Student 39 highlight the change that occurred during the course of the activity in that the student's responses became more specific and correct in subsequent prompts:

First prompt: "Stays at 100" [N.B., this was incorrect]

Second prompt: "Because plants know when it is night time and when they should start the process of photosynthesis"

Third prompt: "In the light-dependent reactions when sunlight is blocked off then the production of oxygen, ATP, and NADPH stop due to lack of sunlight. In the Calvin cycle without sunlight and without the ATP and NADPH produced by the light-dependent reactions then the production of NADP+ and ADP+Pi would stop therefore stopping the production of glucose."

As these students made progress in the series of investigations, they were likely to incorporate new knowledge in their mental models that they, later on, retrieve to construct a scientific explanation. Thus, in computational modeling activities, the accuracy of their observations appear to determine the quality of their scientific explanations.

4.4 Conclusions and Implications

The activity was partially successful in helping students use mechanistic reasoning to describe the cellular mechanisms behind the production of sugar and oxygen in leaf cells. Approximately half of the students retained a tendency to consider the LDR and CC as separable processes, despite scaffolded prompts repeatedly drawing attention to the interactivity. While frustrating for us as instructional designers, it may be unsurprising given the inability of many students to develop mechanistic explanations of cellular processes (van Mil et al., 2013). For these students, the lack of formative feedback may have hindered their ability to address this dimension of complexity.

Traditional strategies for teaching biological systems rely heavily on a reductionist approach that removes elements of complexity from biological systems, including dynamics (Goldstone & Wilensky, 2008). For example, students are commonly asked to interpret static textbook figures when the biological relationships between system components are dynamic and quantitative (Penner, 2000). Through thoughtful pedagogical approaches, instructors can support student progression from tendencies to oversimplify dynamics to understanding the mechanisms that underpin the phenomena we observe (Mayes et al. 2020). As students are taught to notice what makes the system complex, instructors can focus on a limited number of dimensions, structure modeling activities to support modeling and model-based reasoning, and further the students' own reasoning about complex systems.

Students have significant prior knowledge of many complex systems from experience and exposure during primary and secondary school. While they may possess much of the necessary information, reasoning about the mechanisms for emergent phenomena is not frequently taught (van Mil et al., 2013). Hazel and Prosser (1994) and Köse (2008) found photosynthesis concepts related to the mechanisms underlying outcomes as challenging aspects for first-year university students. As higher education instructors, we often hear students say "it's too complex," suggesting that the system cannot be understood therefore they are paralyzed in their reasoning. We suggest that one anecdote is to counter-intuitively avoid oversimplification that effectively permits students to retain reductionist points of view. However, this must be done strategically. For example, it is important to deemphasize the simple equation for photosynthesis that belies the complexity of these systems. Emphasis on the photosynthesis and cellular respiration equations resulted in students thinking these processes acted sequentially instead of simultaneously and likely focused on the outputs rather than the processes (Barrass, 1984). Experts recognize that the systems are, in fact, complex and recognize that they can use modeling to support their reasoning, knowing they understand a small part of the whole.

To further elaborate on Spiro's themes, we propose five steps an instructor might take when designing the instruction of a complex system (Table 4.4). Within these design elements, the first two steps attend to avoiding oversimplification and establishing a clear example context. The third step, modeling, attends to providing students with multiple representations and de-compartmentalizing. The fourth and fifth steps attend to more explicitly asking students to decompartmentalize by drawing important connections.

Avoiding oversimplification in teaching will ensure students recognize that complex systems are indeed complex yet understandable. The activity was bounded by reasoning at the cellular level, with prompts around the inputs and outputs of cellular processes within the leaf cells. At the same time, images included stomata, xylem, and phloem, and prompts were related to inputs and outputs of the LDR and CC subsystems. The activity simplified the organismal processes of stomatal opening and closing and transport of sugar and water.

Table 4.4 Relationship between the theoretical underpinning of the activity, the instructional design of the computational modeling activity specific to photosynthesis, and the suggested steps for developing and teaching complexity in biology classes

Cognitive flexibility theory (Spiro et al., 1988)	Photosynthesis computational modeling lesson	Steps for teaching complexity
Avoiding oversimplification Establishing a clear example context	Focused on LDR and CC occurring within leaf cells	Set the boundaries of the system by selecting the context and biological level of organization (that is, the boundaries) that are most relevant to their course.
	Focused on interactive processes	Determine a limited number of complexity dimensions to address with student learning objectives
Multiple representations	Designed checkpoints around interactive processes	Determine how modeling can assess student learning
Decompartmentalizing by connecting the complexity	Addressed the inputs and outputs that directly and indirectly impact photosynthesis	Situate the complexity: hold in mind the additional ways the system is complex while making deliberate simplifications for the student and instructional materials. For example, understand additional dimensions of complexity at play, as well as how the context fits into levels of organization above and below. Make these simplifications transparent to the student when appropriate.
	Connected molecular processes to organismal processes	Provide connections to the larger, more complex system, including additional dimensions of complexity and additional levels of organization. Use inquiry to make these connections, including – how does the model and modeling practice inform an understanding of the phenomena?

Keeping the system bounded to a single level of organization affords the instructor opportunities to focus students' attention on a single dimension of complexity. While the systems are complex in many ways, this represents a chance to make incremental steps towards reasoning about complex systems. In this lesson, we focused on interactive processes between the LDR and CC for the entire activity. Repetition is an essential step in learning, although it must be balanced with the effortful application of repeated knowledge retrieval (Carpenter et al., 2020). Students repeatedly crossed the conceptual landscape of interactive processes to assist in their learning of the system dynamics.

Computational models should augment, not replace complex systems pedagogy (Smetana & Bell, 2012) and therefore cannot on their own provide a clear understanding of the phenomena. Models are simplified representations of phenomena (Seel, 2017) and focusing on a single level of organization allowed a compact model of photosynthesis that was not overly simple and not overly complex. Imagine the difficulty of scaling up this activity to consider the whole leaf in a large computational model. While experts will construct these massive models, it is unrealistic to expect students to cognitively scale this model to thousands of leaf cells with varying input levels and interactions. Clearly, our model was not overly simple, as students were able to observe the dynamics and many students were unable to accurately generate the phenomena. There is a constant balance for instructors between overly complex and possibly more realistic, yet interpretable by university students with varying backgrounds in modeling and the context.

Ben Zvi Assaraf and Orion (2005) placed student skills related to spatial and temporal variation and dynamics high on their systems thinking hierarchy. Modeling allows emphasis on dynamic processes, and this activity required making predictions and observing results in model representations (see Fig. 4.1) and activity level data figures (see Fig. 4.2). Relating the complexity to a clear example context allowed students to ground their reasoning in a concrete scenario situated within the context of the course. Linking molecular and cellular processes to other biological levels allows students to mechanistically explain biological phenomena (Knippels & Waarlo, 2018). While the activity ends with a few prompts related to stomatal responses, the activity is embedded within a course curriculum. Pedagogically, activities like this provide foundational knowledge structures that can incrementally support broader course objectives related to crossing biological levels. That is, we designed the activity around systems thinking to support biological understanding and to situate photosynthesis within the larger context of plant growth.

De-compartmentalizing concepts by explicitly connecting them across a curriculum will make reasoning about complex systems a part of being a biologist. Instructors must teach complexity in one context and create the opportunity to connect that to other contexts (Gentner, 1983; Jonassen et al., 2005; Seel, 2017). Systems biologists use the systems' models to inform their inquiries into the system's components and relationships and use the specific system to inform their use of models. Creating that approach for students requires a modeling-based inquiry course where students use modeling to guide their inquiry across the course content. We attempted to do that in this course through prompts related to organisms' physiological aspects, stomata trade-offs, and drought effects. Instead of attaching these prompts at the end of the activity, one pedagogical approach may be to sandwich this activity between content in the course. Before the activity, one can introduce transport through the plant vascular system and stomata operation at the organismal level.

Calls for reforming undergraduate biology education include consideration of the complexity of biological systems (Brewer & Smith, 2011). Others have proposed frameworks for teaching and learning about complex systems (Momsen et al., In Review, Ben Zvi Assaraf & Orion, 2010), but these principles have tended towards large-scale changes in curricular emphasis. In the context of that larger effort, this chapter proposes more detailed design elements or steps that an instructor might take to develop single activities contained within a given course. In this way, the instructor can support their student learning of complexity each class period, with an eye towards revising their overall curriculum to fit reform goals.

When challenged to consider how photosynthesis can be a complex system, university instructors have two blind spots: the ways the system is complex and the ways students can learn this complexity. In this activity, we recognize that photosynthesis is complex in more ways than just the interactive processes. However, limiting the instruction to a single dimension speaks to the second blind spot, students, and people cannot learn all the dimensions of complexity simultaneously. Attending to one or a few dimensions of complexity facilitates student attention to ways in which the system is complex and fosters development of reasoning about complex systems that can be broadly applied to other complex biological systems.

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Chapter 5
High School Students' Causal Reasoning and Molecular Mechanistic Reasoning About Gene-Environment Interplay After a Semester-Long Course in Genetics

Marcus Hammann and Sebastian Brandt

5.1 Introduction

Genetic and environmental factors influence virtually all traits, and the term gene–environment interplay refers to the fact that genetic and environmental causation are rarely separate or direct (Berg, 2016; Tabery, 2014; Rutter, 2006). Rather, most complex traits involve multiple genes, multiple environmental factors, and the complex interplay between genes and the environment at the different levels of biological organization (Kampourakis, 2017; Moore, 2015). For genetics educators, thus, it is an important aim to prepare students to deal with the complexity of gene-environment interplay and reason mechanistically about how genes and the environment contribute to the formation of traits (Duncan & Reiser, 2007; Haskel-Ittah & Yarden, 2017, 2018; Marbach-Ad & Stavy, 2000). Mechanistic reasoning about gene-environment interplay includes explaining how genes encode proteins, how proteins mediate between genes and traits, and how genes and the environment interact. The present practice of teaching genetics to high school students, however, has been criticized for failing to deliver such a complex understanding of gene-environment interplay (Jamieson & Radick, 2017). More specifically, there is evidence from multiple studies that gene-environment interplay is not adequately addressed by curricula (McElhinny et al., 2014), educational standards (Dougherty

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et al., 2011) and high school textbooks (Aivelo & Uitto, 2015; Heemann & Hammann, 2020; Hicks et al., 2014; Martínez-Gracia et al., 2006).

5.2 Background of the Study

Gene-environment interplay is a core idea of genetic literacy: "Multiple genes and multiple environmental factors interact in the development of most traits" (Boerwinkel et al., 2017). For understanding why high school students find understanding gene-environment interplay challenging, it is helpful to distinguish between causal and mechanistic reasoning. According to Russ, Scherr, Hammer & Mikeska (2008) causal reasoning is *knowing that* and mechanistic reasoning is *knowing how*. More specifically, causal reasoning is defined as the ability to describe *which* entities/causal agents are involved. Causal reasoning in genetics, thus, is the ability to describe *that* both genes and the environment are involved in the formation of traits, which is problematic for some high school students in and of itself. For example, research in high school students' causal attributions recently revealed that students expressed the view that non-genetic factors (environment and/or personal will) alone cause behavioral and psychological traits (Hammann, Heemann & Zang, 2021). Mechanistic reasoning, in contrast, goes beyond causal reasoning by including the ability to explain how genes and the environment contribute to the formation of traits. Mechanistic reasoning, thus, focuses on entities (for example, genes, gene products, different environmental factors) and activities (for example, gene expression, protein-protein interaction) (Craver & Darden, 2013; Machamer et al., 2000). Mechanistic reasoning, essentially, builds on causal reasoning, but it is cognitively more demanding. High school students' non-mechanistic conceptions (for example, genes are traits) negatively affect their ability to learn the mechanisms underlying genetic phenomena (Haskel-Ittah & Yarden, 2018). Furthermore, for many students the relationship between genes and traits is a black box even though they have been taught about the mechanisms connecting genes and traits (for example, transcription, translation).

Learning progressions (LPs) in genetics lead from a causal (and phenotypic) understanding that genes and the environment contribute to traits to a more advanced mechanistic (and molecular) understanding of *how* they do so (Duncan et al., 2009). More specifically, LPs in genetics specify big ideas and their relevant concepts which students are expected to learn as they progress from basic to more advanced levels of understanding. For gene-environment interplay the relevant concepts are "genetic information contains universal instructions that specify protein structure" (referred to in the LP as concept B), "proteins have a central role in the functioning of all living organisms, and [the functions and interactions of proteins] are the mechanism that connects genes and traits" (concept C in the LP) and "environmental factors can interact with our genetic information" (concept H in the LP). High school students need to interrelate and integrate these concepts, which makes understanding gene-environment interplay challenging. For example, "understanding that the environment can change cell function through changes at the protein level (type and amount)" (concept H, level 2) and understanding that the "environment can cause mutations in genes or alter gene expression" (concept H, level 3) build on central aspects of concepts B and C, which focus on the relationship between genes and proteins, the functions of proteins and the relationship between proteins and traits. Understanding gene-environment interplay, thus, builds on the integration of several increasingly sophisticated concepts, and it requires mechanistic reasoning about molecular mechanisms.

To exemplify that causal and mechanistic reasoning differ in complexity, we analyze two examples of animal coloration, the pink plumage of flamingos (Rutter, 2006) and the red eye color of mutant fruit flies (Hausfeld & Schulenberg, 2015). We juxtapose these examples to illustrate differences between causal and mechanistic reasoning. David Rutter (2006) uses the example of pink plumage of flamingos to show that genetic and environmental causation are not truly separate, which is his main argument in *Genes and Behavior: Nature-Nurture Interplay Explained*:

> Flamingos everywhere are famous for their beautiful pink color. It is known that this is entirely dependent on a particular diet of shrimp and plankton. If flamingos do not have access to their usual diet for any reason, they are white, not pink. Their color is entirely dependent on the environmental influence of diet. On the other hand, the flamingos' ability to turn pink with diet is entirely dependent on their genes. You could feed seagulls forever on the same diet and they would never turn pink. It would make no sense to say the flamingos' color was 50 percent due to genes and 50 percent due to diet. The color is due to the joint action of genes and environment. (Rutter, 2006; 24).

The example shows that traits are entirely dependent on genes and the environment, which act jointly so that their contributions are equally important (for a similar argument see Barlow, 2018). First, traits depend on environments, which is illustrated by the fact that flamingos are pink in specific environments, but not in others. Second, the author deliberately contrasts flamingos with seagulls, which are never pink although they may feed on the same diet as flamingos, to counteract the common belief that environmental factors alone can explain variation in the trait. The contrast is powerful because it is easy to forget about the genetic basis of the trait. However, like most biological traits – if not all – the pink color of flamingos is caused by the joint action of genes and the environment. This aspect is relevant for the present study because prior research has shown that high school students doubt that there is a genetic contribution to many traits (Dougherty, 2009) and favor simple patterns of causality (genes-only explanations and environment-only explanations) over complex patterns involving interactive and multiple causation (Hammann, Heemann & Zang, 2021).

German high school biology textbooks typically exemplify gene-environment interplay by referring to variation in the eye color of fruit flies: Wild-type fruit flies have brown eyes, whereas mutants have red eyes unless mutant larvae receive a special type of food which causes them to develop brown eyes (Hausfeld & Schulenberg, 2015). This example of gene-environment interplay is perhaps less conspicuous than the pink color of flamingos, but it can be explained fully in terms of three interrelated molecular mechanisms: The *physiological mechanism* is that wild-type fruit flies have brown eyes because they are able to synthesize brown eye pigment in a three-step enzyme catalyzed pathway. Mutant fruit flies, in contrast, are characterized phenotypically by the almost complete absence of the brown eye pigment because a failure occurs in the conversion of kynurenine (KYNA) to 3-hydroxykynurenine (3-HK) due to a defective enzyme. This failure results in the block of the synthesis of brown eye pigment. The *genetic mechanism* is that enzyme-encoding genes affect this physiological mechanism. More specifically, the enzyme converting KYNA to 3-HK is lacking or not functioning in mutant fruit flies because an enzyme-encoding gene was altered by mutation. This genetic mechanism explains the block of the synthesis of brown eye pigment. Furthermore, the environment affects the physiological mechanism because substances in the food given to larvae can compensate for the enzyme deficiency. More specifically, brown eye pigment synthesis continues in mutant fruit flies when the missing substrate of the last conversion step is added to the food. This *environmental mechanism* explains the fact that by feeding mutant fruit fly larvae 3-HK, brown pigment synthesis occurs. Summing up, traits depend on interrelated physiological, genetic and environmental molecular mechanisms, which is the core of a molecular mechanistic understanding of gene-environment interplay.

Several aspects of gene-environment interplay are difficult for high school students to understand. First, traits depend on the joint action of genes and the environment, as Michael Rutter's flamingo example shows. This aspect – in and of itself – is a challenge for high school students. One of the possible reasons is that genetics educators traditionally focus primarily on genetic causation and marginalize environmental causation. This focus is hypothesized to strengthen high school students' belief in genetic determinism (BGD), which is the belief that "genetic contributions to phenotypes are exclusively or at least much more important than the contributions of other factors such as epigenetic and environmental ones, even in the case of complex traits such as behaviors and personality" (Carver et al., 2017). Dougherty (2009) argues that most students do not know, because they are not taught, that the environment affects the expression of many monogenic disorders, for example PKU, and that many students doubt that there is a genetic contribution to complex traits such as personality, addiction and cardiovascular efficiency. Furthermore, high school students tend to attribute some traits (mainly mind-related traits, like personality and behavior-related traits, like alcohol-use disorder) to environmental factors alone (environment-only explanations, see Hammann, Heemann & Zang, 2021). Furthermore, the authors found that the students viewed the influence of genes and the environment as independent and separate, and they tended to view the impact of the environment on traits as purely phenotypic. More specifically, most students understood the environment to be social and cultural, which led them to describe the phenotypic impact of the environment on complex traits and behaviors. Furthermore, the authors argued that the interviewed students were unaware of the molecular impact of the environment at the level of proteins and genes and that knowing how environmental factors "get under the skin" is the first step towards enabling students to reason mechanistically about the impact of the environment at the molecular level.

5.3 Aims and Objectives

This study has two aims:

- to characterize high school students' reasoning in a task requiring molecular mechanistic reasoning about gene-environment interplay,
- to validate our interpretation of the students' responses to the task.

To achieve the first aim, we investigated high school students' reasoning in a trait formation task addressing gene-environment interplay for variation of eye color in fruit flies (Hausfeld & Schulenberg, 2015). Trait formation tasks are incredibly rare in German high school biology textbooks. More specifically, Heemann & Hammann (2020) analyzed learning tasks (n = 580) included in the genetics sections of three major German high school biology textbooks. The authors found that 39 tasks (6.7%) were integrative tasks addressing genes, gene products and traits. The most surprising finding, however, was that only two of these integrative traits-formation tasks also addressed the environment. One of the tasks is "The eye color of fruit flies" (Hausfeld & Schulenberg, 2015). In this study, we used this task to fill a research gap because we wanted to know how well-prepared high school students are to explain gene-environment interplay mechanistically in terms of knowledge integration (Southard et al., 2016) and thinking across the different levels of biological organization (Duncan & Reiser, 2007; Knippels & Waarlo, 2018).

To achieve the second aim, we interviewed a subsample about the gene-environment interplay model of trait formation depicted in Fig. 5.1. Based on a precursor originally developed to illustrate the contrast between non-integrated and integrated explanations of trait formation (Heemann & Hammann, 2020), the model allows the visualization of the relationships between gene and gene product (1) as well as between gene product and trait (2). Furthermore, the model visualizes the impact of the environment on both relationships (3 and 4). For the classroom, the

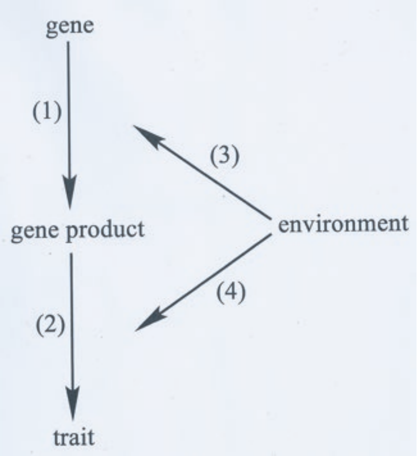


Fig. 5.1 Gene-environment interplay model of trait formation. (1) to (4) are explained in the text

model is expected to be a useful advance organizer for helping students build an integrated understanding of trait formation and avoid fragmented knowledge. The idea to use a model for knowledge integration builds on Pavlova & Kreher (2013), who suggest presenting a foundational framework at the beginning of a genetics course so that students understand where the details they learn throughout the course fit in.

5.4 Method

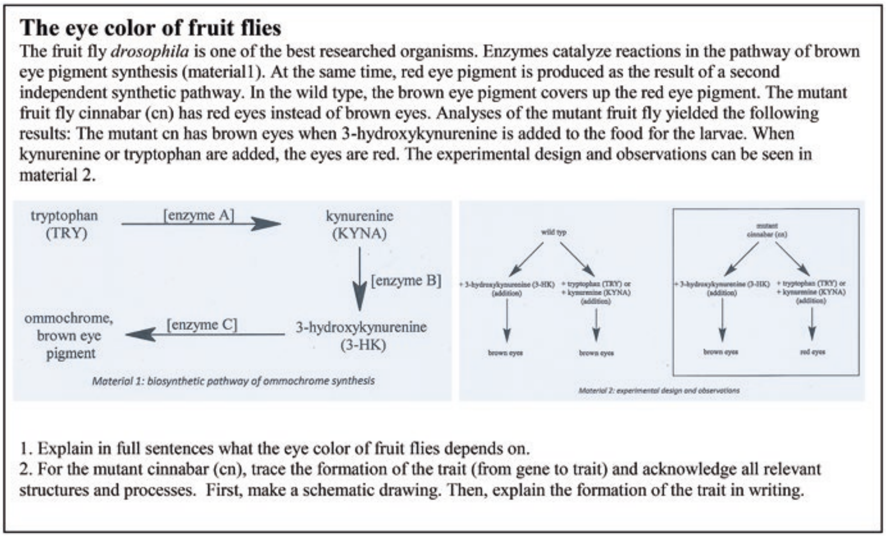
5.4.1 Sample

The sample consisted of 47 students (16–17 years old) from two high school classes, who had been taught genetics the semester before they participated in this study by two different teachers. Both groups of students had completed a semester-long course in genetics dealing with the following topics: meiosis and recombination, analysis of family trees, protein biosynthesis, gene regulation, genetic engineering and bioethics. More specifically, the curricula for the course are structured according to the three basic concepts system (trait, gene, allele, genetic pathway, DNA, chromosome, genome, recombination, stem cell), structure and function (protein biosynthesis, genetic code, gene regulation, transcription factor, mutation, proto-oncogene, tumor suppressor gene, DNA microarray) and development (transgenic organisms, epigenetics, cell differentiation, meiosis). Furthermore, the curricula were standard-based, and one of the standards specified that students were expected to explain the effects of different mutations on the phenotype. In the context of this study, it is also relevant that the semester before the students had been taught genetics, they dealt with enzymes in a course focusing on energy-related aspects of cell biology. We expected the students to be able to describe the mechanisms of trait formation in the task used for this study because the curricula cover all the aspects necessary to solve the task (for example, gene, protein biosynthesis, trait, genetic pathways, mutations and enzymes).

5.4.2 Assessment of Students' Reasoning

We investigated students' reasoning by using the trait formation task "The eye color of fruit flies," which provided students with a short text, two materials and two open-response questions (Hausfeld & Schulenberg, 2015).

For answering the first task in Fig. 5.2, we expected students to describe the following molecular mechanisms (mM), although not necessarily in the order numbered and listed:



The eye color of fruit flies

The fruit fly *drosophila* is one of the best researched organisms. Enzymes catalyze reactions in the pathway of brown eye pigment synthesis (material1). At the same time, red eye pigment is produced as the result of a second independent synthetic pathway. In the wild type, the brown eye pigment covers up the red eye pigment. The mutant fruit fly cinnabar (cn) has red eyes instead of brown eyes. Analyses of the mutant fruit fly yielded the following results: The mutant cn has brown eyes when 3-hydroxykynurenine is added to the food for the larvae. When kynurenine or tryptophan are added, the eyes are red. The experimental design and observations can be seen in material 2.

1. Explain in full sentences what the eye color of fruit flies depends on.
2. For the mutant cinnabar (cn), trace the formation of the trait (from gene to trait) and acknowledge all relevant structures and processes. First, make a schematic drawing. Then, explain the formation of the trait in writing.

Fig. 5.2 The open response task

- mM1: Wild-type fruit flies have brown eyes because enzymes catalyze reactions in the biosynthetic pathway giving rise to the brown eye pigment.
- mM2: Mutant fruit flies have red eyes because enzyme B does not catalyze a reaction in the biosynthetic pathway so that no brown eye pigment is produced.
- mM3: Mutant fruit flies have brown eyes, when larvae are fed 3-HK, which compensates for the fact that enzyme B does not catalyze KYNA to 3-HK so that brown eye pigment synthesis occurs.
- mM4: In mutant fruit flies enzyme B is lacking or not functioning because the gene that codes for the enzyme was altered by a mutation.

Note that the molecular mechanisms mM1 and mM2 are physiological, which affect the trait through the biosynthetic pathway, whereas mM3 is environmental and mM4 is genetic. For identifying mM1, students had to read material 1, which provides information about the biochemical pathway of brown pigment synthesis. For identifying mM2 and mM3, students had to integrate information from materials 1 and 2. Material 1 shows that 3-HK functions as the substrate for step three in brown eye pigment synthesis, while material 2 shows that mutant fruit flies have brown eyes, when their food contains 3-HK. From this contrast, it is possible to infer the physiological mechanism mM2 that mutant fruit flies have red eyes because enzyme B does not catalyze the conversion of KYNA to 3-HK. Furthermore, it is possible to infer the environmental mechanism mM3 that mutant fruit flies have brown eyes, when larvae are fed 3-HK, which compensates for the fact that enzyme B does not catalyze KYNA to 3-HK. For the genetic mechanism mM4, however, the students had to go beyond the materials and use their pre-knowledge because the materials did not refer to enzyme-encoding genes or to mutated enzyme-encoding genes, although the term mutant is used in the introductory text, in material 2 and in question 2.

For answering the second task in Fig. 5.2, we expected students to establish relationships between genes, enzymes, environment and trait. In particular, we expected students to acknowledge enzymes as mediators between genes and traits.

5.4.3 The Interviews

We conducted qualitative interviews with seven students after they had responded to the open-response task. At the beginning of the interview, the students were asked to describe the gene-environment interplay model of trait formation (see Fig. 5.1), comment on the entities and identify the processes. Furthermore, we asked the students to reflect on their prior responses to the task addressing the variation of eye color in fruit flies with the help of the model. For example, we asked the students to identify the gene product and the environment in their written responses to the open task. We were particularly interested in investigating the extent to which students could use the model to integrate their pre-knowledge about trait formation and reason mechanistically about the formation of the trait. Interviews were recorded and transcribed. Analyses focused on validating the different types of reasoning identified in the students' responses to the open-response task.

5.4.4 Coding the Students' Responses to the Open-Response Task

We used three coding steps to characterize students' reasoning about the trait. Because students reasoned about the trait in their responses to the first and second question of the task in Fig. 5.2, we combined the students' responses to the two questions. For example, when a student reasoned that enzyme B must be defective (response to question 1) and provided details about the genetic mechanism mM4 (response to question 2), we combined the information.

First, we formed **category 1** to identify **causal reasoning about the substances in the food** (see Table 5.1). Student reasoning classified as category 1 related eye color to substances in the food as a causal agent without providing any further details about the biochemical pathway of brown pigment synthesis and without describing molecular mechanism mM1–4. This category was formed inductively because we had not anticipated that students would simply reproduce the information from material 1 without relating this information to material 2. Second, we formed **category 2** to identify reasoning as **mechanistic reasoning at the molecular level** (see Table 5.1). We used the molecular mechanisms mM1–4 to divide category 2 into four subcategories.

Table 5.1 Coding categories, subcategories, category descriptions and sample responses

Category	Sub-category	Category description	Students' reasoning is based on …	Sample student response
1. Causal reasoning **about substances in the food**	n/a	Students establish a causal relationship between the **eye color** of fruit flies and **substances in the food.**	Student **reproduces** information from material 2, which shows that mutant fruit flies have red eyes when the food contains TRY and KYNA and brown eyes when the food contains 3-HK.	*The eye color of drosophila depends on which substances are added to the food. Wild-type fruit flies and mutant fruit flies differ in the pigmentation of their eyes. For wild-type fruit flies the substances added do not make a big difference; their eye color is always brown, no matter if 3-HK, TRP or KYNA are added. For mutant fruit flies, eye color is brown when 3-HK is added and red when KYNA or TRP are added.* (A 13)
2. Mechanistic reasoning **at the molecular level**	2.1	Student reasons about mM1: Eye color depends on **enzyme-catalyzed reactions in the biosynthetic pathway.**	Student **reproduces** information from material 1, which shows the three-step enzymatic conversion of amino acids into brown pigment.	*Because of the synthesizing action of the enzymes, the brown eye pigment ommochrome is produced/catalyzed, which is the reason why the eyes are brown. In particular, TRY is converted into KYNA, which is used to produce 3-HK, which is finally synthesized into ommochrome, the brown eye color, by enzyme C.* (A 8)
	2.2	Student reasons about mM2: Mutant fruit flies have red eyes because **enzyme B does not catalyze the conversion** of KYNA to 3-HK so that the bio-synthetic pathway is blocked.	Student **infers** that the biochemical pathway of brown pigment synthesis is interrupted in mutant fruit flies at enzyme B. Student combines information from materials 1 and 2.	*For the mutant, something must be different, very likely something enzyme-related because the red color does not come out. Based on material 1, is it perhaps possible to assume that enzyme B does not work? Because for the wild type, adding the two substances [the student refers to TRY and KYNA] does not change eye color.* (A 9)
	2.3	Student reasons about mM3: Mutant fruit flies have brown eyes, when **larvae are fed 3-HK, which compensates for the fact that enzyme B does not catalyze** KYNA to 3-HK.	Student **infers** that brown pigment synthesis continues in mutant fruit flies when the missing substrate of the last conversion is added to the food. Student combines information from materials 1 and 2.	*In the mutant fruit fly, enzyme B is missing, which is responsible for synthesizing 3-HR. That's why 3-HR is not produced even when TRY respectively KYNA are added, and that's why they have red eyes. When 3-HR is added, enzyme B is skipped and enzyme C can synthesize the brown eye color.* (B 7)
	2.4	Student reasons about mM4: In mutant fruit flies, enzyme B is lacking or not functioning because **enzyme-encoding gene was altered by a mutation.**	Student **infers** that enzyme-encoding gene was altered. Students use their pre-knowledge because there is no reference to genes or mutated genes in the materials (except for the term mutants).	*The eye color of fruit flies depends on 3-HR and the catalysis of this substance by enzyme B. This shows the biosynthetic pathway of the wild type who has enzyme B, which means that the wild type can synthesize 3-HR. the mutant fruit fly cinnabar does not have brown eyes, unless it is given 3-HR. in the mutant fruit fly, thus, the mutation affects enzyme B.* (A 18)

Third, we formed seven **types of students' reasoning** based on which elements captured by the five coding categories in Table 5.1 the students combined. Table 5.2 lists these seven types in increasing order of sophistication. Please note that it is possible to form dichotomies according to which reasoning types are **causal vs. mechanistic** (reasoning types A vs. B-G), **non-inferential vs. inferential** in terms of whether or not the student infers that the biochemical pathway of brown pigment synthesis is interrupted in mutants because of a defective enzyme (reasoning types A-C vs. D-G), **non-genetic vs. genetic** in terms of whether or not the student reasons that genetic mutations affect proteins/enzymes and traits (reasoning type A-E vs. F and G) and **non-integrated vs. integrated** in terms of whether the student reason about the genetic mechanism alone or the environmental mechanism alone vs. gene-environment interplay (E and F vs. G). For the distinctions between causal vs. mechanistic reasoning see Russ et al. (2008), between inferential and non-inferential reasoning see Streumer (2007), and for integrated vs. non-integrated see Heemann & Hammann (2020).

Fourth, we coded students' responses to the tracing trait formation task (question 2 of the task in Fig. 5.2). We used aspects of the LP for genetics education (Duncan et al., 2009), in particular "genes are instructions for proteins/enzymes" (concept B, level 2) and "genetic mutations can affect the structure and thus function of proteins/enzymes and ultimately traits" (concept C, level 3), and, furthermore, students' descriptions of protein biosynthesis to analyze if the students acknowledged enzymes as mediators between genes and traits. Because many students did not do so, we formed the following categories for tracing the formation of the trait inductively: student reproduces information about the pathway from material 1 and/or the experiment from material 2, students provides truncated explanations by describing that genes (or mutated genes) lead to traits, and students describes Mendelian patterns of inheritance or refers to dominant vs. recessive inheritance.

We investigated interrater reliability for the classification of student responses into the seven reasoning types (Table 5.2). We used ten student responses for illustrating the coding rubric, and ten additional responses to train a biology teacher not involved in the study to use the coding rubric. The remaining 27 student responses were independently coded by the first author and the biology teacher. Interrater reliability was substantial (Cohen's kappa 0,73). We closely looked at the six diverging responses and were able to reach consensus on four of them (Cohen's kappa 0,92) due to imprecisions in the coding rubric. No consensus was reached for two of the six diverging responses because one student ambiguously referred to 3-HK either as food (type D) or as environmental compensation (type E), and another student ambiguously referred to the block in the biosynthetic pathway either due to a defective/missing enzyme (type D) or due to the absence of 3-HK (type C).

Table 5.2 Types of students' reasoning

Type	Description	classification	Molecular mechanism	Does student infer that enzyme B is defective?	Does student reason that mutation affects enzyme and trait?
A	Student reasons that eye color depends *entirely* on substances in food.	Causal (food)	n/a	No	No
B	Student reasons that eye color depends *entirely* on **physiological mechanism** (mM1).	Mechanistic (physiological)	mM1	No	No
C	Student reasons that eye color depends on both food *and* **physiological mechanism** (mM1).	Causal (food) and mechanistic (physiological)	mM1	No	No
D	Student integrates type A and B by reasoning about the defective enzyme as a **physiological mechanism** (mM2) to explain why brown pigment synthesis is interrupted.	Mechanistic (physiological)	mM1, mM2	Yes	No
E	Student reasons like in type D *and* reasons about the **environmental mechanism** (mM3) to explain that substances in the food compensate for the defective enzyme.	Mechanistic (physiological and environmental)	mM1, mM2, mM3	Yes	No
F	Student reasons like in type D *and* reasons about the **genetic mechanism** (mM4) to explain that a genetic mutation affects enzyme and trait.	Mechanistic (physiological and genetic)	mM1, mM2, mM4	Yes	Yes
G	Student reasons like in type D *and* reasons about **genes and environment** (mM3 and mM4) to explain why the enzyme is defective and can be compensated for by the environment.	Mechanistic (physiological, genetic, environmental)	mM1, mM2, mM3, mM4	Yes	Yes

5.5 Results

5.5.1 *Findings for the First Question of the Task: What Does the Eye Color of Fruit Flies Depend on?*

Approximately half of the students (n = 24; 51% of the sample) produced responses lacking the conclusion that the biochemical pathway of brown pigment synthesis was interrupted at enzyme B in mutant fruit flies. These 25 students did not integrate information from materials 1 and 2 and were classified as belonging to **reasoning types A-C**. More specifically, ten students (21% of the sample) reasoned causally that eye color depends entirely on substances in the food (**reasoning type A**). They neither referred to the biochemical pathway in material 1 nor to the molecular mechanism m1–4. Six of these students correctly described the information from material 2 that food affects eye color in mutants, but not in the wild type, whereas four students did not differentiate between wild type and mutant and made the general statement that eye color depended on food. A sample response for this reasoning type is student A13 (see Table 5.1). Furthermore, five students (11%) reasoned that eye color depended entirely on the physiological mechanism of brown pigment synthesis (**reasoning type B**). These students essentially reproduced information from material 1 and described enzyme-catalyzed conversions, sometimes in detail, but did not make use of the information in material 2 about the impact of substances in the food on eye color. Responses in this category, thus, simply stated that there is a biochemical pathway for the brown eye pigment. A sample response is student A8 (see Table 5.1). Finally, nine students (19% of the sample) combined causal reasoning about substances in the food with mechanistic reasoning about the physiological mechanism mM1 without integrating the two types of reasoning (**reasoning type C**). These students essentially reproduced information from materials 1 *and* 2 in an additive way and reasoned that food has an impact **and** that there is a biochemical pathway for the brown eye pigment. The following response illustrates this reasoning type. We coded the second sentence as mechanistic reasoning about mM1 and the last three sentences as causal reasoning about food.

> The normal wild type of the fruit fly drosophila has brown eyes. Enzymes catalyze the biosynthetic pathway, which provides the brown eye pigment, as can be seen in material 1. Besides the brown eye pigment, an independent biosynthetic pathway provides the red eye pigment. This pigment, however, is covered up by the brown pigment, so that the wild type always has brown eyes, regardless of whether 3-HK, TRY or KYNA are added, as can be seen in material 2. The cinnabar mutant has red eyes because the food it received contains TRY and/or KYNA. If the food contains 3-HK, the mutant will have brown eyes, as can be seen in material 2 which shows experimental set-up and observations. (A 16)

The other half of the students (N = 23; 49% of the sample) integrated information from materials 1 and 2 by reasoning that the biochemical pathway of brown pigment synthesis is interrupted at enzyme B (**reasoning types D-G**). More specifically, seven students (15% of the sample) identified enzyme B, but reasoned neither about the environmental mechanism mM3 to explain the brown eye color of the mutant nor about the genetic mechanism mM4 to explain why enzyme B is defective or missing (**reasoning type D**). Furthermore, six students (13% of the sample) inferred that enzyme B is defective or missing, and, in addition, described the environmental mechanism mM3 by pointing out that enzyme B can be skipped by adding 3-HK (**reasoning type E**). These students, however, did not relate the defective or missing enzyme to enzyme-encoding genes (mM4). Thus, genetic aspects of trait formation were not addressed. The last two reasoning types in this group referred to the genetic mechanism mM4. In particular, four students (8% of the sample) inferred that enzyme B is defective or missing and, in addition, described the genetic mechanism (mM4) that enzyme-encoding genes were altered by mutation (**reasoning type F**). These students, however, did not reason about the fact that the environment can compensate for the defective or missing enzyme B (mM3). Finally, six students (13% of the sample) described the genetic mechanism (mM4) to explain why the enzyme is defective or missing, and they described that the environmental mechanism (mM3) compensates for the defective or missing enzyme (**reasoning type G**). These six students, thus, reasoned about gene-environment interplay, although none of the students used this term. The following response illustrates reasoning type G. The student states that mutations affect enzymes and trait and describes the effect of adding 3-HK:

> The eye color of drosophila depends on the addition of substances to the food for the larvae. When 3-HK is added, the eyes become brown, and when KYNA and TRY are added, the eyes become red. For the cinnabar mutant, there seems to be a genetic defect, which prevents enzyme B from being added to the pathway of ommochrome synthesis as it happens normally (material 1). For the wild type, in contrast, the eye color always remains the same. [The student added a drawing – omitted here – by adapting material 1 to show that when enzyme B is defective, the mutant has red eyes.] For the mutant cinnabar, enzyme B is lacking which converts KYNA to 3-HK. Only after adding 3-HK, the red eye color is covered up. (A 11).

5.5.2 Findings for the Second Question of the Task: Tracing Trait Formation

The task required students to establish relationships between genes, enzymes, environment and trait. Few students acknowledged enzymes as mediators between genes and traits. We formed two groups of students: students who acknowledged enzymes as mediators between genes and traits versus students who did not. The former group was identical with students whom we had classified as reasoning types A-E in their responses to task 1. None of the students in reasoning types A-E referred to the facts that genes are instructions for proteins/enzymes, that mutations affect proteins /enzymes and traits and that protein biosynthesis links genes and proteins/ enzymes (see Table 5.3, cells are shaded dark grey). Instead, 25 students in reasoning types A-E (53% of the sample) traced the formation of the trait by reproducing information about the pathway from material 1 and /or the experiment from material

Table 5.3 Findings for the open response task "The eye color of fruit flies"

How does the student reason about the trait in task 1? (types are based on coding steps 1-3)			**How does the student describe trait formation in task 2?** (coding step 4)						
		Reasoning Type A-G	student traces the trait by adapting material 1 and/or material 2	student traces the trait by linking gene and trait directly	student traces the trait by referring to Mendelian patterns or dominant/recessive genes	*student explicitly states that mutations affect proteins /enzymes & traits Mutations affect protein and trait*	*student explicitly states that protein biosynthesis links genes and proteins /enzymes*	*student explicitly states that genes are instructions for proteins/enzymes*	student gives no response
		N (%)	*N*	*N*	N	N	*N*	N	N
A	Student reasons that eye color depends *entirely* on substances in food (causal reasoning)	10 (21%)	7	2	2	0	0	0	0
B	Student reasons that eye color depends *entirely* on **physiological mechanism** mM1	5 (11%)	4	1	0	0	0	0	0
C	Student reasons that eye color depends on food *and on* **physiological mechanism** mM1	9 (19%)	5	3	1	0	0	0	0
D	Student integrates type A and B by reasoning about defective enzyme as **physiological mechanism** mM2	7 (15%)	4	1	1	0	0	0	1
E	Student reasons like in type D *and* reasons about the **environmental mechanism** mM3	6 (13%)	5	1	2	0	0	0	0
F	Student reasons like in type D *and* reasons about the **genetic mechanism** mM4	4 (8%)	0	0	0	4	2	3	0
G	Student reasons like in type D *and* reasons about **gene and environment** mM3 and mM4	6 (13%)	3	0	0	6	2	3	0
	Sum total N (%)	47 (100%)	28 (59%)	8 (17%)	6 (13%)	10 (21%)	4 (8%)	6 (13%)	1 (2%)

2 (see Fig. 5.3a for a sample response). Furthermore, eight students in reasoning types A-E (17% of the sample) provided truncated explanations by describing that genes (or mutated genes) lead to traits (see Fig. 5.3b for a sample response), and six students (13% of the sample) traced the trait by describing Mendelian patterns of inheritance or by referring to dominant vs. recessive inheritance (see Fig. 5.3c for a sample response). Table 5.3 shows these students in the cells shaded in lighter tones of grey.

As an example of a truncated explanation, the student who made the drawing in Fig. 5.3b and linked genes and traits directly (although the enzymes A, B and C are involved) wrote the following text:

> When TRY or KYNA are added to the gene by the food, the eyes become red. When you add 3-HK the eyes become brown, as can be seen in the material. (A 13).

Another example of a truncated explanation is the following quote:

> From gene to trait: In the gene, there are synthetic pathways for eye color. There is one for the brown eye pigment and another for the red eye pigment. In the pathway from gene to the trait, the gene mutates so that the fly does not get the brown eye color as usual. (B 27).

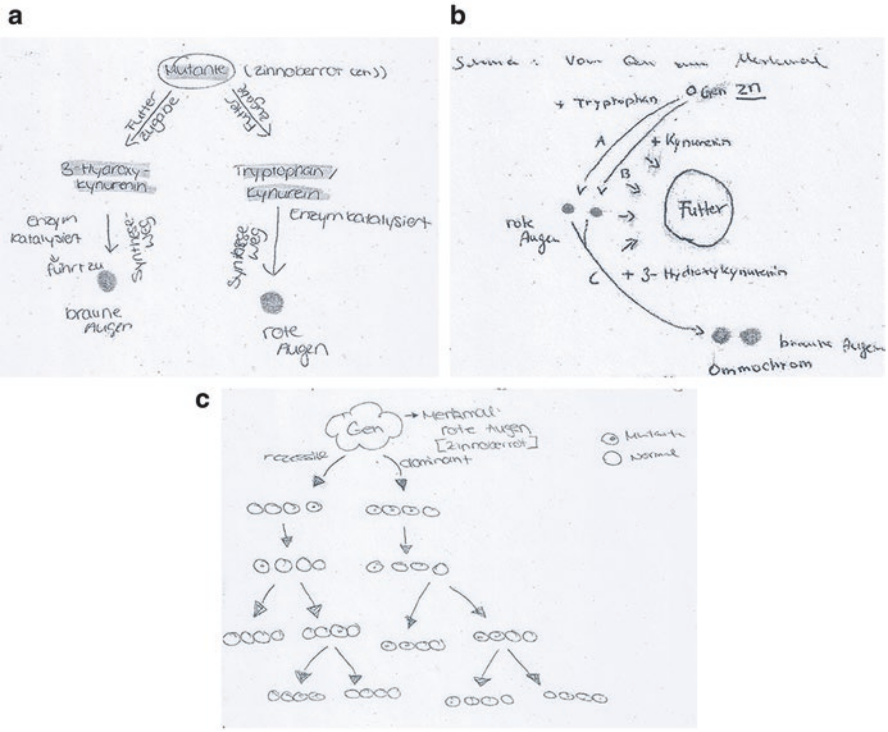


Fig. 5.3 (a–c) Student drawings for the second question of the task "The eye color of fruit flies"

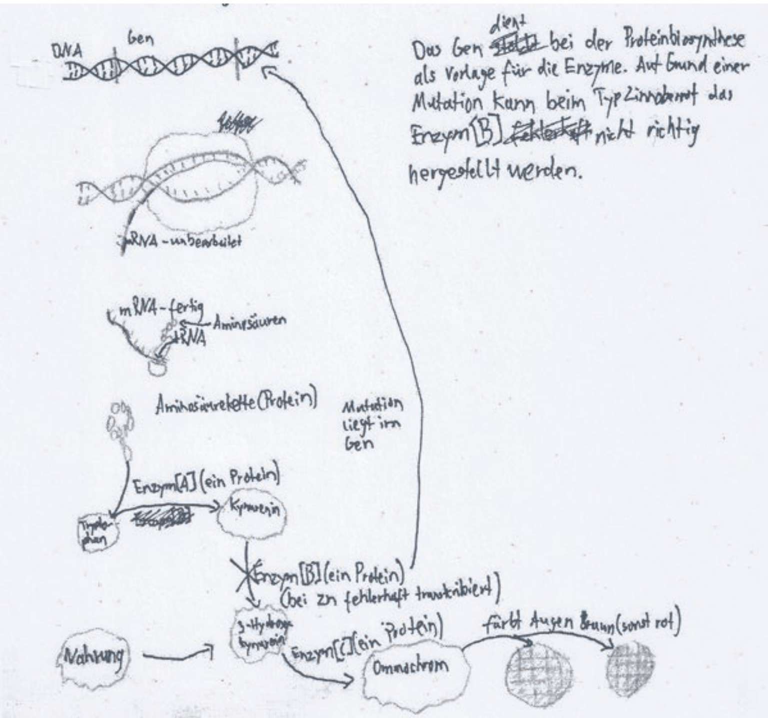
Another student is quoted here to illustrate students who refer to dominant vs. recessive inheritance for tracing trait formation:

Wild type	*+ TRY = recessive gene – brown eyes*
	+ 3-HK = recessive gene – brown eyes
	+ KYNA = recessive gene – brown eyes
Mutant (cn)	*+ TRY = dominant gene – pigment available*
	+ 3-HK = dominant gene – but no pigment available
	+ KYNA = dominant gene – pigment available

> The experiment shows that for the wild type the gene for red eyes is recessive. The recessive gene gives rise to red eyes only, when red pigment is present. However, 3-HK offers brown pigment only. For the mutant, red eyes are dominant and give rise to red eyes as long as red pigment is available. Because red eyes push through only in a dominant mode of inheritance, TRY and KYNA can provide either red or brown color. (B 9).

[comment: The student misinterpreted the information and believes that red pigment covers up brown pigment. He does not acknowledge the pathway as interrelated reactions, but believes that TRY and KYNA can provide red pigment and brown pigment depending on whether the gene is dominant or recessive. Genes, however, do not code for enzymes in this way of thinking, but affect eye color directly.]

All ten students classified as belonging to reasoning types F and G (21% of the sample), in contrast, acknowledged enzymes as mediators between genes and traits by stating that genetic mutations affect proteins/enzymes and traits. Furthermore, six students (13% of the sample) stated that genes are instructions for proteins/enzymes, and five students (11% of the sample) linked genes and enzymes by describing protein biosynthesis. Students in this group differed in how detailed their accounts were. One student, for example, provided an elaborate drawing of transcription and translation to depict the connections between genes and proteins (see Fig. 5.4). In the drawing, the student specified that enzymes are proteins, that enzyme B was transcribed wrongly in the mutant and that the defective enzyme impacts the phenotype. The student wrote: “In protein biosynthesis, genes provide the information for enzymes. Because of a mutation, enzyme B cannot be produced correctly in the mutant.” (B1)



Das Gen ~~stellt~~ dient bei der Proteinbiosynthese als Vorlage für die Enzyme. Auf Grund einer Mutation kann beim Typ Zinnoberrot das Enzym[B] ~~fehlerhaft~~ nicht richtig hergestellt werden.

Fig. 5.4 Student’s (B1) drawing for the second question of the task “The eye color of fruit flies”

5.5.3 Findings from the Interviews

Providing a rich source of information about the ways in which the students reasoned about trait formation, the interviews allowed us to validate our interpretations of the students' responses to the open task. We interviewed three students from reasoning type A (A 13, A 20, B 9), one student from reasoning type C (B 17), one student from reasoning type E (B 13) and two students from reasoning type G (A 11, B 3).

- A 13 linked gene and trait directly (truncated explanation),
- A 20 depicted a family tree and argued that the gene for red eyes is recessive,
- B 9 adapted material 2 and argued that the gene for red eyes is recessive in the wild type and dominant in the mutant,
- B 17 adapted material 1 and reasoned that the allele for red eyes is dominant in the mutant,
- B 13 linked gene and trait directly (truncated explanation),
- A 11 adapted material 1 and reasoned that mutations affect proteins / enzymes & traits,
- B 3 stated that genes are instructions for proteins /enzymes and reasoned that mutations affect proteins / enzymes & traits.

The chief evidence of the qualitative interviews was that students who addressed the genetic mechanism mM4 in their written responses to the open tasks (A 11 and B3) were able to explain that the genetic information specifies proteins/enzymes, and both students were able to describe the effects of mutated genes at the level of the gene product and the enzyme-catalyzed reactions leading to the trait. Furthermore, both students were able to actively produce details about transcription and translation, although student A 11 lacked knowledge about protein biosynthesis, which explains why the student adapted material 1 (instead of providing a detailed description) when tracing trait formation.

In contrast, students who did not address the genetic mechanism mM4 were unfamiliar with the role of proteins in genetic phenomena and often did not differentiate between gene and trait. At the beginning of the interview, student A 13, for example, believed that the gene product was the trait and that the process between gene and gene product was the cell cycle. After the interviewer had informed the student about the fact that arrow 1 represented protein biosynthesis, and encouraged the student to trace the red eyes of the mutant with the help of the gene-environment interplay model of trait formation, the student still attributed enzymes A and B to arrow 1 and enzyme C to arrow 2, which means that the student held on to the idea that the gene product was the trait (red eye color) which the student then believed to be transformed into brown eye color when enzyme C is present (see Fig. 5.3b for a drawing of the same student). Other students in this group were able to activate their knowledge about selected aspects of the molecular model of trait formation through the information they received from the interviewer about the model, but seemed unfamiliar with the role of enzymes for the formation of the trait (process 2 in the model). In particular, student B 9, whom we quoted above to illustrate the Mendelian model of dominant vs. recessive inheritance, argued throughout the interview that enzymes are transformed into the trait, that process 2 was the process of one pigment covering up the other (rather than a series of interconnected enzyme catalyzed reaction) and that the wild type either got brown eyes "from something else" when it was fed TRY or KYNA or that the mutant lacked an enzyme which would produce brown eyes "from something else".

There was considerable variation among the students in this group who did not refer to molecular mechanism mM4, however, concerning which aspects they were familiar with and which not. One student (B 13) in fact had considerable molecular knowledge, but explicitly stated that he did not know if he was expected to refer to "DNA, protein and the level of enzymes or simply to the materials to explain it". Summarizing, the decisive factor which emerged from the interview was whether or not the students were able to differentiate between genes and traits, reason about the role of proteins (enzymes) for trait formation and reason about mutants in terms of mutated enzyme encoding genes resulting in a defective or missing enzyme B.

5.6 Discussion and Educational Implications

The primary aim of this paper is to characterize student reasoning in a task requiring molecular mechanistic reasoning about gene-environment interplay. As a main finding, few high school students showed molecular mechanistic reasoning about the environment (13%) and gene-environment interplay (13%) because the genetic and environmental mechanisms had to be inferred from the materials. In contrast, most students focused on information directly presented in the materials, which they reproduced for causal reasoning about food (21%), for mechanistic reasoning about the biochemical pathway (11%), and an unintegrated (23%) or integrated combination (17%) of both types of reasoning.

Why did so few students show molecular mechanistic reasoning about gene-environment interplay? When we asked students to explain what the eye color of fruit flies depended on and when we encouraged them to trace trait formation, we expected mechanistic reasoning relating the phenomenon visible at the level of the organism (variation in eye color) to the physiological level (biochemical pathway of brown eye pigment synthesis) and the genetic level. Note that the materials did not indicate that genes code for proteins/enzymes. Furthermore, we did not explicitly prompt the students to use their genetics knowledge at the different levels of biological organization. The task, however, explicitly encouraged the students to trace the formation of the trait "from gene to trait", and the term mutant was used several times in the task. Nevertheless, few students explained gene-environment interplay mechanistically because they had to infer the genetic mechanism and interrelate it with the physiological and the environmental mechanisms. The main finding of this study, thus, is that significant numbers of students did not infer the genetic mechanism because of lacking knowledge integration, and the crucial gap in the students' understanding seems to be that enzymes act as mediators between genes and traits. This lack of knowledge integration is similar to students in an evolution course who had completed a genetics course before they were trained in evolution and were reported to be unable to answer the question what evolution has to do with genes (Halldén, 1988).

More specifically, knowledge integration proved challenging for the students in two ways. Half of the sample did not combine information about the effect of food on the trait (material 2) with the enzymatic reactions in the biosynthetic pathway (material 1) and thus did not infer that brown eye pigment synthesis was interrupted at enzyme B. Instead students either reasoned causally that food explained the trait entirely, or they reasoned mechanistically that the biosynthetic pathway explained the trait entirely or they showed an unintegrated combination of both types of reasoning. This is a surprising finding because the students had dealt with enzymes and enzyme-catalyzed reactions in depth in a cell biology course prior to the genetics course, and the knowledge they had received should have enabled them to draw an enzyme-related conclusion about why the pathway is blocked. Furthermore, only ten students (21% of the sample) reasoned about the genetic mechanism by inferring that enzyme-encoding genes affect the physiological mechanism depicted in material 1, and only six of these students (13% of the sample) reasoned mechanistically about gene-environment interplay. Only one-fifth of the sample, thus, reasoned across ontologically distinct levels of biological organization by inferring the genetic mechanism (Duncan & Reiser, 2007). This is the second surprising finding of this study because the task mentioned the term mutant several times, and the students had taken a course in genetics which dealt with all aspects necessary to solve the task. This study, thus, lends support to the argument that educators need to support the students' ability to think across the different levels of biological organization.

Knowledge fragmentation leads to inert knowledge (Renkl, Mandl, & Gruber 1994). Inert knowledge is the most likely explanation for the finding that the students did not infer the genetic mechanism and that they did not interrelate it to the physiological and environmental mechanisms. Students' knowledge about trait formation proved fragmented because most of them were unable to explain causally *that* and mechanistically *how* genetic information specifies proteins/enzymes. This inability was also evidenced by the interviews. As a consequence, most students' responses to the trait formation task did not specify how mutated genes impact trait formation at the level of the gene product and the enzyme-catalyzed reactions leading to the trait. Instead, significant numbers of students traced trait formation by adapting the materials depicting the biochemical pathway and the experiment or by providing truncated explanations directly linking genes and traits. Other students relied on Mendelian explanations of dominant and recessive genes which were equally truncated because they lacked molecular mechanisms. In that sense, this study supports prior findings from studies showing that for many students the relationship between genes and traits is a "black box" (Gericke & Wahlberg, 2013; Lewis & Kattmann, 2004; Venville & Treagust, 1998). Furthermore, findings of this study are related to the scarcity of integrative trait formation tasks in high school textbooks (Heemann & Hammann, 2020). Students from this study learned with one of the textbooks analyzed by Heemann & Hammann (2020) so that it is most likely that inert knowledge resulted from not providing students opportunities for knowledge application.

As educational implications, we suggest using *tracing trait formation* as a teaching and learning strategy, and we recommend using the gene-environment interplay model for implementing this strategy in the classroom. The model can serve different functions in the classroom. As an advance organizer, teachers can use the model to help students understand where the details they learn throughout the course fit in. Many students in the interviews, for example, had problems acknowledging protein biosynthesis as the process connecting genes and gene products, although protein biosynthesis is covered in depth in the curriculum. Furthermore, tracing trait formation can be combined with model building (Reinagel & Bray Speth, 2016) to help students structure their responses to trait formation tasks. Students were unfamiliar with the role of proteins/enzymes in genetic phenomena. Accordingly, we suggest that teachers deliberately use integrative tasks to support students' ability to trace trait formation. These tasks are very rare in German textbooks (Heemann & Hammann 2020), but they are valuable insofar as they allow students to integrate fragmented knowledge and understand why they learn the details of trait formation. Furthermore, genetics educators need to pay particular attention to proteins/enzymes as mediators between genes and traits when students solve integrative tasks (Thörne & Gericke, 2014). Students need to reflect on their responses to trait formation tasks at the meta-level, and the model can provide guidance for students to systematize the different ways in which genes and the environment impact trait formation. Such knowledge should be a major outcome of genetics education. Students, furthermore, should be familiarized with the differences between causal explanations and molecular mechanistic explanations so that they understand whether the task asks for relatively short responses in terms of causal reasoning or extended mechanistic responses with elaborate molecular details (Russ et al., 2008). Finally, educators need to be aware that gene-environment interplay is an important concept for genetics literacy. Gene-environment interplay needs to be given the importance it deserves, for example by restructuring the curricula (Dougherty, 2009; Jamieson & Radick, 2017) and by using integrative trait formation tasks to support students' molecular mechanistic reasoning about the joint action of genes and the environment.

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Chapter 6
Systems Thinking in Ecological and Physiological Systems and the Role of Representations

Sophia Mambrey, Andrea Wellmanns, Justin Timm, and Philipp Schmiemann

6.1 Introduction

The analysis of complex systems plays an important role in many areas of biology as well as in other scientific fields and in addressing global challenges. The consideration of systems represents a holistic perspective and is thus opposed to earlier reductionist approaches. Common to all complex systems is, at a minimum, the presence of various elements and multiple interactions between them. Today, systemic approaches are applied in many areas of biology, such as physiology (Noble, 2002), microbiology (Westerhoff & Palsson, 2004), ecology and evolution (Proulx et al., 2005). For example, microbiology has evolved into systems biology under the influence of the genomic revolution (Westerhoff & Palsson, 2004). Understanding complex systems can be difficult for a variety of reasons: structural and dynamical complexity as well as connection and node diversity are particularly challenging for learners (Strogatz, 2001). Another significant factor in understanding complex systems is the representation that depict the respective system (Eilam & Poyas, 2010). There are content-specific conventions for representing complex systems, which means that particular system properties sometimes remain unpictured. In this chapter, we aim to examine how these unmapped system properties may influence students' understanding of complex systems. We merge findings from three studies and discuss them from the perspective of representations. Our intention is to deduce further insights into the overarching factors influencing systems thinking.

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6.2 Similarities and Differences of Complex Systems

Despite the diversity of fields and systems, several properties can be identified that underlie many or all complex (biological) systems. Biological systems demonstrate strong hierarchical organisation (Dobzhansky, 1964; Pavé, 2006). The interaction of individual elements at one level creates emergent structures and behaviours at higher levels of organisation. One example of emergence is self-organisation in biological systems, which is observable in the schooling practices of fish, the method through which ants form trails, or the formation of honeycombs (Camazine et al., 2003). While these and other properties are ubiquitous, there are also properties that are unique to some classes of systems. To demonstrate the idea of unique properties, we examined ecological and physiological systems. In both systems, unilateral and bilateral and direct and indirect (non-linear) relations occur that can form feedback loops. Many physiological systems, such as the blood glucose regulatory system, seek to maintain a stable state called homoeostasis: that is, the physiological variable, in this case the blood glucose level, is regulated by homoeostatic processes not to exceed defined limits. If the blood glucose level exceeds the normal range, the release of insulin is stimulated as part of a negative feedback mechanism, which leads, inter alia, to an increased absorption of glucose by muscle and fat cells and the stimulation of glycogen metabolism. This mechanism lowers blood glucose levels. When the blood glucose level falls below normal, glucagon secretion is stimulated as part of another negative feedback mechanism, which leads to the breakdown of glycogen and, thus, the release of glucose into the blood. This increases the blood glucose level. As a result, the interplay between these negative feedback mechanisms maintains the balance of the blood glucose level and ensures homoeostasis. Disturbances in this control system have serious medical consequences (Cannon, 1929). In contrast, there is no such balance in ecological systems. Ecological systems have a certain resilience to perturbations, but there is no such thing as a balance of nature (Ampatzidis & Ergazaki, 2018). However, there are many alternative stable states between which ecological systems can switch back and forth when tipping points are exceeded (Scheffer et al., 2001). Generally, food webs (a type of ecological network) consist of a relatively small number of elements that demonstrate rather higher interconnectivity than other real-world systems (Kitano, 2002a). Although both homoeostatic physiological systems and ecosystems are biological systems, they are fundamentally different. Simply put, biological systems and systems in general are diverse.

6.3 Systems Thinking

Although systems from different areas can be very diverse, certain basic principles hold beyond the context of individual systems. Understanding complex systems requires systems thinking skills. Systems thinking is defined as the ability to recognise and describe systems in their full complexity, and to analyse and predict system behaviours based on constructed mental models (Rieß & Mischo, 2010). Given the variety of systems, it is not surprising that the cognitive skills of systems thinking comprise various facets and different theoretical foundations, such as general or dynamical systems theory (Verhoeff et al., 2018). However, an overarching conceptualisation both within the field of biology and across fields is still missing (Mambrey et al., 2020). Of course, the concept of systems thinking is not limited to biology, but is also prevalent in other scientific fields. Research has been conducted on systems thinking in the areas of social systems (Booth Sweeney & Sterman, 2007; Mehren et al., 2018), technological systems (Frank, 2000) and natural systems (Batzri et al., 2015; Booth Sweeney & Sterman, 2007; Mehren et al., 2018). In biology, various fields have been examined from a systems perspective, including physiology (Snapir et al., 2017; Tripto et al., 2017; Wellmanns & Schmiemann, 2020), cell biology (Verhoeff et al., 2008) and ecology (Hokayem & Gotwals, 2016; Mambrey et al., 2020, 2022).

Although there is no unified framework, there seems to be a common ground across conceptualisations that systems thinking includes three essential skills: systems thinking requires (a) identifying and describing the elements and their relations (identifying system organisation; Ben Zvi Assaraf & Orion, 2005; Booth Sweeney & Sterman, 2007; Mambrey et al., 2020; Mehren et al., 2018; Tripto et al., 2017). In biological systems, these structures and their elements vary in size and organisation (Hmelo-Silver et al., 2007). The second skill relevant to systems thinking is (b) analysing mechanisms, functions and dynamics that result from the interaction of elements in order to recognise how a system behaves to fulfil its function (analysing system behaviour; Hmelo-Silver et al., 2007; Hokayem & Gotwals, 2016; Mambrey et al., 2020; Mehren et al., 2018). Finally, systems thinking requires (c) modelling prospective target states (system modelling; Mambrey et al., 2020; Snapir et al., 2017; Tripto et al., 2017). Regarding these conceptual skills, there is no consensus on how students should gain a deeper understanding of complex systems. Although systems thinking is defined as a skill that enables the understanding of complex systems across fields, a study by Mambrey et al. (2020) showed that system specifics have a significant impact on students' systems thinking skills. Similar results were found in the work of Ben Zvi Assaraf and Orion (2005; see also Orion & Libarkin, 2014; Tripto et al., 2017), who found qualitative differences in students' performance across geography and biology. These studies showed that in human body systems, students tend to focus on the system structure, whereas in geography, they are more likely to perceive the dynamic interactions within systems. Further, the results of a study by Sommer and Lücken (2010) suggest that a content-based intervention could improve students' systems thinking skills. The question arises as to why systems thinking, which is supposed to be a superordinate skill, seems to be context-specific. It is possible that the respective immanent system properties increase the context specificity.

6.4 Representations of Complex Systems

Representations are tools used to model complex systems. They can support students in exploring various complex system features and can thus be used to foster students' systems thinking skills. External representations are an essential part of scientific communication (Tsui & Treagust, 2013). The life sciences in particular 'depend on the use of external representations and symbolic language' (Anderson et al., 2013, p. 19). External representations are collections of information that are 'printed on paper or displayed on a computer monitor, that can be perceived by an individual' (Hegarty, 2014, p. 697). The representations of system models can take a variety of different forms, including visual-spatial displays (for example, diagrams and animations) and verbal materials (Hegarty, 2014). Representations support science learning by illustrating complex biological processes or phenomena (Tsui & Treagust, 2013). In addition, representations can provide information about the assumed mechanisms underlying emergent behaviours (Constantinou et al., 2019). The comprehension of representations requires an active cognitive procedure (Schnotz, 2014) through which the learner constructs a model by memorising representational features and applying them to content knowledge. This process leads to the construction of an elaborate mental model that facilitates coherent reasoning.

Booth Sweeney and Sterman (2007) investigated students' and teachers' systems thinking skills qualitatively in a variety of contexts, finding differences in systems thinking between novices and experts regardless of system content: 'without systems-specific content knowledge, individuals appear to default to descriptive, surface features' (Booth Sweeney & Sterman, 2007, p. 305) when explaining complex systems. Consequently, the type of representation is not a sufficient explanation for the variety in students' systems thinking skills across contexts. Rather, it appears that experts integrate system properties in their reasoning beyond contexts, in contrast to novices. These structures appear imperceptible to students, but because they can be identified by experts, they are implicitly integrated into the system representation. As a result, implicit system properties in representations may greatly reduce the ease of understanding complex systems by hindering a deeper understanding of representational characteristics.

6.5 Purpose and Methodology

In this chapter, we address the role of implicit system properties in systems thinking. By implicit system properties we mean those properties that may affect the system but are not directly represented in representations of the system. As these system properties are relevant to the actual system, we assume that consideration of these implicit system properties is also relevant for systems thinking. Accordingly, we address the overarching research question: what influence do system properties which are only implicitly represented in system representations have on systems thinking?

To answer this question, we examine the results of three different studies on systems thinking in the context of ecology and physiology in the light of representations (Mambrey et al. 2020, 2022; Wellmanns & Schmiemann, 2020). First, we present the roles of the representations identified in these studies. We then illustrate the results using exemplary student statements to provide deeper insights into the challenges posed by implicitly represented system properties. In the following section, we briefly describe the potential contribution of each study. The studies investigated students' systems thinking in two different contexts, two studies in the context of ecosystems and one in physiological systems. In both contexts, representations play an important role in visualising the particular systems.

In the studies of systems thinking in ecology, two differing research approaches – a quantitative and a qualitative approach – were applied to examine students' systems thinking. The first, quantitative approach in the ecological context addressed the structure of systems thinking. In this study, about 200 lower secondary students answered items on (a) identifying system organisation, (b) analysing system behaviour and (c) performing system modelling of a food web in a given representation, showing that system-specific properties significantly impacted the students' systems thinking. Thus, identifying unmapped indirect relations was significantly more difficult than identifying direct predator–prey relationships. We discuss how relations that are only implicitly integrated into ecosystem representations can impact students' systems thinking skills. The second, qualitative study provides in-depth results of students' cognitive patterns while undertaking systems thinking in ecology. The thinking-aloud protocols of about 20 lower secondary students regarding a given food web (Fig. 6.1) were analysed to determine the impact of students' conceptions, knowledge and system representations. The understanding of representations emerged as a cognitive pattern which was particularly relevant for the identification of system organisation. To address our overarching research question, we identified the particular impact that the misinterpretation of representational features has on students' systems thinking. The results confirm the strong influence of implicit system properties on systems thinking in ecology. To gain further insight into the overarching validity of this result for systems thinking in general, we further investigated the impact of implicit system properties in physiological systems on students' systems thinking.

High school students' systems thinking skills in the study of physiological systems were also examined using a thinking-aloud approach. Thirty students were asked to analyse system behaviours and regulative measures based on a representation of blood glucose regulation (Fig. 6.2). The reasoning patterns that emerged through qualitative content analysis reveal that – inter alia – students struggled to consider both direct and indirect cause-effect relationships. In the corresponding section, we discuss students' relevant statements to identify obstacles they faced when reasoning with such a representation so as to identify challenges that result from the necessity to extract implicit system properties from a given flowchart. In sum, through the application of these approaches in different contexts, we seek to

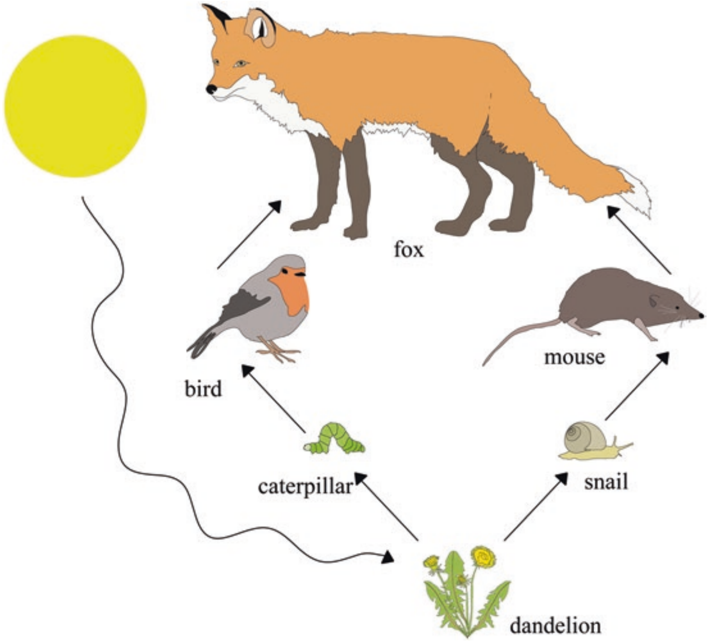

Fig. 6.1 Food web presented to the students in the qualitative thinking-aloud study. (Adapted from Mambrey et al., 2022; CC BY 4.0.)

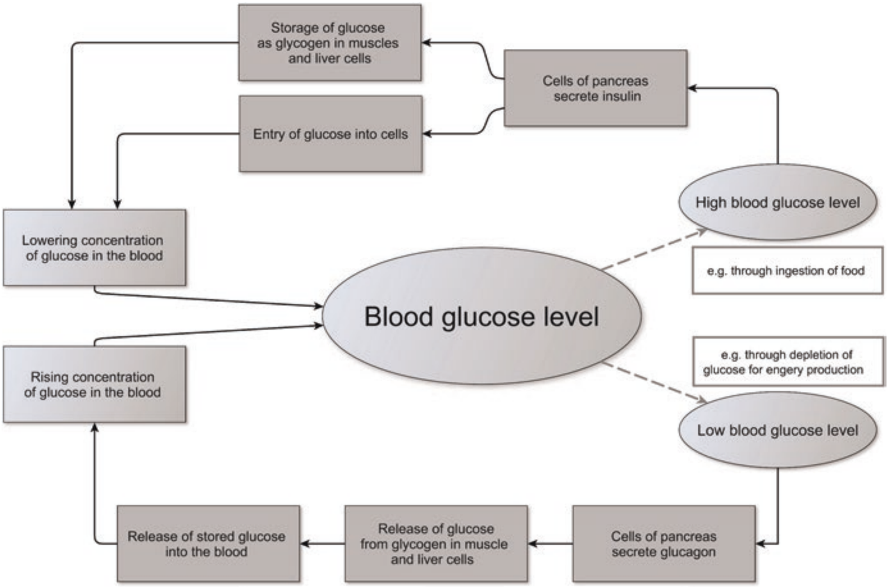

Fig. 6.2 Flowchart used to represent mechanisms of blood glucose regulation in the qualitative study. (Wellmanns & Schmiemann, 2020; CC BY 4.0.)

emphasise the importance of taking implicit system properties into account when building more sophisticated systems thinking skills.

6.6 Systems Thinking in Ecological Contexts

To visualise feeding relations in complex ecosystems, food chains and food webs are used as scientific models to depict the interconnectedness and relations between different species in an ecosystem. A food web is a model of a certain group of elements within an ecosystem (Begon et al., 2006) used to analyse and understand processes such as predator–prey relationships. Thus, the complexity of a given food web depends on the number of elements and the number of interrelations. Scientific conventions are used to express the relevant system properties within the food web. For instance, the smallest unit of a food web or food chain is the predator–prey relationship, depicted by an arrow pointing from an element at a lower trophic level to one at a higher trophic level to represent the flow of energy within an ecosystem. Feedback loop relations and their dynamic effects on the interactions of elements are thereby implicitly integrated into the model of food webs but are not explicitly presented.

Mambrey et al. (2020) quantitatively examined the impact of system specifics and system complexity on the understanding of food webs in 196 grade-five and grade-six students by systematically varying the system complexity and the qualitative type of relationship within the ecosystems. Applying an item response theory approach, they found that direct cause-and-effect relationships were significantly easier for students than indirect effects regardless of the systems thinking skill performed. Beyond that, the complexity had no further influence. These results emphasise the importance of investigating the influence of system properties on students' understanding of complex systems.

To gain further insight into students' understanding of ecosystems, Mambrey et al. (2022) focused on students' reasoning processes when dealing with complex systems so as to identify further influences on students' systems thinking abilities. Therefore, an in-depth analysis of the underlying conceptual understanding was conducted. In their study, 20 students aged 9–12 years conducted thinking-aloud protocols, which are considered a valid tool for accessing cognitive activities in educational and psychological research (Ericsson, 2006; Ericsson & Simon, 1998), while reviewing an ecosystem (Fig. 6.1).

The thinking-aloud protocols not only offered information on students' systems thinking skills, but also revealed their reasoning profiles and potential learning difficulties while verbalising their proceedings when seeking to understand food web ecosystems. Analysis of the reasoning profiles made it clear that difficulties in understanding the indirect effects in ecosystems can arise from the depiction of ecosystems. In particular, the conventionalised use of a food web does not represent the indirect effects of relationships in ecosystems, such as trophic cascades. The only effects integrated are A acts on B (the snail is eaten by the mouse) and B acts on C (the mouse is eaten by the fox). The causal consequence that the fox population indirectly influences the snail population is not depicted. Furthermore, in a food web, the population of an animal is depicted by either a picture of a single animal or by the name of a single element (for example snail or fox). If one assumes that it is not a population but rather a single animal that is depicted, complex indirect relations could not exist in the system. If the only existing snail is eaten by the only existing mouse and the mouse in turn by the only fox, a feedback effect cannot be represented. This effect is possible only under the assumption that populations interact. When students were challenged to construct these relations, it quickly became apparent that their understanding of the qualitative type of relationship was mediated by the representation of the ecosystem. For example, students negated indirect relationships in the ecosystems because "there is no connection between the animals [caterpillar, mouse] in the food web" (Student E1) or "I would assume this connection, but there is no arrow between the animals [caterpillar, mouse] in the food web" (Student E2). Thus, information that is missing through conventions – and only implicitly mapped – constitute a learning obstacle in students' statements regarding representations. These implicit system properties turn out to be a significant learning barrier for students' understanding of ecosystems. Furthermore, they offer a plausible explanation as to why the understanding of indirect relations is a significant learning barrier in all core systems thinking skills in ecology, regardless of the complexity of the ecosystem (Mambrey et al., 2020). Both of these studies (Mambrey et al., 2020, 2022) identify these implicit system properties as having a relevant impact on students' understanding of ecosystems (Mambrey et al., 2020, 2022). The question arises of whether implicit system properties are an ecosystem-specific factor that induces difficulties depending on the type of representation used to model complex systems, such as food webs in ecology.

6.7 Systems Thinking in Physiological Contexts

In contrast to ecological systems, physiological systems are characterised by self-regulation to maintain homoeostasis (Mayr, 1997). Maintaining this balance requires complex and interacting regulatory processes (Bich et al., 2016). The homoeostasis of blood glucose levels is an example of such a complex physiological system. Understanding blood glucose regulation requires integration of the effects of two negative feedback mechanisms. The first feedback mechanism represents a homoeostatic process that counteracts increased blood glucose levels and ultimately decreases blood glucose levels. The second feedback mechanism, active at the same time, acts as a homoeostatic process that counteracts decreased blood glucose levels by increasing blood glucose levels. Both feedback loops are based on processes at the molecular level in various spatial areas (for example, pancreas, muscle, liver and fat cells). To grasp the processes at the molecular level, it is necessary to understand that a multitude of processes and enzymes is involved (van Mil et al., 2016). For instance, insulin binding to cell receptors does not directly trigger the fusion of GLUT4 proteins to the cell surface to facilitate increased glucose uptake, but affects the cell indirectly through a series of molecular events (Jones et al., 2014). In most representations, however, the complex blood glucose regulation system is reduced to the most relevant processes for the sake of simplicity (for example the release of insulin and storage of glucose as glycogen).

Unlike in ecology, the depiction of complex physiological systems, such as blood glucose regulation, is less conventionalised (compare for example the following textbooks: Audesirk et al., 2017; Biggs et al., 2009; Brooker et al., 2018; Freeman et al., 2017; Hoefnagels, 2016; McGlade et al., 2016; Simon, 2017). Flowcharts as qualitative representations provide an overview of the system's structure by depicting, in a more or less conventionalised manner, the relevant system's elements and mechanisms. Elements in such flowcharts are diverse, as they can represent both regulated quantities (for example blood glucose level) and processes (for example release of insulin). Thus, explanations of the representational features may be added. Using the example of blood glucose regulation, a sequence of processes is depicted as a result of either an increased or a decreased value (Fig. 6.2). Compared to ecological food webs, negative feedback loop mechanisms are explicitly represented as characteristic features. While these processes are depicted in detail, other system properties such as the continuity of processes, self-regulation and knowledge about mechanisms as well as time delays remain implicit and must be integrated by the learners.

Wellmanns and Schmiemann (2020) used this flowchart with implicit system properties to examine how students explained blood glucose regulation as a complex biological system. Thirty students aged 14–16 participated in the thinking-aloud study. While solving the reasoning tasks, the students were asked to refer to the associated flowchart (Fig. 6.2), which models the underlying negative feedback mechanisms. Although the flowchart explicitly depicts a sequence of processes triggered by a deviation from the set point, students struggled to consider both direct and indirect cause-effect relationships to explain the consequences of external perturbation. When asked what happens when glucose is taken up with food, several students stated that the blood glucose level rises and then needs to be regulated, without mentioning explicitly represented feedback processes such as the release of insulin (Wellmanns & Schmiemann, 2020). The question arises as to why the students failed to interpret the flowchart and to what extent content knowledge about system properties is necessary for a comprehensive understanding of physiological systems. Based on the thinking-aloud protocols, we identified the challenge of integrating explicitly represented elements as well as relational properties and content knowledge. Process continuity, self-regulation and causal-mechanistic relations are implicit system properties in homoeostatic systems that seem to be challenging for students.

6.7.1 Process Continuity

To grasp complex system dynamics, students need to understand that many processes run continuously. For instance, glucose is constantly broken down at the molecular level, which is necessary for energy supply and thus the maintenance of elementary body functions. This property is shown implicitly in the associated flowchart. The diagram explicitly shows that depletion of glucose in the energy supply triggers a decrease in blood glucose levels. The necessary implication (that is, glucose is continuously broken down) has to be actively constructed by the students through their content knowledge that the body consumes energy even at rest. The lack of integration of content knowledge appears to have hindered students from gaining a deeper understanding of process continuity in homoeostatic systems; for example, student P1 stated:

> If you do not eat any food […], your blood glucose level cannot rise. As a result, the blood sugar level remains constant. The blood sugar level cannot be lowered because you probably do not do any sports during that time. (Student P1)

It is clear that the student did not realise that glucose is continuously broken down for energy supply, even if one does not exercise for a while. The implicit property that processes are continuously running appears to be a learning barrier to further insights.

6.7.2 Self-Regulation

Students' lack of awareness regarding the continuity of processes, such as basal metabolic rate, also influenced their understanding of self-regulatory processes, as they did not recognise that negative feedback processes are always active. Taking the example of the blood glucose level, it can only be maintained between meals through a continuous release of stored glucose triggered by the signalling molecule glucagon. Again, the system property of self-regulation is only implicitly integrated into the representation of the system. The flow chart explicitly shows negative feedback processes as being triggered by a decreased level of glucose; hence, there is a noticeable deviation from the set point. This lower feedback mechanism, however, runs continuously, except in situations where glucose is taken up with food. This implication is an inference of the element property that glucose is continuously broken down. Students failed to integrate these dynamic self-regulation processes into their explanations.

> If you do not eat any food, you will not consume any glucose, so your blood sugar level will not get any higher. When you rest, only a very little amount of glucose degrades, so the blood sugar level remains almost constant. (Student P2)

In this example, the student explained an observed steady state through the non-occurrence of external regulatory interventions (that is, no food intake/less glucose degradation), and thus did not recognise that homoeostasis, as the overall system behaviour, can only be maintained through the continuous effect of negative feedback mechanisms. To summarise, the students failed to transfer the explicit information, that the negative feedback mechanism becomes active after a disturbance, to the implicit extension – negative feedback mechanisms must always be active. A lack of understanding of self-regulation is a possible learning barrier, since students do not fully understand the meaning of regulative processes.

6.7.3 Causal-Mechanistic Relations

Furthermore, several students were unable to generate mechanistic explanations based on causal relations. The arrows in a flowchart explicitly represent causal relations, as linked processes symbolise a cause and subsequent effect. Beyond that, causal relations represent the starting point for the examination of the underlying mechanism. Mechanistic relations refer to implicit structures and processes that explain a causal relationship (Russ et al., 2008). In other words, mechanisms are often implicit but offer the possibility of explaining the linkage between a cause and its effect. Many students did not make any statements about mechanistic relations. For example, the following student identified causal relations but did not explain any further transport or effect mechanisms.

> Eating something results in a high blood sugar level and then causes insulin to be released into the blood. This condition causes glucose to be absorbed into the cells or stored in the liver and muscle cells in the form of glycogen, which leads to a lowering of the blood sugar level. (Student P3)

By describing causal relations, the student referred to the relations explicitly represented in the flowchart. Student P3 did not integrate any implicit relation property, such as that cause and effect are linked via numerous mechanisms, and that the effects occur with time delays. In contrast, Student P4 seemed to decode individual mechanistic relations.

> Insulin may lead to… That is, insulin ensures that glucose is taken up from blood into cells and that glucose is stored in liver and muscle cells. If there is no insulin released or if there is any disorder, glucose will not be stored. Consequently, a high blood glucose level could not be controlled. If you take up more [glucose, food], the level will increase even higher, which is not good. The person would have to do something about the disorder or see a doctor. The person would have to try to use a lot of energy – a lot of energy is necessary. (Student P4)

The student recognised that insulin controls the entry and storage of glucose into the cells. However, the student did not name the exact mechanism (that is, insulin is transported via the bloodstream and binds to receptors in the membrane, initiating protein activation cascades that lead to the insertion of the GLUT transporter). This result is not surprising, since this information was not explicitly presented to the students. Nonetheless, the student recognised that there is such a mechanistic relation, as they pointed out that somehow insulin controls entry and storage. Thus, student P4 identified an implicit relational property and inferred that if there is no release of insulin, the blood glucose level will increase permanently and further increase with each subsequent food intake, since glucose is not taken up into the cells. P3 suspected that external intervention is inevitable, concluding that it would be difficult to decrease the blood glucose level, as doing so would require great energy expenditure. Thus, the student made an assumption about the magnitude of the effect of insulin and activity in decreasing blood glucose levels. However, this information, which is not explicitly depicted in the flowchart, represents the necessary integration of content knowledge.

Overall, we can see that students failed to integrate implicit system properties in their analysis of the blood glucose regulation system. If students do not integrate their content knowledge about the basal metabolic rate, they will not conclude that the negative feedback mechanisms are continuously active. Furthermore, if students do not integrate content knowledge about molecular structures and processes, they will not be able to provide causal-mechanistic relations. Consequently, implicit system properties in physiological representations seem to represent a significant learning barrier, offering a plausible explanation for why the students failed to explain the maintenance of homoeostasis with the effect of negative feedback mechanisms.

6.8 Discussion

We have discussed some examples in which students failed to identify implicit system properties and considered the reasons for such failure. Some implicit system properties are identifiable through logic. Indirect relations in food webs, for example, are reasonably evident on the basis of logical considerations. If population A acts on population B and population B acts on population C, then it can be logically deduced that population A should also have an effect on population C. To be able to classify this inference correctly, however, learners have to integrate the implicit property of the species drawn in the food web into their mental model of the system. Each species represents a population rather than an individual. Consequently, students need representation- and system-specific content knowledge to understand system dynamics.

Flowcharts of the blood glucose regulation system usually explicitly depict negative feedback loops as central mechanisms, but other system properties remain implicit. Due to the basal metabolic rate, maintaining a more-or-less constant blood glucose level is only possible through the continuous release of glucose. However, this information is only implicitly integrated into most qualitative representations of the blood glucose regulation system (Wellmanns & Schmiemann, 2020). We demonstrated that students have difficulties in grasping the implied continuity of processes when working with this type of representation, assuming that both negative feedback mechanisms become active only after a disturbance. This demonstrates that content knowledge is required to fully understand the meaning of the processes and the negative feedback mechanisms involved in blood glucose regulation. In addition, these findings apply to causal-mechanistic relations with time delays. Students did not achieve a deeper understanding of the underlying causal-mechanistic relations due to the hindrance posed by implicit system properties. More precisely, they failed to adduce particular processes that can explain the mechanisms of causal relations. Our results reveal that this discrepancy led to difficulties in students' understanding and hampered the content-specific performance of students' systems thinking.

For a comprehensive understanding of complex systems, both explicit and implicit system properties need to be integrated. These implicit system properties include, at a minimum, implicit element properties, implicit relations and implicit relation properties. We claim that there are three reasons why system properties are not explicitly represented: simplification, convention and emergence. 1) Simplification: The modelling of complex systems for educational purposes usually involves simplifications so as to focus on specific system properties. 2) Convention: How a system is represented graphically depends largely on technical conventions and traditions. In food webs, for example, predator–prey relationships are represented by unidirectional arrows, although the Lotka–Volterra model, which is frequently used to describe individual predator–prey relationships, assumes that predator and prey populations interact. 3) Emergence: Emergent phenomena cannot be represented but arise only through the interactions of system elements.

Our results align with Schnotz's model (Schnotz, 2014) positing that prior knowledge is important for understanding representations. We consider prior content knowledge to be necessary to identify only implicitly represented system properties and integrate them into the mental model of the system, suggesting in turn that systems thinking, at least when examined in relation to representations, is significantly influenced by content knowledge, corroborating Sommer and Lücken's (2010) finding that systems thinking is related to content knowledge. Regardless of the type of influence on students' learning process, it can be perceived that there is a qualitative difference in the systems thinking of novice and experienced learners. Novices are more likely to refer to the surface features of systems, while experts consider the underlying system properties and dynamics as relevant in their reasoning process (Hmelo-Silver et al., 2007; Lee et al., 2019; Tripto et al., 2018).

Because implicit system properties can significantly influence system dynamics, content knowledge is necessary to fully understand a complex system based on system representations. Generally, tasks that require reasoning based on (multiple) system representations are suitable for promoting systems thinking skills. However, static representations of system elements and relations may not be sufficient for grasping, exploring and describing complex system dynamics, underlying mechanisms and emergent system properties (Kitano, 2002b).

There are several ways to overcome the limitations of conventional and static representations: prompts, sequencing and simulations. (1) Prompts are a way of making students aware of implicit properties (Bannert, 2009). For example, insulin is synthesised by the pancreas and affects muscle and liver cells. Therefore, a prompt could encourage students to consider which process the arrow connecting these two processes must implicitly represent. A correct answer would entail that it represents a transport mechanism for insulin, indicating that insulin is passively transported by the bloodstream. (2) Animations can help visualise systems' behaviour and dynamics over time (Lowe & Schnotz, 2014). (3) Simulations are well-suited for examining complex system behaviour under different conditions and the consequences of planned interventions. For example, simulations work well for investigating the consequences of a forgotten dose of insulin or an overdose of insulin in a diabetic patient.

We assume that the aforementioned methods can help improve students' abilities in systems thinking. However, this does not mean that students' skills would automatically increase regardless of the context, for implicit system properties limit the generalisability of systems thinking. The implicit properties vary from system to system, and specific content knowledge is usually required to decode them. Thus, the effective promotion of systems thinking requires an extensive process of analysing the system of interest and the requirements for learners, whereupon learning materials and representations must be designed in such a way that the relevant implicit properties become apparent – for example, through the use of prompting, sequencing or simulations – and to ensure that learners have the tools to successfully identify them.

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Chapter 7
The Zoom Map: Explaining Complex Biological Phenomena by Drawing Connections Between and in Levels of Organization

Niklas Schneeweiß and Harald Gropengießer

7.1 Introduction

Understanding and explaining complex biological phenomena such as the results of climate change or evolution requires students to think systemically. However, systems thinking—namely, relating concepts to the right level of organization or adequately interrelating concepts across levels of organization—is difficult for students. To address this issue, science educators have proposed to apply learning and teaching strategies such as the yo-yo (Knippels, 2002; Knippels et al., 2005) and tools that foster understanding, such as the concept map (Novak, 1990). A characteristic of yo-yo learning environments is addressing and changing the levels of organization.

Nonetheless, teachers can and should encourage learners to interact with the levels. We propose the zoom map as a useful tool to reflect on levels of organization and explain complex biological phenomena. By making levels of organization explicit and incorporating the idea of zooming in and out of a phenomenon, we intend to guide students' explanations across the levels of organization. This chapter discusses how the zoom map encourages learners to reason on different levels of organization.

To begin with, we briefly outline the difficulties of biological complexity with a focus on the role of the levels of organization. After that, we concentrate on biological complexity both from the scientists' and students' perspectives to derive teaching-guidelines from the educators' perspective. Further on, we explain how the zoom map relates to these guidelines and can help cope with biological complexity. Following the description of our methods, we discuss evidence from teaching

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interviews. We conclude by presenting our research's implications for teaching biology.

7.2 What Makes Biological Explanations Complex? The Perspective of Scientists

7.2.1 Characteristics of Biological Explanations

Biologists, chemists, physicists, and other science experts originally performed research to construct the explanations of scientific phenomena of the world around us. Most sciences started with observing and describing phenomena. A currently more advanced science such as biology developed the art of explanation and prediction. An explanation needs an explanandum, that is, something to be explained, and an explanans, by which it is explained. The explanans consists of antecedents, namely initial or boundary conditions that, together with general laws or regularities, result in causal explanations (Hempel & Oppenheim, 1948).

According to Mayr (1961) explanations in biology fall into two forms of explanantia: proximate causes (namely, physiological mechanisms) and ultimate causes—namely, evolutionary mechanisms that explain the existence of a specific trait through variation in a population and non-random survival in a given environment. This distinction has been further elaborated and complemented, but is still regarded as vital (e.g. Laland et al., 2011). Furthermore, the distinction has proved its usefulness in selecting conceptual content for biology curricula (Carvalho et al., 2020). The explanandum in biology is, in most cases, a phenomenon that has no straightforward explanation, unlike the movement of a billiard ball. In biology, the explanans may be structured as a causal chain, but, more often, it is like a net or even a felt, and, as if that were not enough, it runs over several levels of organization.Today, it is commonly accepted that "complexity is endemic in biology" (Mitchell, 2012, p. xiii) because the latter "is constituted by […] multilevel […] systems." We assume complexity when we observe a phenomenon that emerges from entities with specific properties that interact. A system can be described as complex (Dauer & Dauer, 2016; Eilam, 2012; Mitchell, 2012) if it:

- is open.
- is structured into multiple levels of organization.
- has many entities.
- presents interaction of entities within and across levels of organization.
- is influenced by the entities' behavior and.
- has emergent properties.

7.2.2 A Plethora of Biological Levels

We have introduced what makes biological explanation complex. Arguably, the multiple levels of organization significantly contribute to the complexity of biology. To complicate matters, albeit the omnipresent usage of the term levels of organization in biology and biology education, the term is not as clear as its prevalence might suggest. Even fundamental questions such as, "Which are the levels of organization" are not yet definitely answered (Eronen & Brooks, 2018; Schneeweiß & Gropengießer, 2019). As a first step towards a new consensus on levels, we conducted a literature review on the levels of organization in the fields of biology and biology education to shed light on the diversity of levels. The review (Schneeweiß & Gropengießer, 2019) revealed 20 different levels of organization and some more synonyms (Fig. 7.1).

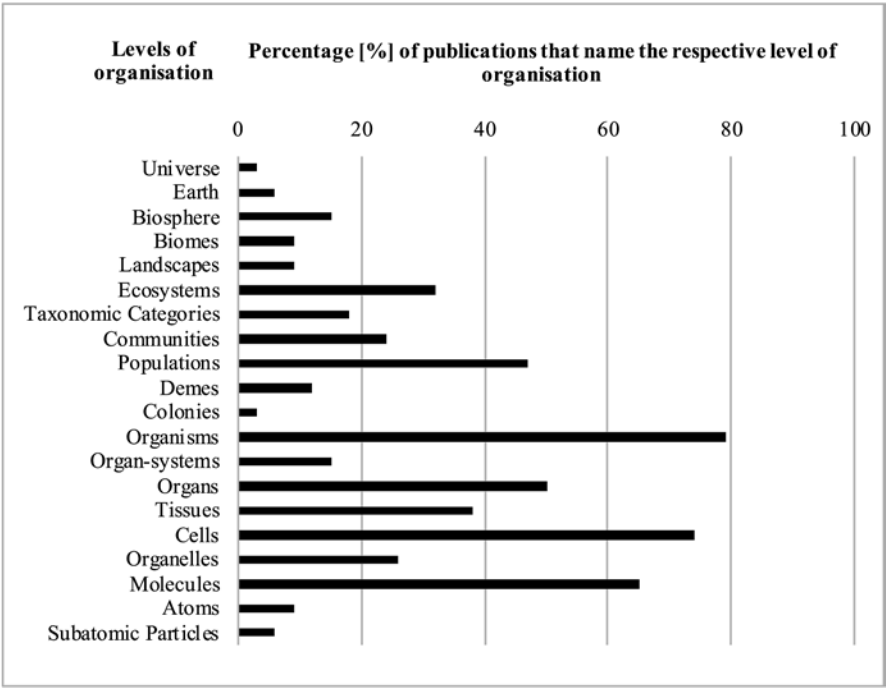

Fig. 7.1 Coding results for individual levels of organization explicitly named in biology and biology education journal articles ($N = 36$). The percentage refers to the number of papers that name the respective level at least once in relation to the total number of papers

7.2.3 Organizing the Levels of Biological Organization

Our review further revealed that levels of organization can be formed, ordered, and related through different relationships—mainly, coevolutionary, matter-energy, and physiological relationships that can be ordered in a system of levels (MacMahon et al., 1978; Schneeweiß & Gropengießer, 2019; Fig. 7.2). Picket et al. (2007) point out that each level has different facets for example behaviour or appearance. Different biological research traditions may focus on distinct facets.

7.2.4 Comparing the Levels of Scientific Disciplines

A look at disciplines such as physics and chemistry suggests that things seem to be less complex, at least regarding the levels. Physicists use a scale of powers of ten to place their objects of study. Philosophers with an evolutionary epistemological point of view hold that our cognitive system is adapted to a world of medium dimensions—a world that we can perceive and interact with. Vollmer (1984) calls this section of the real world the mesocosm. Things that are smaller as the breadth of a hair or larger than the distance to the horizon are hard to understand, as they belong to the microcosm or macrocosm, respectively (Niebert & Gropengiesser, 2015). Chemists use the three levels of microscopic particle, nanoparticle, and substance (submacro, macro, and an extra-symbolic level; Johnstone, 1991). Even if we consider the recent discussion about a nano-level in chemistry, there is no comparison with the multitude of levels in biology (Fig. 7.3).

The shown complexity by levels in biology is challenging, this applies all the more as the levels of organisation—especially in their non-branched version—may invoke the misleading idea that this hierarchy is strictly based on the size of an observed object. But a small log on the forest floor may be regarded as an ecosystem as well as it is part of a large forest community. This led to the construction of an alternative representation, particularly suitable for ecological research (Pickett et al., 2007, 29; Allen & Hoekstra, 2015, 60). Guiding learners to structure an explanation of biological phenomena the levels of organisation still appear appropriate. We will elaborate on the challenges of this task in the next section.

7.3 What Makes Biological Explanations Complex? – The Students' Perspective

7.3.1 Students' Difficulties for Explaining Phenomena

Scientific reasoning is a day-to-day task for experts, but students have various difficulties explaining biological phenomena. As we argued in the previous section, the levels of organization contribute to the complexity of biology. Unsurprisingly,

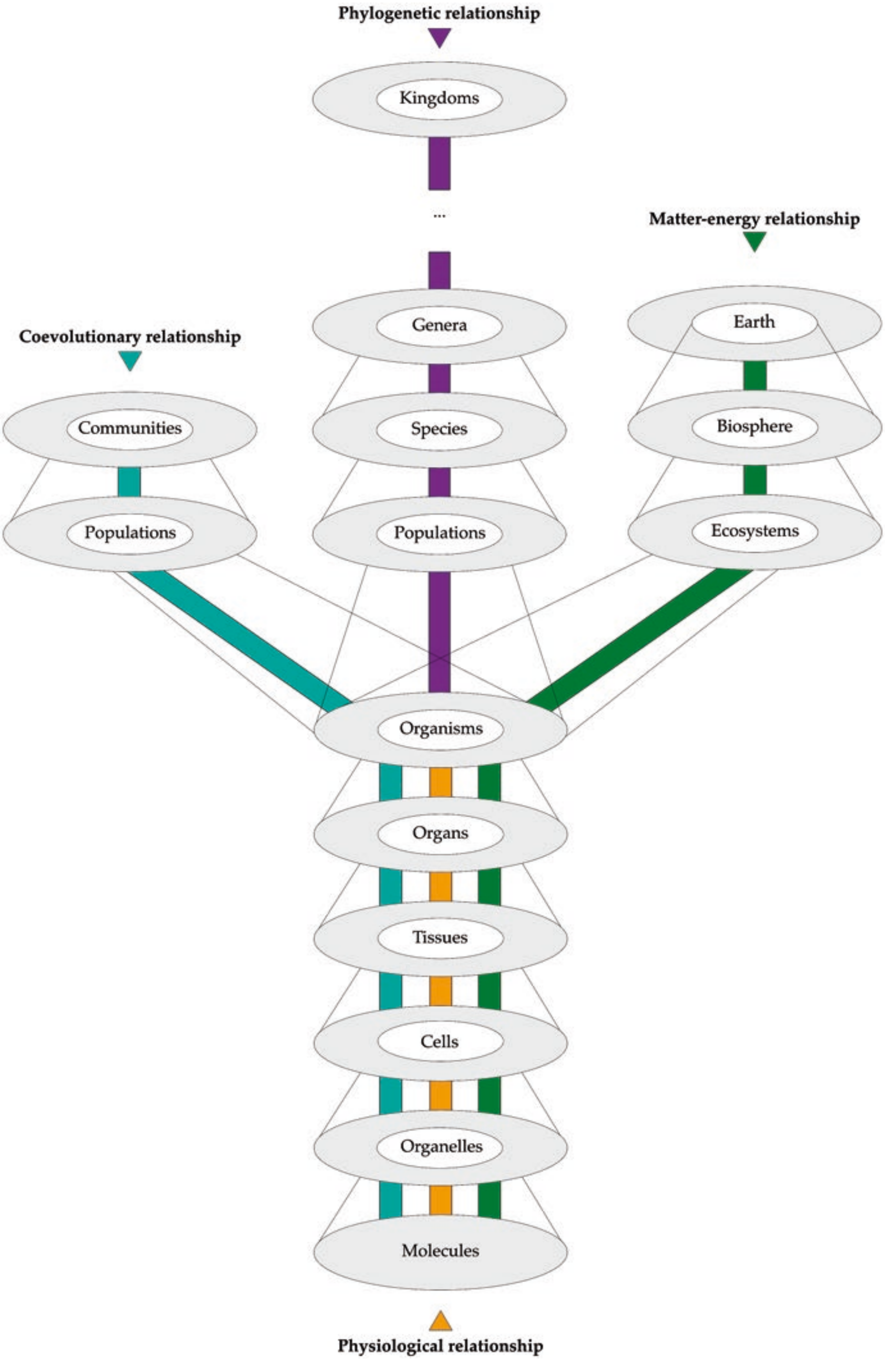

Fig. 7.2 A system of levels of organization for biology education. The system makes the relationships between the levels explicit and incorporates the idea of zooming. (Schneeweiß & Gropengießer, 2019, p. 14)

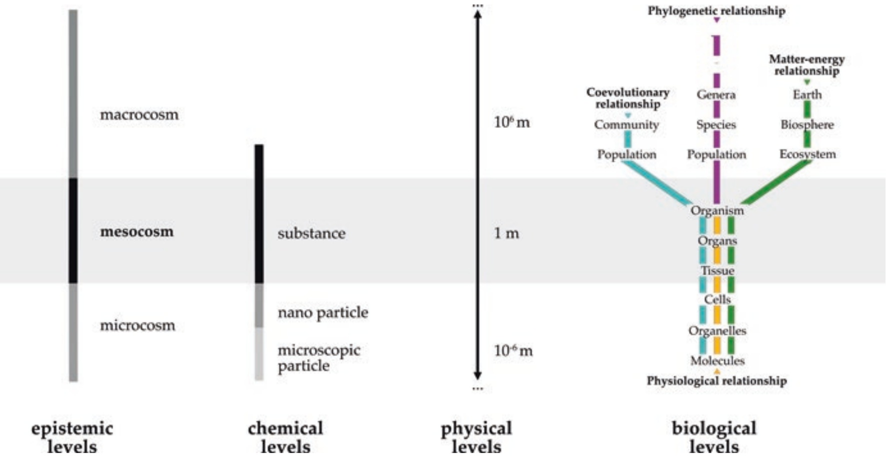

Fig. 7.3 Comparison of organizational levels of different scientific disciplines

minding the levels of biological organization seems to be a significant obstacle for students (Hammann, 2019). Research on many different biological topics, such as cell biology, genetics, or physiology, revealed learning difficulties related to levels of organization (Hammann, 2020; Schneeweiß & Gropengießer, 2019).

Typical difficulties are the confusion of levels (Wilensky & Resnick, 1999), explaining only on one level (Jördens et al., 2016), or failing to interrelate levels (Brown & Schwartz, 2009). For example, in ecology, some students can describe the processes of photosynthesis and respiration at the molecular level yet fail to interrelate the two processes at the level of the ecosystem (Brown & Schwartz, 2009). In this example, the individual elements of knowledge are not connected. This may be termed as fragmented knowledge. Learners may combine their fragmented knowledge differently, depending on the phenomenon, thus resulting in different explanations. (Clark, 2006; DiSessa et al., 2004; Izsak, 2005; Wagner, 2006). Learners often do not succeed in finding adequate causal explanations across the levels of organization. Therefore, interventions that foster the integration of knowledge are needed.

The difficulties described in the literature may be related to the construction process of an explanation, as we will elucidate in the next section.

7.3.2 Zooming in on the Construction of Explanations

Explanations are generated ad hoc. Students thereby interact (i) with the phenomenon, (ii) with incitement from peers, teachers, or texts, and (iii) with their own available cognitive resources, namely their conceptions, knowledge, and ideas. This “emergent construction in interaction” (Boersma & Geraedts, 2009; Schwarz et al., 2008) may lead to different explanations for similar phenomena. Guidance will help activate and integrate the available knowledge and draw useful connections between conceptions at different levels. Guidance should focus on the problem-solving process rather than the possible answers (Schwarz et al., 2008).

A fruitful structure for guiding the process of problem-solving and explaining in biology is the yo-yo learning and teaching strategy. Named after a famous toy, this strategy proposes moving up and down the levels of organization like a yo-yo (Knippels, 2002; Knippels et al., 2005). Our study relies on adapted yo-yo learning principles as listed in Table 7.1 (Jördens et al., 2016, p. 961; Tripto et al., 2016, p. 568).

We have now explored the complexities of biology from both the scientists' and the students' perspectives. In the following section, we take the educators' perspective and introduce learning principles and the zoom map.

Table 7.1 The zoom map supports yo-yo learning

Yo-yo learning (Jördens et al., 2016, p. 961; Tripto et al., 2016, p. 568)	Support by the zoom map
1. Distinguishing different levels of organization	The zoom map explicitly displays the system levels as stacked wide ellipses.
2. Identifying the entities and processes of a system (and relating them to a level)	System entities can be assigned to a system level by writing them into the ellipses. In Fig. 7.11, the cell membrane and the cell wall are assigned to the cell level.
3. Linking concepts at the same level of organization (horizontal coherence)	The system entities are linked by words or phrases forming propositions if the reading direction indicated by arrows is followed. The rules for the construction of concept maps apply. Propositions should be meaningful.
4. Linking concepts at different levels of organization (vertical coherence)	In the zoom map, one can zoom into each structure and describe the system at a lower level ($n - 1$). The different levels can be related vertically. See 11 as an example.
5. Thinking back and forth between levels (also called yo-yo learning)	In an effort to explain a phenomenon, learners should start at that very level. With the help of supporting material, learners can move downwards and explore each level repeating steps 1 to 4. Finally, based on their zoom map, they can try to give a mechanistic explanation of the phenomenon or identify missing knowledge. This step usually involves moving upwards in the zoom map.
6. Meta-reflection about the question of which levels have been transected	Moving across levels and reflecting on levels are an immanent process of the construction of a zoom map. The first reflection on levels occurs when system entities are assigned to levels. The second reflection on levels concerns the horizontal and vertical interrelations. In the construction process, learners have to discuss these interrelations. After the construction of an individual zoom map, meaningful comparisons to other zoom maps may support learning. The teacher should give feedback and orientation if needed.

7.4 Guiding the Process of Explaining with the Zoom Map—The Educators' Perspective

7.4.1 Theoretical Learning Principles for Teaching Complex Phenomena

The development of the zoom map is grounded on six key insights:

1. Biological phenomena need to be examined and explained at multiple levels. Depending on the phenomenon, explanations require different sets of levels, which relate to the various relationships that facilitate the levels. Explanations may use components from lower or higher levels of organization of a given phenomenon (Brooks, 2021; Novikoff, 1945; Schneeweiß & Gropengießer, 2019);
2. Levels of organization can bring structure to otherwise unstructured scientific problems if they are made explicit (Brooks, 2019; Hammann, 2019; Schneeweiß & Gropengießer, 2019);
3. To support students in explaining phenomena, teachers should structure learning environments according to systems thinking principles—for example, via yo-yo learning (see Table 7.1; Knippels, 2002). Teaching should focus on interrelating concepts within and across levels of organization (Hammann, 2020);
4. Students need guidance during the problem-solving process (Schwarz et al., 2008);
5. Students do not automatically consider the levels of organization; they need to be encouraged, and levels of organization have to be made explicit (Hammann, 2019; Reinagel & Bray Speth, 2016).
6. Zoom levels and zooming in and out are student-oriented metaphors for the levels of organization and change between them (Schneeweiß & Gropengießer, 2019).

7.4.2 The Zoom Map

To make the theoretical learning principles operative, we invented a tool to cope with the complexity of explaining biological phenomena—the zoom map. This new graphic organizer guides learners in the process of explaining and prompts them to consider the relevant entities and their relationships, as it makes levels of organization explicit. As the name reveals, the zoom map draws on the metaphor of zooming. This metaphor's experiential source domain is bringing an object near to the eye to see more details or stepping back to get an overview, not to mention image scaling on digital devices that allow magnifying or shrinking. Zooming biological phenomena consequently leads to stopovers at the levels of organization. Zooming in focuses on smaller sections of the scientific problem; zooming out takes the whole or the context into account (Brooks, 2019; Schneeweiß & Gropengießer, 2019). Moreover, zooming calls for relating the entities at the different levels. The zoom map fosters students' causal explanations across levels of organization through the inherent demand to consider the respective levels. Therefore, the zoom map may help students structure and interrelate fragmented knowledge and achieve integrated knowledge.

Within the levels, the horizontal relations were drawn similar to the mode of concept maps (Novak & Cañas, 2006). We adapted the concept map because it has already proven fruitful in the context of systems thinking (Brandstädter et al., 2012; Dauer et al., 2013; Schwartz & Brown, 2013; Schwendimann & Linn, 2016) and is known for its capability to foster conceptual interrelations (Fischer et al., 2002; Novak & Gowin, 1984; Van Drie et al., 2005). Combining zooming with concept-mapping is the core idea of the zoom map.

By zooming into an entity at one level, one reaches a lower level. In the zoom map, this is implemented in the following way: Ellipse shapes indicate levels of organization. Each level features its own concept-map displaying the structures and relations concerning a phenomenon. By zooming into the term that denotes a structure at one level, one reaches another lower level. Vertical arrows indicate vertical interrelation; horizontal arrows indicate horizontal interrelation (Fig. 7.4).

Since levels are phenomenon-specific, the zoom map layout may and should be adapted to the phenomenon in question. For example, explanations of physiological phenomena will require the level of the organism to give context and significance, the level in question, and the one below that gives the explanans, such as causes and mechanisms. In general, not less than three levels and their interrelations have to be considered for an adequate explanation of a phenomenon: the focal level, a level below, and one above (Allen & Hoekstra, 2015, 18). Depending on the phenomenon—for example, when comparing two different organisms—it may be adequate to juxtapose or diverge the zoom maps (Fig. 7.5).

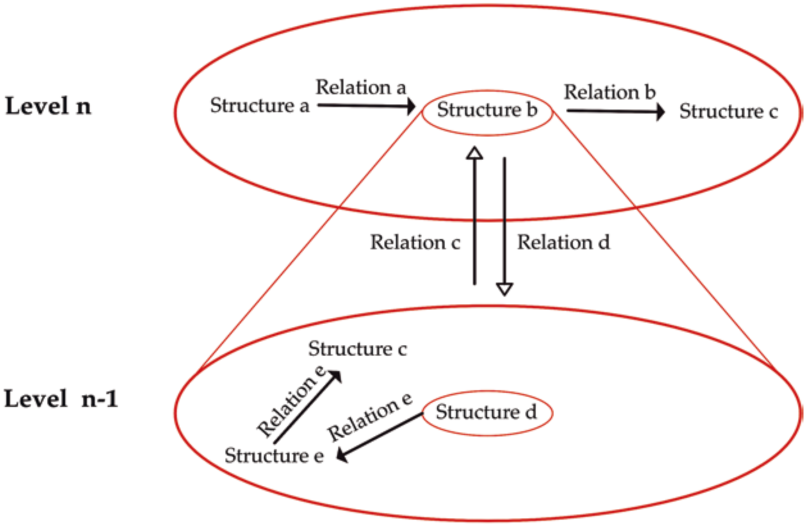

Fig. 7.4 Principle of the zoom map

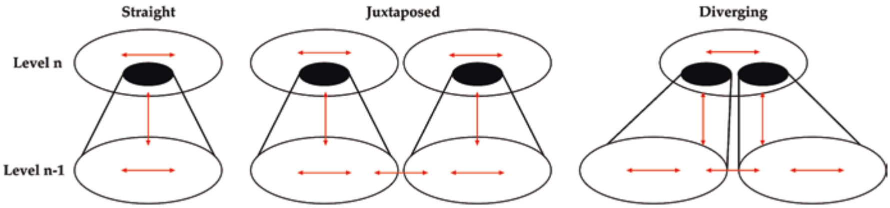

Fig. 7.5 Different ways of zooming in the zoom map. Red arrows indicate horizontal and vertical interrelation

To support students explaining phenomena, teachers should structure learning environments according to the principles of systems thinking—for example, with yo-yo learning (Knippels, 2002). The zoom map supports the construction of explanations according to systems thinking, as shown in Table 7.1. While yo-yo learning focuses on units or lessons, the zoom map focuses on the individual learning opportunity.

7.5 Design of the Study and Materials

In our study, we examined how students construct scientific explanations of the wilted painted nettle with the zoom map's help. We developed and conducted teaching experiments (Komorek & Duit, 2004; Steffe & Thompson, 2000), as well as a study design that is open and flexible and allows for interventions (see Fig. 7.6).

We showed two painted nettles (Fig. 7.7) and asked, "Why are the leaves of the left plant upright and the leaves one the right wilted?"; a typical student explanation would be, "Because the water went out" (Torkar et al., 2018, p. 2273).

The student's explanation is viable in everyday life, but a biologist would formulate a mechanistic explanation that connects water to the leaves' appearance and structure. A short version of a mechanistic explanation would be: Water filling the cells protoplast will be pressurized by straining the cell wall. The cell wall is a somewhat elastic, tensile strength structure. Due to its properties, the cell wall limits the expansion of the protoplast (Campbell et al., 2008, p. 770; Thoday, 1918). The hydraulic interaction between protoplast and cell wall results in a turgid cell, comparable to an inflated football. Interacting with the other cells of the mesophyll, the leaves become turgid, comparable to several inflatable tubes that form a boat. This mechanistic explanation spans several organization levels, such as organelle, cell, tissue, and organ. We included these levels in our material, as we will demonstrate in the next section.

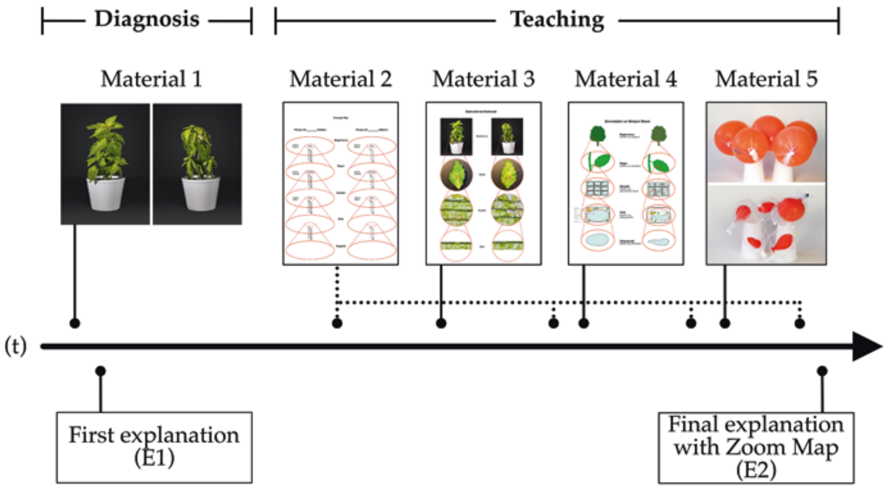

Fig. 7.6 Timeline of the teaching experiment

Fig. 7.7 Material 1 (M1) shows a painted nettle (Coleus scutellarioides) in regular and wilted condition

7.5.1 The Zoom Map Prepared for a Particular Explanation

The students received a series of instructional materials (M2–M5). Apart from the material, the teacher offered no further explanation of the phenomenon. Instead, the teacher instructed the students to interact with the material with impulses such as “describe” or “what do you see?”. The first material that the students received was the zoom map (M2). Since students had never worked with this tool, we chose a semi-structured approach. The zoom map already displayed the relevant levels of organization (Fig. 7.8). Throughout the teaching segment, we asked participants to complete the zoom map.

7.5.2 Experience-Based Conceptions Are Needed to Construct an Explanation

The zoom map is intended to guide the process of a phenomenon’s explanation. Even if the phenomenon is plainly perceptible, the causal explanation entities are probably not well known. Students need to develop conceptions based on experience with the phenomenon. This experience is especially relevant if students have to consider levels that are within the microcosm (Niebert & Gropengiesser, 2015). Therefore, one key aspect is that students get the opportunity to investigate the phenomenon themselves or are provided with external representations of entities and their properties. Ideally, the phenomenon at all relevant levels of organization is depicted (Figs. 7.9 and 7.10). We show our worksheets on the phenomenon of wilted and erected leaves as an example.

7.5.3 External Representations Depict the Mechanism

We handed the participants two models that were intended to represent the mechanism needed for explanation. The models consisted of balloons connected with nets. One model had firm and one limp balloons. The balloons were intended to represent the protoplast, the nets the connected cell walls at the level of tissue. At the end of the teaching experiment, students were asked to explain the phenomenon based on their zoom map (E2: final explanation with the zoom map).

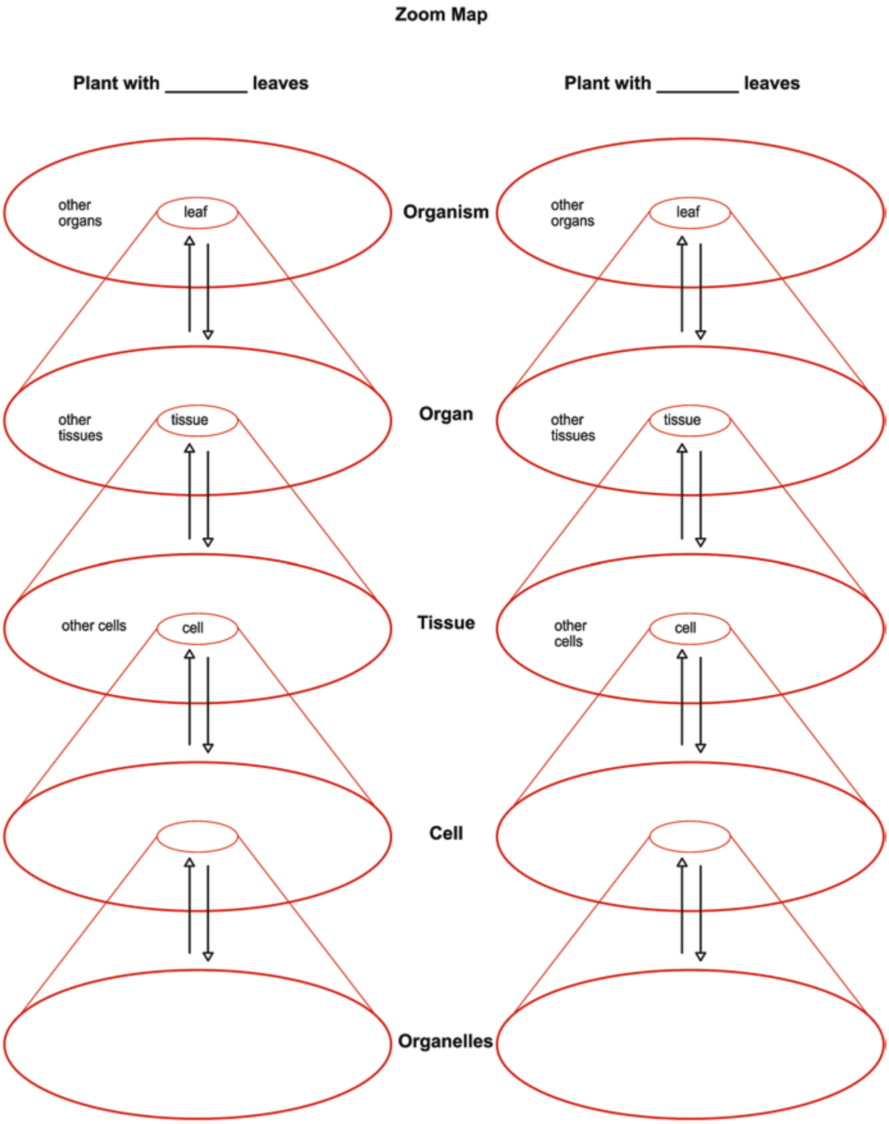

Fig. 7.8 Material 2, the zoom map used in the teaching experiment (translated)

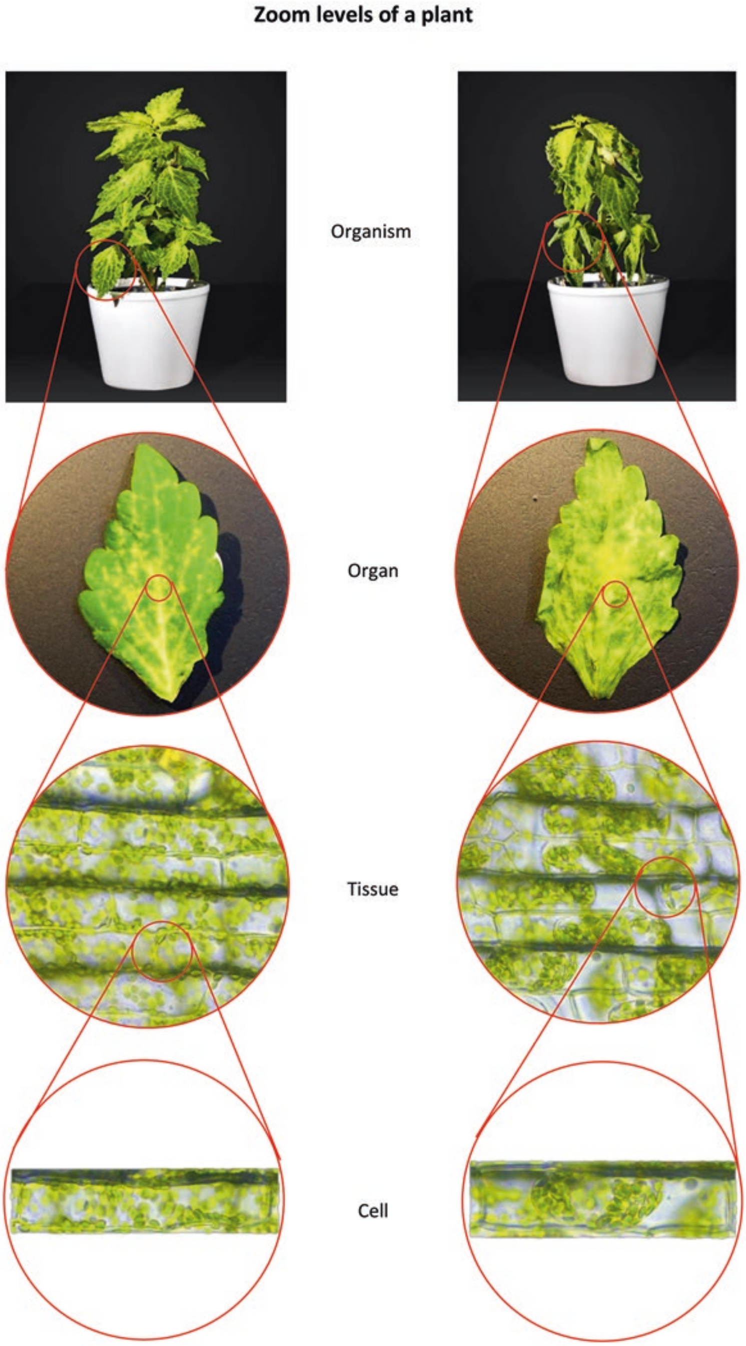

Fig. 7.9 M3 shows photographic images zooming from organism to cell

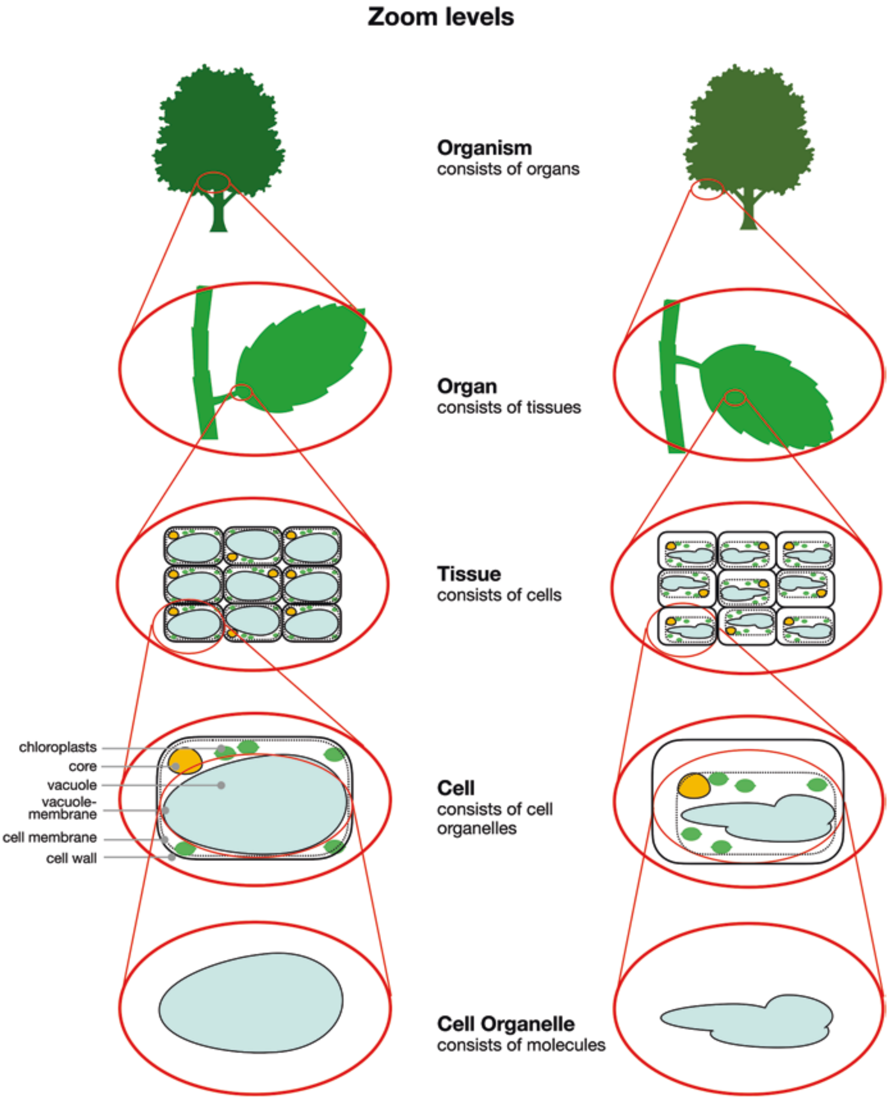

Fig. 7.10 M4 illustrates the phenomenon from the level of organism to organelle

7.5.4 Participants

We conducted the teaching experiment with 13 students in seven groups. The students attended a public high school in northern Germany. For analysis, we recorded the audio and video of each teaching experiment. On average, the teaching experiments lasted about 48 min (Table 7.2).

Table 7.2 Participants

teaching experiment	A	B		C		D		E		F		G	
Students	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Age [years]	15	17	16	16	17	16	16	16	16	17	17	17	17
Duration [min]	43	50		78		39		40		49		38	

7.5.5 Analysis

To prepare the analysis, we transcribed the interviews. During the interview, the student edited the zoom map (Fig. 7.8) by filling in their explanation of the phenomenon on different levels of organisation. For further analysis, we scanned and digitized the student-edited zoom maps.

We then identified the sections of the interviews relevant to the explanation of the upright and wilted leaves. We named these sections the first explanation (E1) and final explanation with the zoom map (E2). The analysis was based on the computer-supported qualitative analysis (Kuckartz, 2010).

To investigate the levels of organisation and the direction of the students' explanations, we developed a code system. One part of the code system were the levels of organisation: organism, organ, tissue, cell and organelle. The other part of the code system concerns the direction of explanations. We expected five different directions: one level only with no direction in the proper sense, downwards, upwards, downwards-upwards, and upwards-downwards. All six transcripts were coded by the first author and discussed with the second author. If statements were unclear, we investigated the zoom maps of the respective students. If the statement was not related to a level on the student-edited zoom map, we categorised it as 'not defined'. We present the results of the analysis in the following section.

7.6 Results

To provide an example of the interaction with the zoom map and the resulting explanations, we describe teaching experiment C. In the remainder of this section, we illustrate the process of working with the zoom map and explain why exhaustive editing is needed. Finally, we analyze the students' explanations with regard to the levels of organization and the direction of the explanation.

7.6.1 A Zoom Map to Explain Upright and Wilted Leaves

The zoom map of teaching experiment C explains the phenomenon at the relevant levels (organism to organelle) and interrelates system parts. Downward links are labeled with "consist of" (Fig. 7.11). Students, therefore, used the part-whole

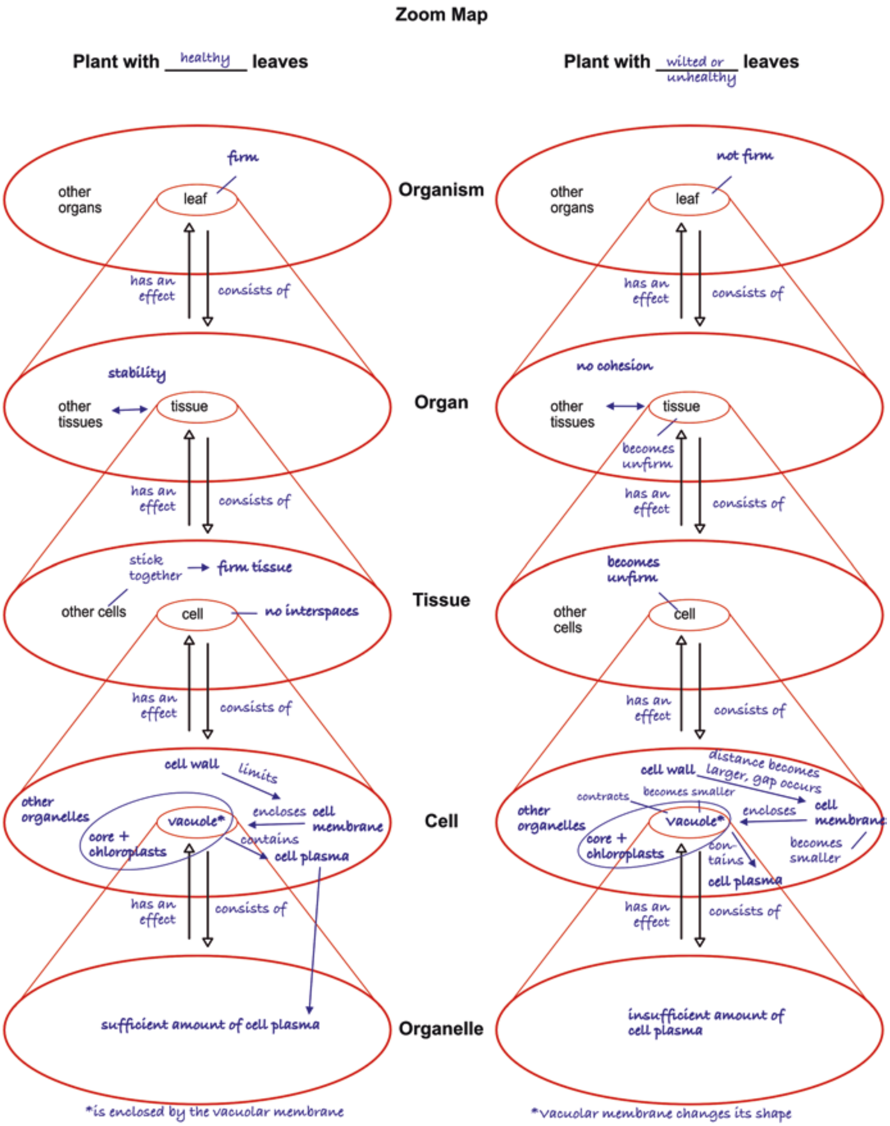

Fig. 7.11 Zoom map constructed by students S4 and S5 of teaching experiment C. The students' answers are shown as handwritten. (digitalized and translated from German)

scheme to explain how lower and higher levels were related. The lower levels have "an effect" on the higher levels, as labeled on upwards links.

Based on their zoom map, Student S4 and S5 explained the phenomenon as such (translated from German):

S5: "Well, the individual cells are filled in a fitting manner by the nucleus, chloroplasts, and also the vacuoles, which actually take up a large part of the cell. Therefore, when the vacuole is filled with sufficient quantity, it presses against the cell membrane, and this, in turn, presses against the cell wall, which is why the individual cells are very stable—because they are pressed from the inside out and cannot collapse somehow. Therefore the cells are—no, therefore the tissue, which consists of different cells is also … well, it presses everything against each other, and that is why it is very stable, and then individual tissues press against each other, and that is why the whole leaf is filled from the inside and cannot collapse at all—because everything is filled from the inside." (C, S5, l. 317)

S4: "Then with wilted leaves … so the general problem is that there is too little cell plasma, and this is the reason why the vacuole decreases. Because there is too little water or too little substance in it, it [the vacuole] contracts and because it takes up a large part of the cell, the cell membrane, and in general the whole cell, is shrinking. Therefore, it can no longer fill the cell as a whole, meaning on the outside. And that's why gaps are created that then make the whole unstable. If we are now here at the tissue level and there is no cohesion within the cell membrane and the outer part [cell wall], it limits it, doesn't it? Well, in any case, it [the tissue] becomes unstable because of these spaces that are created by this, and the whole leaf appears to be withered." (C, S4, l. 318)

In their explanation, students S5 and S4 addressed the levels from organ to organelle. To explain the upright leaf, student S5 started at the cell level by describing its filling. He then switched to the level of the organelle and reported that the vacuole was filled. His explanation of the interaction between vacuole, cell membrane, and cell wall (pneu principle) was at the cell level. He continued with the tissue level in his explanation: stable cells pressed against each other, which made the tissue stable. At the level of the organ, tissues pressed against each other, making the leaf itself stable.

Student S4 explained the withered state. Its mechanism started at the organelle level, with missing cell plasma in the vacuole followed by contraction of the vacuole. The student then switched to the cell level and reported that the cell was shrinking and that gaps were created that had an effect on the level tissue, which became unstable. Therefore, the leaves appear withered.

7.6.2 A Zoom Map Demands Exhaustive Editing

The difficulties that students face during the construction of a zoom map can be turned into learning opportunities. As an example of a zoom map that can be improved, we present the map of teaching experiment G (Fig. 7.12). The zoom map explains the phenomenon only at the levels of tissue to organelle. Most of the few interrelations that were drawn are unlabeled. In their final explanation, the students did not further elaborate on these unlabeled arrows.

With their zoom map, the students offered the following final explanations of the phenomenon:

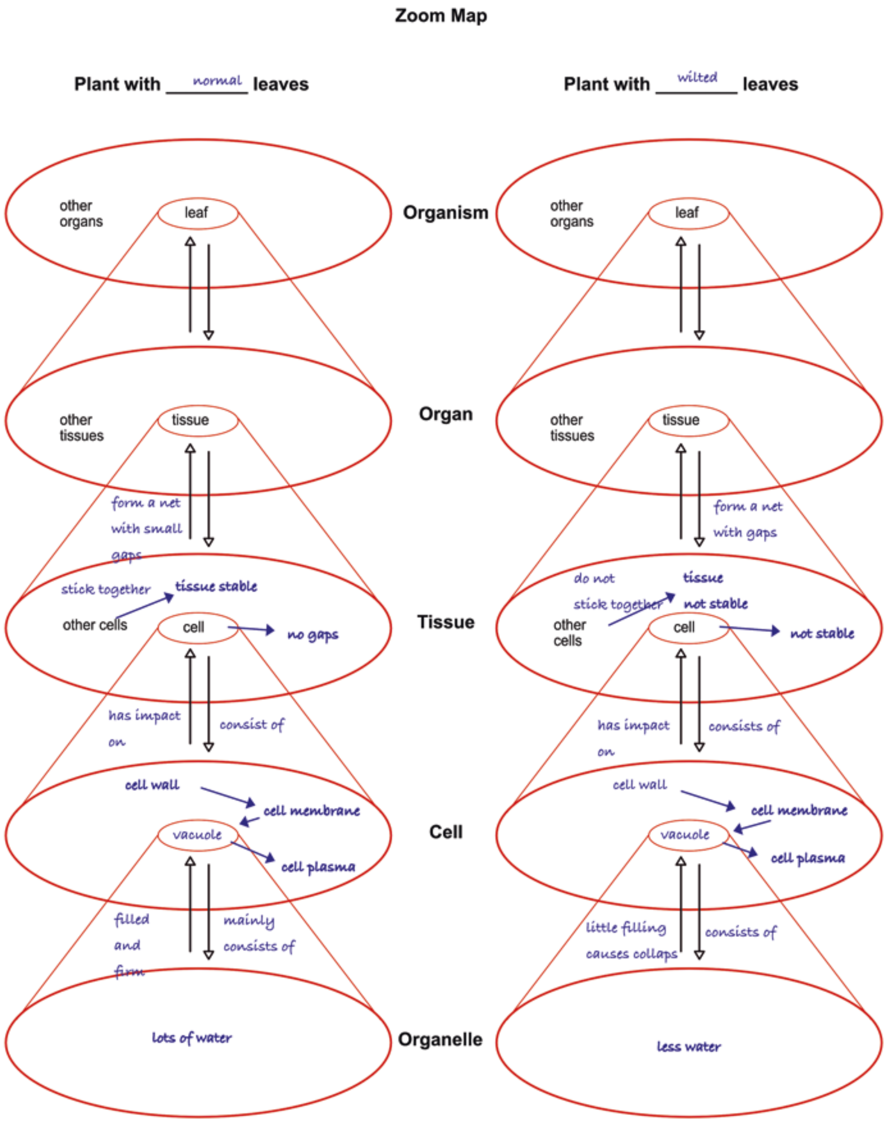

Fig. 7.12 Zoom map constructed by students S12 and S13 of teaching experiment G. The students' answers are shown as handwritten. (digitalized and translated from German)

S13: "Yes, I would say the phenomenon simply refers to the vacuole. That is, it [the vacuole] has the greatest effect on the appearance of the plant. Simply, if there is a corresponding amount of water or cell sap, whatever, that fills the vacuole. Then the leaves will look green, and they will stand by themselves. And the less water is in this vacuole, the more wrinkled and wilted these leaves will look. And then they don't have as much stability."

(G, S13, l. 224–229)

S12: “Yes, well, I think it is also possible that the plant is drying up or simply was not watered … that is, then it dried up. And because of that, there is too little water or cell plasma in this vacuole, as you just said. This causes the cell, no, the vacuole, to contract. Thus, it also shrinks the cell. The cells are no longer in good contact with each other. This causes gaps to form, and the tissue … so this is the tissue. And on the organ level, it just withers and collapses.”

(G, S12, l. 230–336)

In their final explanation, students S12 addressed levels from organism to organelle, while S13 skipped the levels of tissue and cell. S13 did not describe a mechanism but presented the vacuole (level of organelle) as the cause of the leaf’s appearance. This may be due to the unclear interrelations at the level of the cell and the tissue. The explanation of S13 was closer to a mechanism. At the level of organelle, he pointed to missing water and filling of the vacuole. He mentioned the vacuole’s contraction and the cell at the level of the cell, although he did not write it down in his zoom map. With cells not being in contact with each other, the tissue was a “net with gaps.” The leaf was therefore withered.

A zoom map requires exhaustive editing. Students may tend to write down only parts of their explanation at first. In that case, they need to be motivated to complete their explanation and thus visualize it exhaustively. In our teaching experiment, we asked all students to develop their zoom map further and label the interrelations. In a classroom setting, the students would present their zoom map to be discussed by their peers.

By asking, “How does the vacuole affect the leaf?”, we made the missing interrelations explicit. Since S13 skipped the levels of tissue and cell, he might not have been able to label the interrelations at these levels. In cases such as this, students should write down questions and difficulties arising during the construction process.

7.6.3 Learners Drill Down to Lower Levels in Their Explanations

Addressing the required levels of organization is a guideline for teaching complex phenomena (see the first section). We therefore expect students to address (more of) the relevant levels.

The first explanation was conducted without the zoom map. Twelve students put forward an explanation; one student (S10) did not explain the phenomenon. An example of a first explanation mentioning only the two levels organism and organ is:

S1: “On the right [plant], the [leaves] are partly curled up as if they were contracting, as if there was some kind of lack of liquid. So, the leaves also contain liquid somehow and as if that would be missing. The left [plant] is different; it looks healthy, like normal leaves. […] This is because the plant on the left has been watered and treated sensibly.” (A, S1, l. 7-11, translated)

In the first explanation, students focused on the level of organism (eight students) and organ (eight students). One student each considered the levels of tissue and cell. None of the students addressed the level of the organelle.

In the final explanation of the phenomenon, 12 students put forward explanations; student S7 did not explicitly explain the phenomenon. After instruction, student S1 explained the phenomenon at levels from the organelle to the organism:

"S1: "This is because in the cell organelles, the vacuole, they contain liquids. And in the healthy plant, there is simply more liquid in the vacuole than in the dried-up one; there is less. Because of this, the cell membrane contracts because of the less [liquid], and there is space between the cell membrane and the cell wall. The cell membrane encloses the nucleus, the chloroplasts, and the vacuoles. Here, the nucleus and the chloroplasts are present in both [plants], but the difference lies in the size of the vacuoles. And this is where it contracts.

I: What contracts?

S1: In the dried [plant]. […] The cell membrane contracts, and the cell wall remains the same. This means that there is some space in the tissue between the two, and that is why it seems to have shrunk. And here, in the healthy [plant], the cell membrane needs more space to enclose the larger fluid in the vacuole. […] This means that there is less space in between, and the leaf looks healthier because there is more liquid in it." (A, S1, l. 166-170, translated)

Students addressed the relevant levels for the causal argument in the final explanations guided by the zoom map. Eleven students elaborated on the organ and organelle levels, and 10 students on the level of tissue. Eight students each addressed the levels of organism and cell. Overall, in the final explanation with the zoom map, students considered more and lower levels. In some oral explanations, students addressed different levels than in their zoom maps, as shown for teaching experiment G (Fig. 7.13).

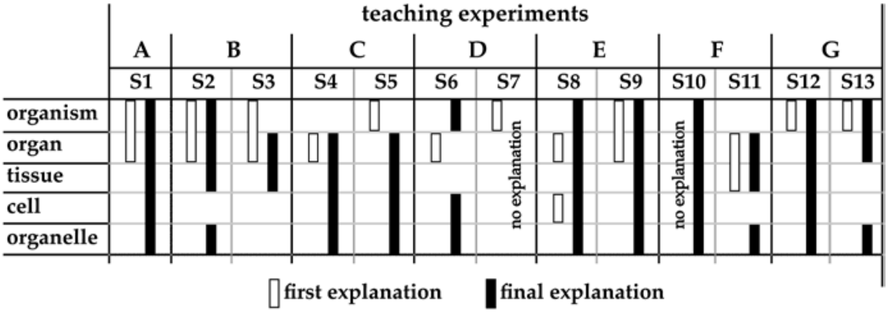

Fig. 7.13 Levels that students addressed in their oral explanations

7.6.4 *Direction of Explanation: Top-Down, Bottom-Up, or yo-yo*

One guideline of yo-yo learning is moving up and down (or down and up) the levels of organization. Since the zoom map should support yo-yo learning, students should be enabled to move across them.

We identified five possible directions of explanation: one level only (O) with no direction in the proper sense, downwards (D), upwards (U), downwards-upwards (D-U), and upwards-downwards (U-D).

Of the first explanations, we coded seven explanations as O, focusing only on one level of organization. An example of an explanation at one level only is the first explanation of S7: "Maybe the plant has not been watered" (D, S7, l. 4). Three explanations could be rated D; they moved from a higher level of organization to at least one lower level. Two students gave an explanation that we rated as D-U. Their explanation moved to a lower level and back to higher levels. None of the first explanations moved upwards or upwards-downwards—arguably, because the microcosm entities such as cells or organelles are not as familiar as mesocosmic leaves or plants.

The direction of most students' explanation changed in the final explanation: seven moved U, four moved D-U, and one moved U-D. None of the final explanation was rated O or D.

In general, the direction of students' explanations shifted from O or D to U or D-U (Table 7.3). The yo-yo principle, that is, D-U or U-D, was realized two times in the first explanation and five times in the final explanation.

7.7 Discussion

Our results indicate that the zoom map fosters explanations across the levels of organization.

In our analysis of the students' first and final explanation, we were able to point out two aspects: First, after learning with the zoom map, students considered more of the relevant levels. Second, the students considered lower levels—those of the cell and the organelle (Fig. 7.13).

In our analysis of the direction of explanation, we were able to show that the direction of their explanations changed (Table 7.3). While the prevalent first explanation was restricted to one level only, the prevalent direction in the final explanation was upwards, and five out of 12 students even used the yo-yo principle to some extent.

To explain the case of upright and wilted leaves in everyday situations, one may refer to the mesocosm, namely sufficient or missing water. This explanation is sufficient in everyday life, because it leads to the appropriate action of watering the plant.

Table 7.3 Direction of students' explanation (O: One level only, D: Downwards, U: Upwards, D-U: Downwards-Upwards, U-D: Upwards-Downwards)

	First Explanation (E1)					**Final Explanation (E2)**				
	O	**D**	**U**	**D-U**	**U-D**	**O**	**D**	**U**	**D-U**	**U-D**
S1				●				●		
S2	●									●
S3	●								●	
S4	●							●		
S5	●							●		
S6		●							●	
S7	●					no explanation				
S8				●					●	
S9		●							●	
S10	no explanation							●		
S11		●						●		
S12	●							●		
S13	●							●		

Most of the students in our teaching experiments initially brought forward a similar explanation of the organism and organ levels. Only a few explanations went beyond entities that can be seen with the naked eye. A biological explanation, in contrast, is more challenging because it includes a mechanism. The phenomenon that should be explained, in most cases, needs to be related to lower levels of organization that lie within the microcosm—a part of reality that is only accessible through the use of science-based technologies such as microscopes. Processes in the microcosm are predictably hard to understand (Niebert & Gropengießer, 2015).

Students, therefore, need support through visualizations or models (see M3-5, Figs. 7.9 and 7.10).

Since biological phenomena are context dependent, inquiries should not only consider downward questions, but upward questions as well (Allen & Hoekstra, 2015). This is in accordance with yo-yo learning (Knippels, 2002) and can be supported by the zoom map.

In our teaching experiments, students managed to construct zoom maps that explained the upright and wilted leaves of the painted nettle, albeit the maps differed in the explanation's quality. Working with a zoom map will not by itself lead to a correct explanation. To grasp the scientific explanandum's mechanism, learners need to understand and apply the pneu principle as realized in footballs or plant cells and extend it to the level of tissue, leaf, and plant. A pneu consists of a flexible but tensile hull and a pressurised filling (Frei, 1994).

However, the zoom map can explain the relevant levels by demanding explicitly stated relationships between the entities at different levels and asking for links within and between levels. Even if not all aspects of an explanation are known or understood, one can identify the knowledge gaps. Nonetheless, exhaustive editing is a prerequisite. Zoom maps can be easily compared, and discussions can be conducted in a highly structured manner.

7.8 Implications for Biology Teaching

Students have difficulties in constructing adequate explanations of complex biological phenomena, especially when they require them to move between different levels of organization. For adequate explanations, students need experience-based conceptions of a phenomenon. This experience may be achieved through models or experiments. However, conceptions alone are not sufficient, as appropriate integration is what primarily poses difficulties to students. Hence, learning environments and biology teaching should be structured according to systems thinking principles—for example, via yo-yo learning. Levels of organization should therefore be made explicit. Students do not consider them on their own accord; they need guidance and reason to do so. The zoom map can be used to guide students across levels of organization and foster adequate explanations. With the zoom map, students consider more and lower levels of organization and change between levels.

Yo-yo learning has already been used to teach complex phenomena such as genetics. As our results demonstrate, the zoom map can be a fruitful tool to implement yo-yo learning guidelines in the classroom. We anticipate that this tool can be used in other fields that require explanation at multiple levels, such as chemistry.

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Chapter 8
Pre-service Teachers' Conceptual Schemata and System Reasoning About the Carbon Cycle and Climate Change: An Exploratory Study of a Learning Framework for Understanding Complex Systems

Gregor Torkar and Konstantinos Korfiatis

8.1 Introduction

Understanding carbon-transforming processes is essential for environmental literacy because the human impact on the global climate is explained in terms of these processes (Eggert et al., 2017; Jin et al., 2013). It is also central to scientific literacy because explanations of carbon-transforming processes are examples of applying scientific reasoning to real-life situations (Jin et al., 2013). The carbon cycle is a complex topic that requires integrating insights from various fields, such as biology, physics, and chemistry (McNeal et al., 2014). It takes place through various forms of biological and ecological structures, and students must understand their interconnectedness in order to comprehend how carbon flows, transforms, and recycles itself through the carbon cycle. For example, students must comprehend the interconnections between trophic levels (producers, consumers, and decomposers) as well as the carbon flow between different carbon reserves (e.g., between the atmosphere, biosphere, hydrosphere, and lithosphere). Moreover, students need to understand the physiological processes through which carbon compounds are transformed (e.g., photosynthesis, cellular respiration, and microbial decomposition). Furthermore, students should be able to interpret climate change as a disturbance of the carbon cycle.

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This study focuses on pre-service teachers' understanding of the carbon cycle and climate change. It also evaluates a learning intervention using the Structure-Behavior-Function (SBF) conceptual framework for understanding complex systems (Hmelo-Silver et al., 2007), as both an educational framework as well as a methodological framework for data collection and analysis.

8.1.1 Knowledge About the Carbon Cycle and Climate Change

The ability to understand the many carbon-transforming processes and to track carbon compounds through systems is central to understanding climate change (Mohan et al., 2009). Students' alternative conceptions about the carbon cycle are related to their failure to trace matter and energy through biological and biophysical systems at multiple scales, especially at the atomic and molecular scales (Hartley et al., 2011; Mohan et al., 2009). Furthermore, students of all ages often find it difficult to understand photosynthesis, cellular respiration, and decomposition (Asshoff et al., 2020; Düsing et al., 2019).

Studies investigating students' knowledge of climate change reveal the difficulty in understanding the complexity of the processes involved (Monroe et al., 2019). Children, students, teachers, and other adults hold many incorrect conceptions about climate change and its effects (Aksit et al., 2018; Arslan et al., 2012; Harris & Gold, 2018; Liu et al., 2015; Majer et al., 2019; Shepardson et al., 2011; Walz & Kerr, 2007). Similar to young children and adolescents, many university students, pre-service teachers, and in-service teachers hold incorrect conceptions about climate change. Some think that the ozone layer is causing the greenhouse effect (Arslan et al., 2012; Boon, 2010; Liu et al., 2015). It has also been reported that many university students associate climate change with all harmful environmental impacts, such as environmental destruction, waste disposal, radioactive waste and weapons, chemicals, fertilizers, sprays, and acid rain (Papadimitriou, 2004). Similarly, Herman et al. (2017) found that many secondary school science teachers believed that the use of pesticides and the use of aerosol cans contributed to climate change, or that nuclear energy causes climate change.

These non-scientific ideas about climate change can lead to incorrect conclusions about climate change processes (Majer et al., 2019), as well as to misconceptions that could further lead to insufficient climate literacy for effective decision-making and collective action (Stevenson et al., 2018). The lack of public consensus on climate change may be partly due to a lack of knowledge about the underlying science (Weber & Stern, 2011).

8.1.2 Climate Change Education

Various authors have attempted to develop educational sequences and learning material for teaching about climate change (Düsing et al., 2019; Harker-Schuch et al., 2020; Jin et al., 2013; Niebert & Gropengiesser, 2013; Ouariachi & Elving, 2020; Wu & Lee, 2015). However, despite these studies, it is argued that there has been relatively little research to inform approaches helping students learn about climate systems, and that they are characterized by a focus restricted to the individual components and processes of the carbon cycle (Düsing et al., 2019; Jacobson et al., 2017). According to Jin et al. (2013), current science curricula and instructions have not yet been successful in teaching students about this topic: curriculum materials often address reactants and products of carbon-transforming processes without articulating the big ideas of how matter and energy transform. Düsing et al. (2019) state that the main focus of research on student conceptions of the carbon cycle lies in individual components and processes, such as photosynthesis or respiration, whereas to comprehend a complex topic like the carbon cycle it is necessary to understand both its constituent processes and their interactions. Monroe et al. (2019) conducted a systematic review to understand what research can contribute to ideas about effective climate change education. Engaging in deliberative discussions, interacting with scientists, addressing challenges of misconceptions, and implementing school or community projects have been recognized as effective educational approaches that empower learners. Nevertheless, students often hold scientifically inadequate conceptions regarding climate change even after instruction (Ekborg & Areskoug, 2006).

8.1.3 Systems Thinking and the Structure-Behavior-Function (SBF) Conceptual Framework

This chapter suggests that education about the carbon cycle and climate change should be relevant to students in terms of systems thinking. A systemic approach is both important and essential for understanding interactions in natural systems (Lefkaditi et al., 2014). It is also of utmost importance for the understanding of interactions between the social, economic, political, technological, and environmental aspects of life (Jacobson & Wilensky, 2006). The United States Next Generation Science Standards (NGSS Lead States, 2013) recommends the introduction of systems and system models as crosscutting concepts (i.e., as concepts that have application across all domains of science), emphasizing in this way the importance of systems in science education. It is proposed that ecological phenomena and processes—including the carbon cycle, the greenhouse effect, and climate change processes—be better taught and understood by students when their systemic nature becomes explicit (Korfiatis, 2018).

Various models have been proposed for the study of the systemic nature of biological and ecological phenomena and processes (Evagorou et al., 2009; Gilissen et al., 2020; Tripto et al., 2018). This investigation uses the conceptual framework developed by Hmelo-Silver et al. for studying natural systems (Hmelo-Silver et al., 2007, 2017). Specifically, based on the ideas of Goel et al. (1996), Hmelo-Silver et al. (2007) proposed the Structure-Behavior-Function (SBF) conceptual framework for understanding complex systems. "Structure" refers to the elements of a system (e.g., the different species in a food web), "behavior" refers to the role of each element in a system (e.g., the role of producers, consumers, and decomposers in a food web), and "function" refers to the dynamic mechanisms that produce a response or outcome within a system (e.g., changes caused in a food web after a disturbance). In 2017, Hmelo-Silver et al. proposed a revised version of the SBF framework, called the Components-Mechanisms-Phenomena (CMP) conceptual representation. In the CMP conceptual representation, "C" stands for the components of a system that interact, and therefore consist of a mechanism (M) that produces a certain natural pattern, or phenomenon (P). We suggest that both frameworks are largely comparable, with their main difference being a matter of emphasis rather than a different description of what a system is.

Specifically, Hmelo-Silver et al. (2017) declared that the CMP conceptual framework reflects the mechanistic reasoning of ecosystem learning, whereas "the SBF representation guides students to broadly consider the relevant structures, observe their behavior and their functional role in the context of a complex system" (p. 56). Both frameworks have been recognized as useful for educational activities relevant to understanding complex systems (Ben Zvi Assaraf & Orion, 2005, 2010; Gnidovec et al., 2020; Hmelo-Silver et al., 2007; Korfiatis, 2018; Lee et al., 2019; Mambrey et al., 2020; Snapir et al., 2017). However, we suggest that the nomenclature of the SBF framework helps learners focus on the processes taking place in a system. Processes are considered the key for understanding ecological systems (see, e.g., the educational approaches proposed by Hokayem & Gotwals, 2016; Jacobson et al., 2017; Ruppert & Duncan, 2017), and therefore we prefer the SBF framework rather than the CMP one in the quest to build successful educational interventions for biological and ecological understanding (for implementations of the SBF framework, see Demetriou et al., 2009; Gnidovec et al., 2020; Korfiatis, 2018).

Furthermore, we prefer the SBF conceptual framework over other well-grounded approaches to systems teaching (e.g., Evagorou et al., 2009; Gilissen et al., 2020; Tripto et al., 2018) because of its simpler architecture: the SBF framework's emphasis on the three basic characteristics of a natural system—that is its structure, processes (behavior), and function—serves to design learning progressions for teaching about natural systems, using these steps (structure, behavior, and function) as anchors in the development of a learning progression.

Nonetheless, we believe that the other frameworks, such as those mentioned above, could be extremely useful for designing more advanced courses on natural systems in general and on climate change in particular, because they pay more attention to the more complicated and difficult to understand aspects of a system (for example the connection between the submicroscopic, microscopic and macroscopic processes of the carbon cycle).

8.1.4 *Research Objectives*

Teachers play a crucial role in educating future generations about global climate change, and therefore it is critical to develop comprehensive knowledge about this complex issue (Liu et al., 2015).

We are specifically interested in studying the following:

- Pre-service teachers' understanding of the structure, behavior, and function of the carbon cycle and its connection with the greenhouse effect and climate change;
- Pre-service teachers' understanding of the consequences of climate change; and
- Based on the SBF framework, the effectiveness of a learning intervention to improve pre-service teachers' understanding of the carbon cycle and climate change.

8.2 Methods

This research has the form of three independent case studies, with three groups of pre-service teachers from two European countries (Cyprus and Slovenia). However, this is not a comparative study: the aim is not to discuss similarities and differences between the three groups' performance, but rather to highlight the elements that could make a learning intervention about the carbon cycle and climate change effective. In this sense, it should be seen as a pilot study seeking to contribute to a better understanding of a systems approach to climate change education.

8.2.1 *Participants*

One group of 24 pre-service lower secondary school biology teachers from the Faculty of Education at the University of Ljubljana and two groups (one with 11 participants and the other with 26) of pre-service primary and preschool teachers from the Department of Education at the University of Cyprus participated in this study.

8.2.2 *Learning Intervention*

We used the SBF conceptual framework as an educational framework to design a sequence of learning activities for studying the carbon cycle and climate change: we used concept maps for studying the structure and behavior of the carbon flow as a system, and laboratory experiments and simulations for studying the behavior of the system.

The learning intervention lasted for 49-min lessons. The participating students worked in groups of two to four students.

The learning sequence was organized as follows.

8.2.2.1 Concept Maps

During the first meeting, students were asked to construct a concept map of the carbon cycle and its “links” with climate change. Concept maps are diagrams that provide a visual representation of the relationships between concepts and the framework of a person’s ideas within a given topic. In other words, a concept map is a graphic organizer that provides a visual representation of a student’s knowledge and thoughts (Novak & Gowin, 1984). The structure of a concept map reflects the concepts that the person who created it associates with a particular subject and the relationships that the person sees between them. Concept maps allow students to link processes (e.g., photosynthesis, respiration, and fuel emissions) to the nodes representing the system components (e.g., living organisms and the atmosphere).

8.2.2.2 Lab Experiments

During the second lesson, students conducted an experiment that allowed them to study the mechanism of the greenhouse effect. In particular, the experiment helped the participants understand how CO_2 concentration can alter the function of the system (i.e., increasing the Earth’s temperature). Three large transparent containers, a table lamp, three thermometers, (the thermometer should be able to measure to at least one decimal place), and plastic wrap were used. The mouths of the containers were covered with one, five, or ten layers of plastic wrap to represent different CO_2 concentrations in the atmosphere. It was emphasized that the plastic wrap should not be perceived as layers of CO_2, but as an increased concentration of CO_2 in the atmosphere. The containers were then evenly lit with a lamp and the temperature in each container was measured every 2 min, for 30 min altogether. Students had to record their data on a worksheet, create graphs, explain their results, and answer questions such as the following:

- What does the plastic wrap represent in the experiment?

- What happened to the air temperature in the containers? Are there differences in the air temperature in Containers 1, 2, and 3? Give your explanation of the observations.
- Make a drawing explaining what happened in the containers and connect it to the carbon cycle.

8.2.2.3 Computer Simulations

The third lesson consisted of two interactive simulations. Simulations can make visible ecological processes and phenomena that are not accessible through direct experience, and they can support students in understanding the complex connections and interactions in a system (Wu & Lee, 2015). Simulations can also provide opportunities for students to engage with evidence and processes that underlie the phenomenon under study. First, students used the PhET simulation called Greenhouse Effect (https://phet.colorado.edu/en/simulation/greenhouse), which allowed them to alter the various conditions of the greenhouse effect (e.g., concentration of CO_2, CH_4, and H_2O, mimicking Ice Age atmospheric conditions and atmospheric conditions in preindustrial times) and study their impact on Earth's temperature and climate.

With the second simulation, The Habitable Planet's Carbon Lab (https://www.learner.org/wp-content/interactive/envsci/carbon/carbon.html), participants studied the carbon cycle. By manipulating fossil fuel use, the deforestation rate, and melting of the tundra, students observed and compared carbon amounts in the lithosphere, hydrosphere, biosphere, and atmosphere.

Students recorded their observations on a worksheet that provided tasks and questions for evaluating their comprehension of the simulations. Some sample tasks and questions are the following:

- What happens to the sun's rays when they strike the surface of the earth?
- Turn on the display for the year 1750. What do you think 1750 represents? Is the air temperature changing? Now turn on the Ice Age display. Has the air temperature changed again? Discuss the results.
- What happens to the sun's rays when they strike the ice?
- What happens if CO_2 is set to zero, and what if it is set to the highest concentration?
- What happens to the carbon in the atmosphere due to changes in fossil fuel use and deforestation?

8.2.2.4 Concept Map Revision and Reflections

During the fourth (and last) lesson, the students redesigned their maps to reflect on their study of the carbon cycle and climate change. Discussion with tutors followed the construction of the concept maps in the case of the Slovenian group.

8.2.3 Data Collection and Analysis

Data were collected through the following sources:

- Students’ concept maps before and after the learning intervention, and
- Recorded focus group interviews after the end of the learning intervention.

8.2.3.1 Concept Map Analysis

We also used the SBF conceptual framework as a methodological framework for data analysis. Specifically, for the purpose of concept map analysis, we created a rubric to evaluate the correctness of the depiction of structures, behaviors, and functions in participants’ concept maps.

As a reference for the rubric, we used Fig. 8.1, in which we depicted the features of a carbon cycle diagram, which also includes the causes and consequences of the greenhouse effect. Although the diagram is much simpler than the actual phenomenon, it still represents a basic understanding of the carbon cycle and climate change processes, which should be considered sufficient for a non-specialist.

According to the diagram, a simple but complete concept map should include the following:

A. Structure: six elements (producers, consumers, decomposers, detritus, atmosphere, and human sources of CO_2 emissions)

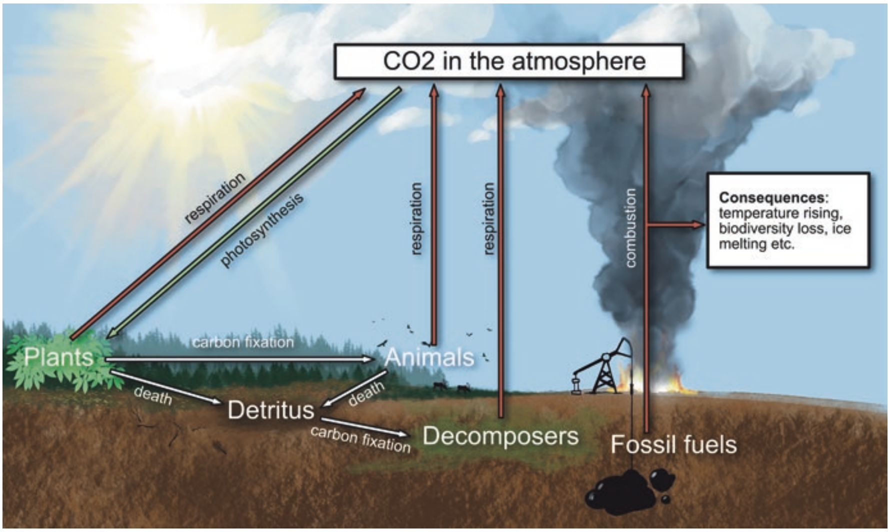

Fig. 8.1 Carbon cycle diagram, including causes and consequences of the greenhouse effect

Table 8.1 A rubric for evaluating students' concept maps

Criteria	Rating scale		
	Poor	Intermediate	Advanced
Structure (number of elements)	Two or less	Three to five	Five or more
Behavior (number of processes)	One or none	Two or three	Four
Function (number of connections)	Three or less	Three to seven	Eight or more
Function (number of consequences)	One or none	Two or three	Four or more

B. Behavior: four processes (respiration, photosynthesis, decomposition, and fossil fuel combustion and other anthropogenic emissions, including vehicle emissions, as well as industry and agricultural emissions, burning forests, etc.)
C. Function. A thorough description of the function of a system should include connections between elements and processes as well as the consequences of any change in the system. In the case of the carbon cycle and climate change, connections and consequences are as follows:
    (a) connections: eleven connections between elements and processes (e.g., industry emits CO_2 in the atmosphere through combustion; plants absorb CO_2 from the atmosphere through photosynthesis)
    (b) consequences: five major consequences (temperature rise, ice melting, sea level rise, biodiversity loss, socioeconomic consequences)

In accordance with the above, the rubric shown in Table 8.1 was created to evaluate students' concept maps.

8.2.3.2 Interview Analysis

Focus group interviews were transcribed verbatim. Data were analyzed in an iterative manner to identify themes relevant to the SBF framework; that is, participants' comments that referred to the structure, behavior, or function of the carbon cycle and its connection with climate change.

8.3 Results

8.3.1 Group A: Slovenian Pre-service Lower-Secondary-School Biology Teachers

The twenty-four participating pre-service biology teachers were in their third or fifth semester of the bachelor's program. During their university studies, the students completed several compulsory courses related to the carbon cycle and climate change, such as organic and inorganic chemistry, botany, zoology, and microbiology. These courses consisted of theoretical lectures and experimental exercises.

The participants worked in teams of four to construct their concept maps. Therefore, six maps were constructed by this group. As can be seen in Table 8.2, the Slovenian students' concept maps depicted only some elements, behaviors, and functions of the carbon cycle as a system. In fact, their initial concept maps tended to focus on the human causes of changes in atmospheric CO_2 concentrations: human use of fossil fuels (coal, oil, and natural gas) was highlighted by all students as the cause of the increased concentration of carbon dioxide in the atmosphere. To a lesser extent, the clearing and burning of forests, industry, transport, and agriculture were mentioned in the initial concept maps. Some groups specifically highlighted the production of plastics, food consumption and waste, and electricity as reasons for increased carbon dioxide emissions. Human population growth was also frequently mentioned as an indirect source of the increase in carbon dioxide emissions into the atmosphere and as a driving force for changes in the human activities mentioned above. In contrast, the direct impact of human and other organisms' respiration on the carbon cycle was not demonstrated. Among the factors responsible for the increase in carbon dioxide emissions in the atmosphere, some misunderstandings were observed: some students cited aerosol sprays (chlorofluorocarbons, or CFCs) or acid rain as one of the sources or consequences of the increase in carbon dioxide emissions into the atmosphere.

Some groups of students also highlighted the consequences of rising carbon dioxide emissions in concept maps—for example, melting ice, rising sea levels, food shortages, destruction of coral reefs, natural disasters, and extinction of species—and they pointed to measures that could help reduce these emissions.

Table 8.2 Participants' concept map ratings before and after the learning activities

	Rating Scale					
	Poor		Intermediate		Advanced	
Criteria	Before	After	Before	After	Before	After
Structure (no. of elements)						
Slovenia, Group A	3	3	3	3	0	0
Cyprus, Group B	1	0	2	0	0	3
Cyprus, Group C	18	5	6	1	0	8
Behavior (no. of processes)						
Slovenia, Group A	3	3	3	3	0	0
Cyprus, Group B	2	0	1	2	0	1
Cyprus, Group C	26	7	0	14	0	5
Function (no. of connections)						
Slovenia, Group A	5	4	1	2	0	0
Cyprus, Group B	3	0	0	2	0	1
Cyprus, Group C	26	8	0	14	0	4
Function (no. of consequences)						
Slovenia, Group A	5	1	1	4	0	1
Cyprus, Group B	3	2	0	1	0	0
Cyprus, Group C	16	9	10	16	0	1

The learning intervention proved to be advantageous for the conceptual understanding of the climate change effect as presented in the final concept maps. These maps provide more details of the processes associated with increased carbon dioxide emissions into the atmosphere; for example, infrared photons radiating from the Earth's surface through the atmosphere, photons heading back from clouds down toward the surface, CO_2 molecules retaining photons, and other photons escaping into space. Furthermore, all groups correctly named the main human causes of changes in atmospheric CO_2 concentrations; namely, the use of fossil fuels in industry and transport, and clearing and burning of forests for agriculture and other human purposes. However, other aspects of the concept maps did not change significantly (Table 8.2).

During the interviews, the students showed that they better understood the mechanisms of the greenhouse effect, as the following quotations show: "The greenhouse gas CO_2 returns red photons (IR photons) to the Earth's surface." "A cloud can reflect photons of light coming to Earth. IR photons, on the other hand, are reflected back to the Earth's surface by clouds and thus retain heat" (female student).

Students correctly stated that the concentration of carbon dioxide is rising. When asked how this could be changed, one student first noted "many things" (female student), and then others continued that "it is necessary to reduce or stop the use of fossil fuels" (female student) and that we should "plant more forests to accumulate carbon in trees." They were able to conclude: "The simulation clearly shows how the use of fossil fuels changes the ratio of carbon in the atmosphere, hydrosphere, and lithosphere" (female student).

The students were asked whether they saw a connection between rising carbon dioxide emissions and biota. They mentioned the rise in sea level and consequently smaller terrestrial ecosystems for fauna and flora, polar bears and the loss of sea ice, and the recent catastrophic floods in Venice (in 2019). When they were asked about the effects on flora, they initially had no idea. They emphasized their concern about the influence of climate change on flowering plants; specifically, changes in the time of blooming and frosts. The students were also asked how this would affect humans and the economy. They first discussed the decline in winter activities and sports in Slovenia. They believe that climate change in Slovenia is also visible through the disappearance of the Triglav Glacier, the increase in annual average temperatures, and more frequent droughts and severe storms. At the global level, they mentioned the exponential growth of the world's population; for example, population growth in China and how this affects climate change, desertification, rising sea levels, the disintegration of coral reefs, and the decline in the production of fish and other human food sources. Last but not least, students discussed how would they react if they were confronted with a person who denies the reality of climate change and does not believe in scientific evidence. They expressed support for the science of climate change and their feelings toward "unbelievers": "I would condemn them depending on their arguments" (male student), "They close their eyes to reality" (female student), "Maybe they do not have enough knowledge" (female student), "They are not thinking causally enough" (female student), and "I think they may still have good reasons for not accepting the evidence, but deep down you still condemn them" (female student).

8.3.2 Group B: Cyprus Pre-service Primary School Teachers

This was a small group of 11 pre-service primary school teachers participating in the elective course Advanced Themes in Biology Education at the Department of Education. They were in the third year of their program at the university, and they had already taken the introductory course Environment and Living Organisms during their first year at the university. Studying the flow of material and energy was part of that course. However, their engagement with the carbon cycle was entirely theoretical, in the form of a short presentation and discussion during that course's lectures. No practical, experimental, or computer activities were involved in teaching about the carbon cycle.

Group B constructed concept maps in teams of three or four students. The concept maps drawn by the students during the first lesson of our intervention depicted their prior knowledge, but in quite a fragmented manner (Table 8.2); for example, the students remembered that plants or decomposers are part of the system, but they did not remember how they are connected with each other or how they contribute to the equilibrium of the carbon flow. Thus, their concept maps included quite a few elements of the carbon cycle, but not enough of the processes and the connections between elements and processes (Table 8.2).

The learning intervention improved students' understanding of the carbon cycle and the interconnections between biotic and abiotic elements of organization, as shown in Table 8.2. This was also expressed during focus group discussions: Part of a female student's description of the carbon flow was as follows: "carbon circulates between producers, consumers, and decomposers, and then goes into the atmosphere with respiration." Another female participant described the role of photosynthesis: photosynthesis recycles carbon in a way." A male student described how carbon from fossil fuels enters the carbon cycle: "Carbon is released from fossil fuels and is then accumulated in trees, the atmosphere, and the oceans."

After the lessons, students expressed an understanding of the role of humans: "In comparison with the past, carbon dioxide is rising in the atmosphere and will continue to rise in the future. We need to change many things to change this; we should stop using fossil fuels" (female student). However, most of the students did not feel confident explaining the origins of human emissions. A student's response to the question about how humans affect the carbon cycle was: "it's the oil, the coal … it's coming from underground rocks, from the earth, isn't it?" (female student).

Students also expressed difficulty in giving the "big picture" of the carbon cycle and climate change by including the socioeconomic "layer" in the system. They referred to the possible socioeconomic consequences of climate change, without thoroughly connecting them with the disturbances of the carbon cycle. A characteristic statement from a male student was: "We are all going to die!" A female student said: "There will be money, but not food," which does not really capture the complex socioeconomic implications of the climate crisis.

8.3.3 Group C: Cyprus Pre-service Preschool Teachers

The twenty-six participants had not studied the carbon flow and climate change during their university studies. This was presented in their concept maps, which were constructed individually during the first lesson of the learning intervention. In fact, the students' concept maps were actually lists of concepts rather than conceptual frameworks. The participants mentioned various environmental problems caused by climate change (mainly ice melting, temperature rise, forest fires, drought, and, to a lesser extent, sea level rising). Some human-induced causes of climate change were also mentioned (mainly air pollution and cars). It is noteworthy that some environmental problems not relevant to climate change were reported quite frequently, in particular ozone depletion and waste production. The participating students did not establish any links with carbon flows in natural systems. Furthermore, there was little evidence of processes such as photosynthesis, combustion, or respiration, or of the components of the carbon cycle.

The situation described above changed dramatically after the learning intervention (Table 8.2). The greatest improvement concerned students' ability to relate environmental problems to the increase in CO_2 concentration in the atmosphere and, consequently, to the increase in the Earth's temperature. Furthermore, many students were able to prove these connections on their concept maps. For example, one female student said during the interview that "the CO_2 concentration in the atmosphere has so far remained in equilibrium due to the CO_2 exchange between plants and animals. Animals and plants release CO_2 into the atmosphere through respiration, and plants absorb CO_2 through photosynthesis. Microorganisms decompose dead organic material and release CO_2 into the atmosphere. These processes keep the carbon cycle going. What has changed in our days is that too much CO_2 is released into the air." Another female student said: "Solar radiation warms the Earth, but some of the heat escapes into space. The increased CO_2 captures much of this warming, and so the temperature of the Earth rises." These quotes show that the students gained a very good understanding of the role of CO_2 in the temperature increase on Earth.

Finally, we also noticed that this group of students has difficulty expressing the socioeconomic dimensions of the climate crisis. The following excerpt, for example, expresses a naive impression of the socioeconomic consequences of climate change: "there will be changes in social life because it will be impossible to live outside the home, and house bills will become extremely expensive" (female student). Other students draw a picture of total destruction due to climate change: "because of the melting of ice and the temperature rise, villages will disappear, cities, plants, animals … it's a complete chain" (female student).

8.4 Discussion

The research presented here was guided by the hypothesis that teaching the complex phenomenon of climate change should be approached from a systems perspective. In this aspect, we agree with authors such as Jacobson et al. (2017) and Jin et al. (2013), who state that research on education about climate change should focus on complex system ideas (e.g., interactions, feedback loops, and emergence properties), which can provide a conceptual basis for understanding climate systems and the impact of human influence on climate change.

The analysis of the participants' initial concept maps yielded results that are in line with those of previous studies on people's perceptions of the carbon cycle and climate change, regardless of the age of the participants. Specifically, it was shown that participating students had a fragmented knowledge of the components of the carbon cycle and how they are interconnected, as was reported in studies by Düsing et al. (2019) and Shepardson et al. (2011). We also found that many participants made connections between climate change and environmental problems that are not relevant, such as waste production and disposal. According to Shepardson et al. (2011), it is a common response from students of all ages to identify all air pollutants as greenhouse gases and to blur all kinds of environmental problems with climate change (e.g., ozone depletion or waste pollution).

However, it should be noted that the majority of participants in the Slovenian group avoided misconceptions about the causes of climate change. This group was already familiar with the concepts of climate change thanks to courses they had attended during their university studies. They were able to recall, at least partially, the information they had learned. Similarly, in Group B, the students were able to remember information about the carbon cycle (albeit in fragments). Therefore, we fully agree with Shepardson et al. (2011) that curriculum planning and lesson design is a difficult and challenging process, made even more difficult and challenging by the need to start from students' mental models.

Furthermore, our results support the idea that an emphasis on the systemic nature of the carbon cycle is essential for a thorough understanding of climate change consequences. In this regard, we have to admit that the effectiveness of concept maps as a tool to assist students in studying the components and behavior (mechanism) of the carbon cycle has been rather moderate. Our hypothesis is that this is due to the nature of the concept maps. We suggest a virtual version of the concept maps, which would allow students to experiment with different ideas and structures, and also to study how the system they designed works more efficiently to achieve the expected learning outcomes. The results are probably also a consequence of the way the question was posed: students were asked to create a concept map of the carbon cycle and its link to climate change. Some groups of students focused mainly on the consequences of rising CO_2 levels in the atmosphere. Consequently, their concept maps did not show significant improvements in their understanding of the carbon cycle.

On the positive side, the simulations proved to be particularly useful in helping students understand the relationship between the increase in atmospheric CO_2

concentration and the rise in global temperature. As the results showed, their explanations of the greenhouse effect were much more detailed than before the learning intervention, including, for example, IR photons and clouds. Our findings confirm claims that simulation models provide a rich context for productive inquiries (Hmelo-Silver et al., 2007, 2017). This is apparently due to the ability of simulation tools to make the underlying mechanisms behind system dynamics explicitly visible (Hmelo-Silver et al., 2007).

Physical models, on the other hand, although they have been shown to be useful in convincing students that the air temperature varies according to circumstances (i.e., according to the thickness of the layers of the plastic membranes), can increase misunderstandings; for example, that CO_2 forms layers in the atmosphere that trap all the heat. Therefore, the lab experiment deserves a second look and should probably be replaced by a similar experiment with glass boxes, one filled with air and the other with CO_2, equally lit with a lamp, as was used by Niebert & Gropengiesser, (2013).

Finally, scaffolding students through a discussion of findings and concept maps was a tactic the educator used in the Slovenian group, and it helped students understand the socioeconomic aspects of climate change, which did not happen to the same extent with the groups from Cyprus.

8.4.1 Educational Implications and Suggestions for Future Research

The findings presented in this chapter show that the SBF framework can be implemented as a methodological tool for describing and analyzing students' attempts to perceive the complexity of a natural phenomenon. They also show that the SBF framework can be used to support learning by guiding teachers to construct educational sequences and students to understand the aspects of structure, dynamics, and function embedded in natural systems.

The findings also highlight the value of virtual environments for understanding complex systems. Indeed, in terms of participants' learning gains, the most successful part of our intervention was the simulation inquiry, whereas it turned out that the physical experiment requires serious scaffolding in order to be effective. The same could be reasoned for concept map activities; that is, a virtual rather than "pen and pencil" option for concept maps could be more effective in helping students express their ideas. A crucial part of a learning intervention should also be discussions with students, not only for scaffolding purposes, but in particular for exploring various opinions about climate change as a social science issue. Classroom discussions on climate change can also help communicate aspects of the nature of science that people often misinterpret, such as the uncertainty or temporality of scientific theories (Kampourakis & McCain, 2019).

Within this line of reasoning, we would like to recommend that virtual concept maps and the SBF approach be used to support other educational suggestions as well. As an example, we can mention the work of Düsing et al. (2019), which suggests an instructional strategy of tracking carbon atoms across levels of biological organization when teaching the carbon cycle. They argue that students do not need to know the detailed chemistry of photosynthesis and cellular respiration to understand the carbon cycle, but they should have a basic understanding of what carbon compounds are and how they are transformed in order to understand carbon flows. We suggest that their education recommendation could be feasible through virtual concept maps and simulations. Future research could investigate this hypothesis.

Another interesting point for future research is whether students first learn ideas about complex systems and then try to apply them to a specific scientific topic, or whether it is better to let students learn concurrently about complex systems and about specific scientific topics as part of the learning activities. Future research could also explore the proposal by Goldstone and Wilensky (2008) and Jacobson et al. (2017) to use complex systems ideas as organizational principles for learning scientific knowledge and skills.

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Chapter 9
Teaching Students to Grasp Complexity in Biology Education Using a "Body of Evidence" Approach

Tina A. Grotzer, Emily Gonzalez, and Eileen McGivney

9.1 Introduction

Epistemology in the biological sciences includes approaches that respect the connectedness within systems, the value of accumulated evidence, long time scales and attention to steady states in addition to change. Helping students to understand the epistemic origins of biological knowledge—how we come to understand and agree upon knowledge based upon how evidence is gathered and claims are made in the discipline—is critical to their deep understanding and appreciation of it. Yet often, science education focuses on disciplinary knowledge to the exclusion of how knowledge is generated, how epistemology differs across scientific disciplines, and how such assumptions relate to the inherent complexity and connectedness of systems concepts. When there is a focus on scientific practices, these seldom reach down to the level of the epistemic assumptions underlying the generation of knowledge in the biological sciences. In this chapter, we focus specifically on ecosystems science as an exemplar within the biological sciences.

Efforts to introduce students to epistemology in science are often narrowly framed as an isolation and control of variables approach and a stereotyped version of the scientific method; centered on lab-based approaches and manipulatable phenomena, these efforts ignore approaches that draw upon accumulated evidence (Sinatra & Hofer, 2016) as in the biological sciences. A focus on isolating and controlling for variables misses the larger complex causal dynamics in ecosystems and does not begin to approach how ecosystems scientists engage in research. Helping students to learn the multitude of ways that ecosystems scientists develop

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evidence-based explanations for systems concepts in a complex world should be an essential part of biological education.

Yet even as science education reform documents push beyond a single, narrow version of the scientific method, resources for supporting teachers' efforts to broaden the epistemological approaches that students are exposed to are relatively few (Kamarainen & Grotzer, 2019). A study of how K-12 teachers understand epistemologically authentic approaches in ecosystems found that while they held relatively sophisticated perspectives on the diverse approaches used by ecosystem scientists, these were not reflected in the descriptions of their practices within their ecosystem science units. The results suggest the need to support teachers in adopting the epistemologically authentic practices within ecosystems science and in finding ways to translate those to the classroom (Kamarainen et al., 2021).

This chapter argues for the importance of introducing students to the epistemic assumptions that biological scientists make when framing their work particularly as they relate to understanding the connectedness of systems. It discusses an approach called a "Body of Evidence Approach" (BOE) for analyzing the causal complexity of ecosystems and introduces a study that was conducted to assess the impact of teaching this approach to middle school students.

9.1.1 What Is a Body of Evidence Approach?

Through a series of open-ended interviews with ecosystems scientists, Kamarainen and Grotzer (2019) found that they characterize causal patterns and relationships in ecosystems as embedded in a complex matrix of interactions, subject to inherent and sometimes irreducible variability and not always subjectable to manipulative experimentation. In these situations, they use strategies to construct understanding of complex systems through constructing a Body of Evidence approach—integrating results of multiple approaches, measuring and describing variability, conducting experiments in context, taking advantage of natural experiments, thinking across levels and considering the limits to generalizability. Ecosystems scientists also demonstrated considerable "epistemic fluency"—referring to the ability to discern and engage in a variety of investigative approaches for gaining knowledge in a certain field (Goodyear & Zenios, 2007).

At the core of a BOE approach are ways to think about the nature of causality that fit with the information available to ecosystems scientists. Kamarainen and Grotzer (2019) argue that, "Moving from a correlational to a causal account involves epistemological assumptions in any discipline. It presents particular challenges when phenomena involve multiple causes, time-lags, feedbacks, or thresholds as is the case in ecosystem science. While reductionist approaches may contribute to explanatory efforts, investigation in ecosystems science requires a systems perspective" (p. 533). The ecosystems scientists in the study pushed against the notion that complex systems can be understood through reduction alone. They argued for the use of confirmatory approaches such as developing complementary possible models to consider, holding models in consideration until enough evidence exists to determine that they are clearly wrong, considering multiple lines of evidence and the soundness of the evidence for possible mechanisms (Pickett et al., 1994). They also argued for using 'natural experiments' and non-traditional forms of experimentation (Jensen et al., 2012) for instance, dividing a pond with a nylon curtain and treating one side and not the other as a comparison study (Bennett & Schipanski (2013) or placing a tent over a steam to exclude leaf litter and accessing the impact over time (Strayer, 2013).

9.1.2 A BOE Approach for Middle School Science: Understanding Goals

How might this approach translate to what students in secondary school are taught? The following set of Understanding Goals represents the substance of how we approached teaching students about the ways that ecosystems scientists think about causality in complex contexts:

1. It is not always possible or desirable to conduct an experiment.
2. When it is not possible or desirable to do an experiment, ecosystem scientists use an approach where they systematically look for lots of different types of evidence. (They call this a "Body of Evidence" approach.)
3. The more evidence that can be gathered in support of a claim, the more likely it is that that the claim will be accepted. The evidence should be from different and varied sources.
4. In addition to trying to find out what makes something happen, scientists try to collect as much information as they can on how the cause and effect relationship varies—the range of possible outcomes. (For example, a variable might cause an outcome when it reaches a certain amount, but not at lesser amounts. It also might not cause more of an outcome as you keep adding more. Or it might be that the amount of outcome increases stepwise with the amount of the causal variable.)
5. Sometimes nature "conducts experiments" that scientists can interpret. They use these as natural opportunities to learn about what happens. Natural opportunities can be especially helpful in cases when an experiment is not possible or desirable.
6. Scientists talk about how much certainty they have in a set of findings. They may express uncertainty. They may express certainty at different levels of analysis of a problem and not at others. They may talk about certainty in some contexts but say that it is not generalizable to other contexts (limits to generalizability).

9.2 Research Questions

The case study described below incorporated these Understanding Goals (UGs) into a broader ecosystems science unit to investigate how students responded to the BOE UGs and how it influenced their learning. Their understanding was contrasted to students who experienced the unit without the BOE components. The study sought to address the following questions:

1. What characterizes the understanding of students in each class?
2. What can be learned from the contrast about helping middle school students to learn about BOE as an approach in ecosystems science that can inform future educational efforts?

We hypothesized that students experiencing the BOE components would demonstrate understandings that are more closely aligned with the UGs above and that they would be more likely to seek out multiple and corroborating forms of evidence.

9.3 Methods

9.3.1 Design

The impact of teaching a BOE approach to middle school students learning about ecosystems complexity was explored by comparing the understanding of students in two classes from an urban school who participated in a Problem-Based Learning (PBL) Curriculum called EcoXPT (with the XPT used as shorthand to capture its specific focus on experimentation within ecosystems science) in a case study. Both classes participated in the curriculum; One class had additional instructional components related to a BOE approach infused (EcoXPT+ BOE) while the other did not (EcoXPT). Assessments included concept-maps (containing evidence for each claim) and post-interviews. Students also took an on-line pre- and post-inventory as in other studies of the impact of the EcoXPT curriculum, but given the small n, no clear patterns emerged so this data is not included here. The pre-inventory data suggested that the groups were equal upon expectation at the outset of the study.

9.3.2 Participants

Two seventh grade classes of the same teacher participated. The students were from an inner-city charter school with 91% minority enrollment, low socio-economic status (SES) and low scores on a state-wide, standardized test (the Massachusetts Comprehensive Assessment System (MCAS)) (Math Proficiency—27%; Reading Proficiency—34%). A total of 22 students participated with 12 students in EcoXPT and 10 students in EcoXPT + BOE. Students worked on the curriculum in pairs and participated in both individualized and pair assessments. As a case study, the sample size was quite small and thus is a limitation to the generalizability of the findings.

9.3.3 Curriculum

Both classes participated in the EcoXPT curriculum for 14 days (See overview in Appendix). The curriculum centers on an immersive virtual world that depicts a pond ecosystem. (See Fig. 9.1.) (A full description of the EcoXPT curriculum and the Teacher's Guide are available here: https://ecolearn.gse.harvard.edu/projects/ecoxpt). Students worked in teams of two to a computer. During Curriculum Days 1–3, they explored the world and were instructed to "get to know it." On about the third Curriculum Day, students discovered that a fish die-off had occurred on a certain day within the virtual world. They then began to investigate possible causes for the fish die-off by traveling in virtual time before and after the event to observe and collect data on population levels and water quality measurements. They used data tools in the world to view and graph this data which allowed them to see patterns between the different types of data. On Curriculum Day 7, students in both classes had access to experimental tools and to scientists in the world who shared the rationale for certain kinds of approaches and their epistemological assumptions. The experimental tools varied widely to include lab-based experimental tools such as tolerance tanks and comparison tanks and in-situ experimental tools such as mesocosms, tracers and a water buoy that collected data over a period of virtual months. (See in-depth descriptions of these tools in Appendix.) Other sources of information

Fig. 9.1 Image of the EcoXPT immersive world

available to students included observation of organisms, changes over time, a microscope that allowed them to zoom in on microscopic organisms in the pond, the testimony of virtual scientists and other non-player characters in the world and a field guide that offered information about the organisms that they found in the ecosystem.

Throughout the curriculum, students in both classes were introduced to a set of science-related thinking moves, illustrated by classroom posters that they could refer back to (thus reducing the memory demands of learning the thinking moves) while working in EcoXPT and short explanatory videos supported by in-depth teacher support notes to help students to learn how ecosystems scientists engage in scientific practices. These included a set of five posters for both groups: *Deep Seeing* which asks students to engage in careful observation of the ecosystem; *Evidence Seeking* which stresses the importance of using evidence to support one's claims; *Pattern Seeking* which asks student to look for patterns in the on-going processes and steady states of the system; *Analyzing Causality* which encourages students to seek out the causal mechanisms relevant to the relationship; and *Constructing Explanations* which asks students to put together the available evidence to construct the best causal story or explanation that they can. (See Appendix.)

9.3.4 BOE Intervention Components

It is possible to add elements into the virtual world and to turn their appearance on or off. Using this capability, additions were made to the virtual world in the BOE condition. So, while both classes worked in a rich, contextualized immersive simulation, certain elements were present only for those in the BOE class. These included: additional dialogue by some of the virtual scientists in the world. For instance, students in both groups find Dr. Jabir standing outside near a set of mesocosm experiments. In both groups, he says, *"Let me tell you about the mesocosm experiment I've been running here for the last two weeks." However, for the BOE group, first he says, "Lab experiments are great for isolating and controlling variables, such as whether phosphate level affects fish. But mesocosms let us consider how other variables in the real world, like sunlight and temperature, interact with variables we are testing. Even though it is not the same as experimenting on the actual pond, it gives us more certainty about what is going on without hurting the pond."* The BOE students also meet Dr. Aziza Al Dahan standing near Amelia Pond which has turned bright green. She says, *"Hello, are you noticing what I am noticing? This small pond has turned bright green. What do you think is going on? Think about it for a little while and then come back to talk to me."* Later, they run into her again and she says, *"I investigated and found out that a farm worker put a new manure pile in a place where the run-off comes to this pond. This has caused a spike in the algae levels in the pond." "As an ecosystems scientist, there are times when something happens that was not intended, but that we can learn from. We wouldn't have done an experiment directly on this little pond, but now that it has happened, I am studying it to learn from what happened." "In this case, a person made this* *happen, but sometimes nature creates opportunities to study changes in the ecosystem—such as when a hurricane comes through and changes a landscape or fire removes the smaller trees and understory from a forest.” “Does anything that you are seeing here corroborate what you are finding out about Scheele Pond?”*

Students in the BOE class were introduced to the BOE Thinking Move and saw a poster and accompanying video (See Appendix for script) explaining the *Body of Evidence Approach,* encouraging them to collect evidence from multiple sources, look for corroborating evidence of different types (including perceptual evidence, patterns in data and graphs, numerical information and testimony from trusted others) and to assess the validity and reliability of the sources of evidence. They used a Body of Evidence Worksheet (See Appendix) to consider how more evidence leads to greater certainty/stronger claims and worked with a partner to evaluate evidence through a BOE lens. Both classes did talk about different types of evidence and what can be learned from different types as part of the Evidence-Seeking Move and filled out a worksheet focused on this topic (See Appendix), however only the Plus BOE group discussed it within a BOE framework. Supporting materials included ways to talk about BOE for both students and teachers (see Appendix).

9.4 Data Sources and Analysis

9.4.1 Concept Maps

Each pair of students developed an online concept map of their understanding of the causal dynamics within the virtual ecosystem. On the sixth day of the curriculum, students in both classes were introduced to a concept-mapping tool in the immersive world. (See Figs. 9.2 and 9.3.) Students choose from a set of images of factors that become the nodes of the map. They then define claims by drawing an arrow from one node to another and by choosing how to label the arrow (affects, does not affect) (for example, “phosphates affect green algae”). A button on the claim window invites them to state the evidence for the connection. This button opens to an index from the on-line notebook within the program where they track things that they are finding out in the virtual world. It offers evidence that is linked to the source that students used to identify the evidence. A text box asks students to explain their reasoning for how the evidence bears on the claim. For the purposes of this study, the concept mapping tool was modified to include a number along each arrow to alert the students as to how many pieces of evidence they had used to explain each arrow in their concept map. (See Fig. 9.4.) A box appears on the lines of each connection in the concept map to show how many pieces of evidence students provide for that given connection.

An analysis of student concept maps was conducted to look for potential differences in the number of connections, amount of evidence provided for each connection, as well as the percentage of connections for which they provided both evidence

Fig. 9.2 Concept-mapping tool

Fig. 9.3 Links to evidence within the tools

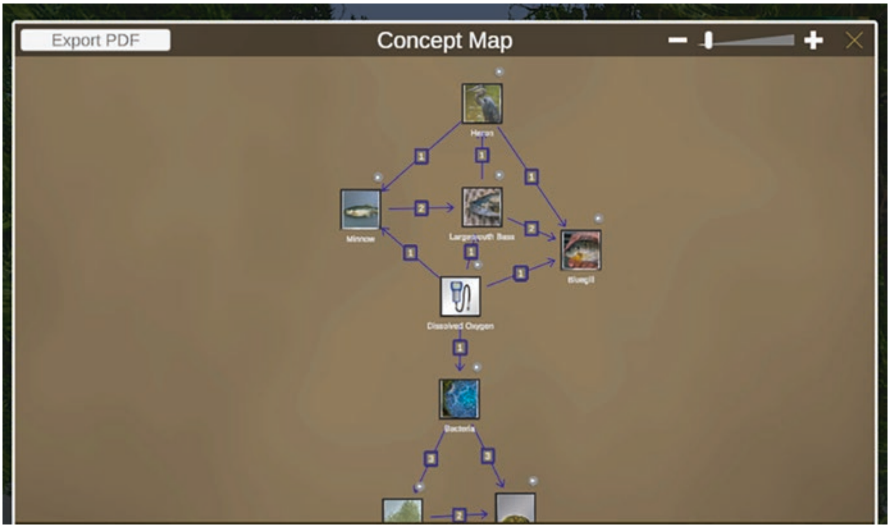

Fig. 9.4 Boxes along lines in concept map show number of pieces of evidence

and reasoning. The maps were coded for the different types of evidence provided in each connection for each pair’s concept map and the frequency of use of different types of evidence was calculated to offer a quantitative view of how they considered evidence. These frequencies were calculated into class averages. A second round of coding analyzed the concept maps qualitatively. Major themes were identified from the connections that students made, the factors that they used, the evidence they provided in relation to the connections they made, as well as the type of causal connection they made (in that, “does not affect,” “affects each other,” “affects”).

9.4.2 Post-interviews

A set of interview questions focused on epistemology in ecosystems science and BOE were developed. It included questions such as: *“What are some things that ecosystems scientists do when they cannot conduct an experiment and want to make causal claims about what has happened in the ecosystem?” “Have you ever heard the term “Body of Evidence”? If yes, what do you think it means? If no, a Body of Evidence means “a collection of evidence.” What do you think that means?” Why is it important for ecosystems scientists to collect a “Body of Evidence” or a “Collection of Evidence”? What are some reasons that they do it?”* These questions were followed up with open-ended probes, such as, *Can you tell me more? What does that word mean to you?* etc., to get at students’ intended meanings. Following the intervention, eight students, four from each class, were interviewed in sessions that lasted approximately 30 min. This analysis included an emic process of surfacing emergent themes within each interview (Strauss & Corbin, 1967), capturing these as a memo about each subject's knowledge and then looking across memos for themes across interviews generally and as clustered by the two classes.

9.5 Results

9.5.1 Concept Maps

As seen in Table 9.1, EcoXPT students made more connections but had fewer pieces of evidence within their connections than students in the EcoXPT plus BOE students. They also did not include both evidence and reasoning in their connections as much as EcoXPT plus BOE group. The EcoXPT plus BOE students made fewer connections but had more pieces of evidence within their connections. They also had higher rates of both evidence and reasoning in their connections. The EcoXPT Only students tried to use more factors to make more connections and to construct more of the causal story. This response pattern was frequently witnessed with students using less relevant reasoning to the connection they were constructing, but it would often help tell the "story" (in that reasoning often explained the connection or elaborated on it by "telling parts of the story."). Some students also didn't make broader or more complex connections, but instead they made minor connections (only two or three factors) across the causal scenario. They also used the same piece of evidence for multiple connections even if it wasn't the best evidence for a given connection. The EcoXPT with BOE students generally made fewer connections and there was a tighter range with less variability in the number of connections that they made. However, they included more of the "foundational" part of the story (usually related to fish, herons, abiotic factors you can test in a lab, etc.) and they tried supporting it well with evidence and reasoning. The tighter range with less variability may be due to the greater cognitive load of processing more evidence for each piece. It is not possible to know conclusively given the small n in each class and might also represent differences in the student samples.

The most frequently used types of evidence across both groups were the tolerance tank results and the field guide. (See Figs. 9.5 and 9.6.) This makes sense because of the progression of the Thinking Moves and curriculum. The curriculum

Table 9.1 Concept map comparisons in EcoXPT vs. EcoXPT + BOE classes

Intervention condition	Average number of connections	Average percentage of connections that contain both evidence and reasoning	Average number of pieces of evidence per connection
EcoXPT only (n = 12)	10.3 (range 2–21)	55.67% (range 17–100%)	0.76 (range 0–2)
EcoXPT + BOE (n = 10)	6.6 (range 4–12)	75% (range from 0–100%)	1.12 (range 0–3)

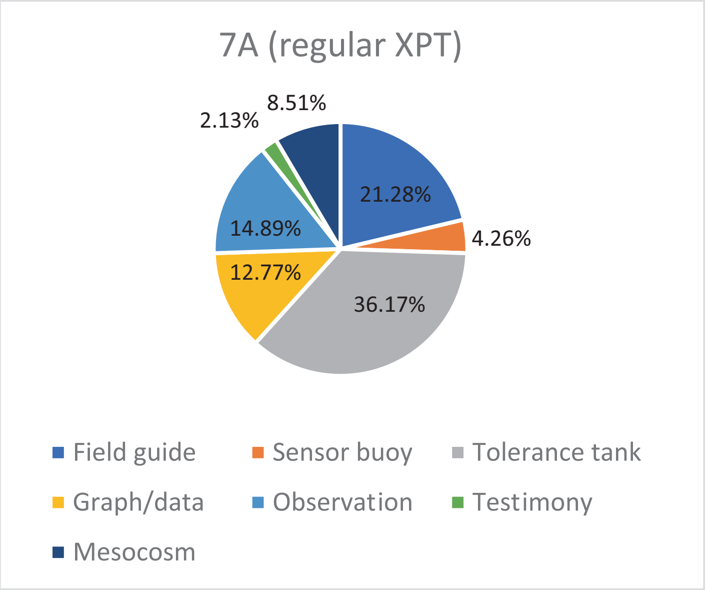

Fig. 9.5 Evidence use by EcoXPT only students

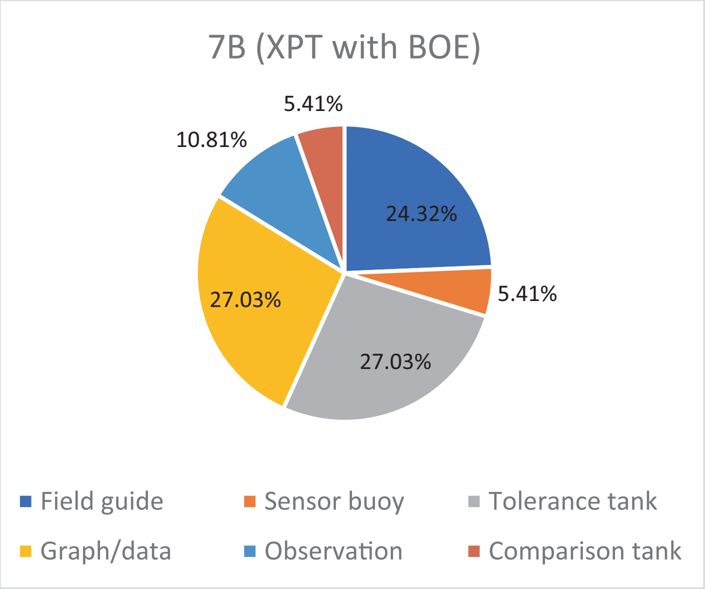

Fig. 9.6 Evidence use by EcoXPT Plus BOE students

encourages observing and taking notes (or looking at notes, as in the field guide) and then analyzing causality (which is usually first explored through the use of the tolerance tanks in the lab because it's easy to isolate direct causal relationships). The BOE class tended to refer to pattern data (in the graphs) to a greater extent whereas the EcoXPT Only class used testimony to a greater extent.

9.5.2 Interviews

The interviews suggest that some students in the BOE groups were able to grasp some aspects of a BOE perspective including the importance of varied sources, the belief that ecosystems scientists try to study the environment in ways that don't harm it—a "do-no-harm" perspective—and the value of holding multiple possible models in consideration, as elaborated below. Their ability to reflect explicitly on the framing for their evidence and the encompassing epistemology was somewhat more limited than anticipated and there were some clear challenges as well. The following themes were evident.

9.5.2.1 Confounding Causal Factors with Sources of Evidence

Students focused more on multiple causal factors involved in the eutrophication scenario than on the meta-level concept of multiple sources of evidence as necessary to support causal claims. When questioned about sources, they tended to confound them with factors. This response pattern occurred to some extent in both groups.

Most students gave sophisticated explanations of the complex causal factors involved in the eutrophication scenario. They seemed well able to think about complexity and multicausal scenarios and explained how causality might work. However, when asked about sources, students in both groups conflated multi-causal explanatory factors with the concept of multiple sources of evidence (as exemplified by subjects 3, 4 and 6 below).

Some students focused this part of the conversation on what they needed to do to find evidence—the behaviors that they would engage in, to a greater extent than the nature of the evidence itself and the meta-concept of the epistemology and a strong body of evidence. For instance:

Subject 3 (EcoXPT Only):

> *I-…can you give me examples, more examples, when you say they are collecting evidence?*
> *S3-They go to, they test the water, to see if the water is okay for animals to live. They check the soil and the plants to see if okay, that plant life can breathe. They try to find animals, see if there's a lot of animals or not that many animals.*

I-…Yeah, you're kind of talking about this claim, there's evidence. Tell me more about how they connect.
S3-Oh they connect because we looked at the days- the day before they died, the day after they died and the day they died. And we looked for a pattern, something changed. And we thought the dissolved oxygen went down a little bit and [inaudible]
I-So in that case you're saying the claim-...
S3-Was like the dissolved oxygen killed the fish- was the cause of the fish died.
I-And what was the evidence?
S3-The evidence was that the day before the fish died, I think like the dissolved oxygen was perfect and then when the fish died the dissolved oxygen went I think either down or up.
I-OK. …why is it important for ecosystem scientists to collect a body of evidence, or a collection of evidence? And what are some of the reasons they might do it?
S3-It's important for them to collect because they want to say how the ecosystem changed in that time they collect evidence. And it's important because what if something bad happened to the ecosystem and they didn't collect evidence they don't know why, or what caused it.

Subject 4 (EcoXPT Only):

I-Tell me more about that, what do you mean by evidence to support their reasoning about the ecosystem?
S4-Well, evidence and their reasoning, they're going to want to find more evidence that actually is relevant for what they think is the reason why the ecosystem is damaged, or succeeding, or whatever state it's in.
I-Can you think of some examples about that type of evidence, or what they might be doing, ecosystem scientists?
S4-Well they would do, probably use tracers, so harmless chemicals that give off a glow, put them into an ecosystem to see what kinds of factors are going inside the water, or doing these certain things and affecting these. …Some other evidence is like, trying to find out populations. Trying to find out about the microorganisms, because microorganisms are a very big part of ecosystems, a very big part. …Because microorganisms, you may not see them, but they do a lot of things. Bacteria can travel real far. So you also gotta measure bacteria the most. There's a type of bacteria that's from Japan, that's native to Japan, that was found on a person, he lived in the USA. But the thing was, this person had never been to Japan. That is how far bacteria can travel. It can travel in and out of ecosystems, just like that.
I-So do you think that's something ecosystem scientists are doing?
S4-They're trying to see mostly all the factors. Mostly all, not really all because it's hard to find all factors. If you don't have all the stuff you try to find most of them, so that makes the most sense.

Subject 6 (Plus BOE):

> *S6-Ok. Umm… Um, algae, bacteria levels. So algae multiplied because of the heat and the sunlight. They started growing too much. And then after it grew too much they died and then all the plants below start dying too because of lack of sunlight. Then bacteria started decomposing it and then the bacteria levels started increasing which made the dissolved oxygen levels decrease. So that's when it's being caused. Algae caused bacteria to increase which caused dissolved oxygen to decrease.*
> *…Well, they can get data and turn it into a graph to figure out how and what is causing the other one. Like the example that I used before- algae, bacteria and DO levels. That's the one that's causing it. And it could also be like something I thought before about the herons eating all the fish, so that was my answer at first because the heron population was increasing and the fish population was decreasing. So then that was my main, like source. But then I started thinking about it and then I figured out that wasn't correct because if the food source is going down then so should the predators.*

This focus on figuring out the factors involved in explaining what happened at the pond and on the actions that one would engage in to find out, by subjects in both conditions, is not, in retrospect, surprising. The response has more behavioral coherence with what they are being asked to do in EcoXPT—to investigate and develop an explanation for what has happened to the fish. Focusing on the sources of evidence introduces a meta-level to that process. It is possible that the increased cognitive load of the task was more than students in both groups were able to engage with. As considered in the discussion, this raises the question about whether there are instructionally more effective ways to get students to focus on sources of evidence—such as evaluating someone else's data and deciding whether information is trustworthy.

Two students, subject 5 from the BOE class and subject 2 from the EcoXPT Only class, clearly did differentiate between factors and sources—not confounding them—and talked about the importance of multiple sources, suggesting that students are able to do so. Subject 5 (BOE) talks about the importance of multiple sources of information in providing for a body of evidence. For example:

> *S5-Because you can't really rely on one source of something because you have to get a lot of sources to see if they match up. And some news can be fake from what you've heard, so you have to learn from other sources.*
> *I-…do you think it's better to have multiple different types of evidence or one type?*
> *S5-Um the same thing, multiple types of evidence because the thinking move body of evidence has something to do because you can maybe mark out like one claim we had about it and then something debunks it, we can't really see what debunks our claim of the situation if we only have one source of evidence.*
> *I:-Could you tell me what you think the term body of evidence means?*
> *S5-Um, it says body in it, so it means like, I think a lot of things like a lot of evidence to debunk your claim or support your claim, or maybe new questions along the way.*

> *I-Is there anything else we should know about body of evidence?*
> *S5-Um, don't have like, don't be disappointed or have high hopes. Just clear your mind and just not think about it too much. Or have an open mind about it.*
> *I-Should they be different sources, same sources?*
> *S5-I think they should be both so you can have a variety. …so you can have different types of sources to go back to. ….I guess it would be nice to have a variety in my opinion. I'd rather have a lot of things instead of like one source. I'd rather have a variety of sources.*
> *I-Why is that important?*
> *S5-Very reliable. It's very reliable to have a lot of sources or a lot of things.*

Subject 2, an EcoXPT Only class member, also differentiated between sources and factors. However, s/he insisted that evidence that is all from the same source is better, that if the evidence came from different sources that would not be as good. While s/he recognized that multiple pieces of evidence are helpful and gave a preference for experimental evidence, s/he explicitly rejects varied sources. It is possible that the student was expressing a distrust of testimony in particular and the need for additional evidence to back it up, but the interviewer did not probe this aspect of understanding further. For example:

> *I-Well we're just talking about having multiple pieces and are all of the pieces of evidence from the same source, or different sources?*
> *S2-All from the same source.*
> *I-Let me think of an example. Pretend my claim is, dissolved oxygen affects fish and I have two pieces of evidence and they're both testimony, so I heard someone say something. I heard a scientist say "I know from my experimental experience that low dissolved oxygen causes fish to die," and someone at the pond said "I heard dissolved oxygen can cause the fish to die" Is it better to have two of the same type of evidence, does that make it strong?*
> *S2-Yeah, because they both gave you really big pieces of evidence. And you could probably get something out of it, too, by yourself or something. And then probably make it stronger and stronger.*
> *I-What if you had two different types of evidence? Let's say you had testimony and you had data. Is that also good or not as good?*
> *S2-I think it's not as good because the testimony, you're testing it- I'd try the experiment thing though, because what people- what if they don't know what to do and they just said it to you? I would test it to see if it actually works. I would test it because it would be- you could get a lot of evidence out of it.*
> *I-…Is it better to have two of the same- for example two people said something. Or is it better to have evidence from two different sources? So for example someone said something and data you collected.*
> *S2-I think the same*
> *I-because…?*
> *S2-Because if they're thinking the same way, they can probably, we can all work together, try to find something else.*

9.5.2.2 Expressing the Value of Multiple Possible Explanations/Models

At least one student expressed the value of multiple possible explanations and holding different possible models in mind (which is different from multiple factors, multi-causal explanation), connecting it to open-mindedness.

Subject 8, a student in the BOE Class expressed that s/he was holding more than one possible explanation in mind implying an open-mindedness that fits with the epistemic value of holding multiple possible models and the uncertainty and humility with which the ecosystems scientists considered possible explanations and supporting evidence (Kamarainen & Grotzer, 2019).

> *S8-And if the algae probably doesn't, this is my other theory- if the algae doesn't uh, like if the algae doesn't uh… Ok so, if the algae is like not working right, like if the algae is uh… Let's see… Oh yeah, so if the algae like uh… If the algae uh… Can you skip it? Skip it. Because I can't have an explanation for it.*
> *I-Yeah, do you want to think about it for a second? We have time.*
> *S8-Uh, yeah sure. Uh… Oh ok! So I got it now!*
> *I-Yeah.*
> *S8-So the nitrates probably activated the algae, so the algae can be produced more, the algae might cover up the, like the top of uh, the ceiling of water. And it probably can't make the photosynthesis go to the water, so the fish can't, so the plants down there can't do photosynthesis so they can't make oxygen for the fish. And when it does that, the fish is going to die because oxygen. And the bacteria is going to break it down and also there's more bacteria, bacteria also takes up the water, it takes up more water, the fish might not have a lot of water to breathe. So I think something caused the algae, like nitrates, or nitrogen probably taking up the oxygen I think.*

9.5.2.3 Recognizing a Collection of Evidence Intended to Support a Claim

Interviewees in the BOE Class offered descriptions of BOE that included recognition that the evidence is a collection, not just randomly chosen and that the intent is to prove a claim.

Subject 7 made explicit comments to indicate that a Body of Evidence has meaning beyond just a bunch of random evidence, for example:

> *S7-They collect a bunch of evidence for um, so they will have more than one reason of why something would cause the other or something that happened. …A body of evidence, um… So a body of evidence is this like, collecting evidence and running tests to see if your right or wrong every day until you get it right eventually, or if you fail. And a bunch of evidence is like, just having evidence and basically not doing anything with it. I guess.*

S8 viewed BOE as needing to prove claims (though not necessarily in the context of broader epistemological considerations).

Subject 8 (BOE):

> *I-Have you ever heard the term body of evidence?*
> *S8-Yes.*
> *I-Ok, what does it mean? Can you tell me?*
> *S8-It means like, say for scientists there’s like an experiment, you need evidence to show the experiment that he did or she did, so he or she would probably be doing an experiment about fish and they will see what happens in the ecosystem like five days after it rained. They need a body of evidence, so they need to take like notes, or like body work, or they need to like take pictures, to see how many, like a lot of body of evidence that they have to include and talk to other scientists to see what the can do to fix it.*
> *I-Ah, ok. So tell me more. You mentioned they might have notes, they might have like temperature, things like that. Tell me what that means in terms of the body of evidence, like what is it?*
> *S8-They’d probably have to take notes like, uh, like the turbidity went down below like 50 degrees, or uh, 50 Celsius I think. And they had to that and see what happens like everyday and see what happens during the day, see where body of evidence is- how much evidence that they have.*
> *I-And so why, why is it important that ecosystems scientists collect a body of evidence? Like what are some reasons why they would do it?*
> *S8-Because they need body of evidence, because if they just say it then like, oh yeah that happens, but then they need like a claim that can like prove their explanation.*
> *I-So is this something that you did when you did EcoXPT? Did you think about this?*
> *S8-Yeah I thought about that if I just say something I need to back up with evidence. If I just say that the algae killed the fish I have to go and research and have to go around and do temperature, water temperature, see what happens on the algae on this day, on the day that the fish died, the population of the algae, the green algae, blue algae and see what happens. Because if you say like it’s algae- prove it! So I have to go out, search for stuff, research it, get like a body of evidence. So, yeah…*

9.5.2.4 Making Connections to Other Learning about Evidence

Despite the lack of introduction to BOE as a concept, when asked what it might mean, students in the EcoXPT Only class made connections to what they had learned about providing evidence when writing in general and in science, in particular.

Students in the EcoXPT Only group made connections to an idea that they appear to have learned in class about writing and perhaps scientific writing in general where you have an introduction, then a body of evidence, then a conclusion. For example:

Subject 1 (EcoXPT Only):

> S1-*So, body of evidence could be- like in an essay you have the introduction which has a claim. Then you have the body of the claim, which has three, two, or some, or a certain amount of body evidence in your essay. …It's like an essay, when you have the body evidence, which is the evidence from the claim that you're making.*

Subject 3 (EcoXPT Only):

> *S3-Well I think like a hamburger, is like the meat is the middle, what you're doing, like an essay- no, not like an essay. Body, a paragraph- the middle of the, experiment? If you have evidence… …like if I explain something, I'm going to have to have evidence. So I'm going to have like the middle.*
> *I-So what does the term "body of evidence" or a collection of evidence in the context of ecosystems, what do you think that might mean? OR what we might use it for?*
> *S3-To see if the evidence goes with the claim you are trying to make.*
> *I-Okay, tell me more, why is that important?*
> *S3-Because if the evidence has nothing to do with the claim you're trying to make, it's going to be hard to back up your claim.*

9.5.2.5 Acknowledging Ecosystems Science Experimentation as Sensitive to Not Harming the Environment

Students in the BOE Class talked about how ecosystems scientists attempt to "do no harm" and how this impacts experiments that they would not do.

Students in the BOE Group did seem to come away with a clear sense that ecosystems scientists try to do "do no harm" investigation—that they don't burn down the forest to see what happens and that they might investigate things that naturally occur (what is called "natural experiments" or "opportunistic investigation" in the curriculum) even if the students did not explicitly use those words. For example:

Subject 8 (BOE)

> *I-What are some things that ecosystem scientists do when they can't conduct an experiment but they want to make a causal claim?*
> *S8-Uhh, they probably might, uh let's see… Maybe they might do a tolerance tank, they might get a lot of fish and put a lot of stuff inside to see what kills them because they can't go outside and do that to all the fish to the ecosystem because they, it won't be good.. So yeah, the fish would probably die really fast, so they had to do it in a tank and see what happens. Or they probably, um,*

> *they probably just do something that makes like, I'm not really sure, but I have an example. So say like, they want to go and see how many forest fires happened that one year, not forest fire that happened every once a year, a forest fire happens like, how high the temperature of the forest fire can get. …They're not going to go burn a forest fire and burn it. So they might probably get like a couple of branches and trees and they might like put it in their office and burn on fire and see what happens.*

Subject 5 (BOE):

> *S5-So, if something like in the past, a lot of things happen in the US here or worldwide, so um, like a forest fire. They can't just put a forest fire on an actual forest because it could hurt the ecosystems in there that it's producing. And they could use some research of it from recent years, or how long it is and see the effect of it how it was before.*
> *I-Anything else?*
> *S5-Um, an internet one? Like an online one, like how you did it with EcoXPT without actually harming any fish in real life. ….Oh wait, what if they get already passed on fish and conduct an experiment on that?*

The interviews suggest evidence that some students are able to understand and use aspects of Body of Evidence reasoning, but also that the ability of the broader group of students to reflect explicitly on the framing for their evidence and the encompassing epistemology was somewhat more limited than anticipated.

9.6 Discussion

The findings suggest that there were subtle shifts in how students viewed the importance of evidence in support of their claims and that the BOE students focused on constructing a compelling body of evidence in support of each claim. Some of the interviews indicated an appreciation for holding different possible models in mind and considering multiple lines of evidence as the scientists did. It may have come at the expense of a fuller explanation of the complex causal scenario as they constructed less of the explanation in their concept maps. At the same time, their explanations focused on causal dynamics that were central to the eutrophication scenario. Given the period of time over which the curriculum plays out and the primary tasks of investigating the reasons behind the fish die-off, it makes sense that a focus on BOE in addition to constructing the causal connections would divide students' time and attention to some extent.

Both groups of students revealed understanding of the importance of evidence. The BOE group used more evidence in support of their concept map connections. Some of the BOE interviewees were able to talk explicitly about constructing a set of evidence and the importance of having corroborating evidence. The EcoXPT Only students also thought carefully about the types of evidence and the importance of providing support for testimony. The EcoXPT curriculum materials support these understandings (even without BOE framing) through the Evidence-Seeking Thinking Move and the supporting materials (See Appendix).

The findings also suggest that students in both groups focused more on talking about developing explanations with multiple causal connections and including multiple possible facts than multiple sources of information/evidence for each factor. This response pattern makes sense given that developing the causal story is more directly aligned with the primary goal of figuring out what happened to the fish and the other is at the meta-level of how they establish the causal connections and generate the scientific knowledge behind their explanations. The finding that the BOE focus translated into a stronger focus on collecting corroborating evidence even if it did not result in as much of an explicit awareness of the epistemology as anticipated is a step towards acknowledging the epistemological underpinnings.

There was clear evidence that BOE students understood that ecosystems scientists needed to find ways to construct causal explanations that did not harm the environment, that they entertain different possible explanations, and that they focus on constructing strong explanations and that this relates to the evidence that they can provide to support their explanations. Students in both classes expressed understanding of the value of experimentation in providing evidence.

This initial, exploratory study is promising, but limited in what can be learned from it. One could imagine that a longitudinal study would reveal more about how these understandings can be developed over time. With greater time to build such understandings, it seems that it would be possible to build the meta-level understandings about varied and multiple evidence and constructing a powerful explanation as an integrated part of figuring out what one believes to be the causal connections. A longer and somewhat larger study might also reveal particular points of difficulty in learning these ideas—both where they are challenging to learn and where they may interact with other concepts in ways that could lead to misunderstandings. It is also possible that students would learn more about the particulars of how ecosystems scientists construct complex causal explanations of systems if they had opportunities to contrast these epistemologies to approaches in other areas of the sciences as such juxtaposition would help to highlight the features of each. Despite its limitations, this study does suggest possibility and promise for developing important understandings in how biological systems are understood.

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Appendix

Overview of the Plus BOE Curriculum

Overview:		
Day One: *Essential question of the day: How can I get to know an ecosystem through exploration?* Students begin exploring EcoXPT and focus on getting to know the layout of the world, what organisms live there (both micro- and macroscopic) and how the field guide tool works. They are introduced to a thinking move called Deep Seeing	**Unlocked:** Camera Field Guide Submarine Notebook	**Locked:** Data View Calendar Water Tools Weather Tool Population Tool Atom Tracker Concept Map Lab (includes scientists)
Day Two: *Essential question of the day: How might things change in an ecosystem over time?* Students continue exploring EcoXPT and focus on traveling over time and seeing what can be learned on different days. They may also start collecting water quality measurements and gathering data for those measurements across time. The weather tool, population tool and Data View are also unlocked on the second day and some students will find them and use them. They will be more formally introduced on Day Three	**Unlocked (in addition to what was unlocked on previous days)** Calendar Water Tools (Weather Tool) (Population Tool) (Data View)	
Day Three: *Essential question of the day: How can I collect evidence to help me figure out what’s going on?* Sometime during Day Two and Three, students will have found the fish die-off. If they have not yet found it by the beginning of Day Three, they are guided to exploring the date of July 28. They focus on their initial hypotheses about what may have happened and begin collecting evidence in support of their hypotheses. They are introduced to the move of Evidence Seeking. As they collect pieces of information, or evidence for what might be happening in the world, they are able to collect evidence in relation to each claim. The opening PPT draws their attention to the Population Tool, Data View and Weather Tool		
Day Four: *Essential question of the day: How can I look for patterns that suggest what might be going on?* Students continue seeking evidence in support of their ideas about what happened to the fish. They are introduced to the move of Pattern Seeking as they explore patterns in the data that suggest what might be going on		

(continued)

Overview:	
Day Five: *Essential question of the day: How can I start to connect the information that I'm gathering?* Students continue seeking evidence in support of their ideas about what happened to the fish. They are introduced to a Concept Mapping Tool that will help them to make possible connections and seek evidence for each claim represented in their concept map	**Unlocked:** Concept Map
Day Six: *Essential question of the day: How can I use experiments to answer the questions that I have about what's going on?* Students continue seeking evidence in support of their ideas about what happened to the fish and exploring patterns in the data that suggest what might be going on. Once they have discovered patterns between algae, bacteria and the fish die off, typically on Days Five or Six, they are introduced to the differences between correlation and causation and the Analyzing Causality Thinking Move. The "Lab Building" and related tools are unlocked so that they can begin to conduct experiments to confront some problems in reasoning only from patterns and will begin to see how it is important to explore the mechanisms behind the patterns. The Atom Tracker Tool appears on the Tool Bar but is not discussed until Day Seven	**Unlocked:** Lab (includes: Lab building Tracers Mescosm And related Scientist NPCs) (Atom Tracker)
Day Seven: *Essential question of the day: How can I continue to use experiments to test my claims, collect evidence and build causal connections?* Students focus on asking questions about what might be going on in the ecosystem and on studying through experimentation and other forms of investigation about what might be happening. They continue working with the Evidence Seeking and Analyzing Causality moves to hypothesize about what might have happened in the world. The Atom Tracker is introduced	(Atom Tracker)
Day Eight: *Essential question of the day: How can I think about what parts of my explanation seem incomplete and what else I need to fill those gaps?* Students step back and reflect upon what they do and do not know and to focus on getting the information that they need to really understand what is going on. As part of a class discussion, they consider the difference between seeing patterns and determining causality. They continue to refine their questions and to make sure that they have evidence to back up their claims	
Day Nine: *Essential question of the day: How can I use multiple pieces of evidence and multiple types of evidence to further develop my explanations about what's going on?* Session Nine introduces the Body of Evidence Approach. Students learn from the PPT and the BOE Thinking Move how the BOE approach requires using multiple pieces of evidence and multiple types of evidence and how this can help them to evaluate the overall strength of each claim and to consider the level of certainty or uncertainty that is possible for each claim. Students evaluate two Bodies of Evidence and then evaluate their own explanations to see how they can further collect evidence to support their growing claims	*Remind students to talk to new NPC- Dr. Aziza Al Dahan

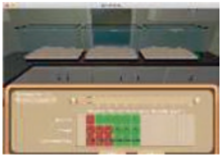
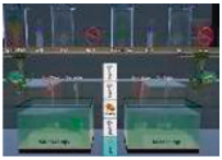
(continued)

Overview:	
Day Ten: *Essential question of the day: How can I construct a scientific explanation about what's going on?* This session picks up where Day Nine left off as students continue piecing through their explanations. They continue conducting experiments and using the evidence from their experiments to understand, as fully as possible, what is going on in the ecosystem. They are introduced to the "Constructing Explanations" Thinking Move. It is used along with the Concept Mapping Tool to support them in making sense of the "big picture" as they put all of their clues together	
Day Eleven: *Essential question of the day: How can I think about the values and limits of different types of evidence?* Students transition from building their concept maps to finishing compiling their evidence and preparing to present their work to others. Students focus on building the fullest explanation that they can with their concept maps. As they are working, the teacher circulates and helps them to find gaps in their explanation. They use confirming and disconfirming evidence to support their explanation. With help from the visual cues/codes in the concept maps, they reflect on the kinds of evidence that they are using (patterns, textual information from the field guide, testimony from characters and outcomes from experimental studies) and figure out if there may be information that is missing from their explanation	
Day Twelve: *Essential question of the day: How can I communicate my findings about what's going on?* For the first third of class, students continue preparing their concept maps to present to the class. They make sure that all of their evidence is listed and that there are no gaps in their explanations. They include confirming and disconfirming evidence in their concept maps. The teacher then stops them and asks them to carefully review their evidence and concept maps. Then the computers are put away and for the rest of class, students write up an individual essay explaining what they think happened to the fish	
Day Thirteen: *Essential question of the day: How can I communicate my findings about what's going on?* Students share their findings for what happened at the pond. They are charged with listening carefully to each other's presentations and to help their classmates discover what is well-supported in their arguments and where evidence for claims may be missing. If conducted as a whole class discussion, it is facilitated so that all of the students are able to contribute aspects of the complex causal scenario underlying what happened in the ecosystem. The session underscores that a good explanation is a well-supported, well-reasoned one in which the mechanisms for the causal connections are explained	

(continued)

Overview:	
Day Fourteen: *Essential question of the day: How can I reflect on my experience in EcoXPT?* This is a day of reflection on the big lessons from EcoXPT. It is not about the explanation that they came up with but about the messages that they learned about science, ecosystems science and coming up with an explanation. Students have an opportunity to reflect upon their own ideas and then the class has a discussion about it	

Experimentation Tools in EcoXPT

Experimentation Tools in EcoXPT	
	The Tolerance Tanks display three virtual fish tanks, each with a different type of fish and allow students to test any of seven factors to see if different levels of those factors would directly kill each type
	The Comparison Tanks display two virtual fish tanks within a 3D lab environment. Each tank has an associated shelf of objects: a fan, a fish, a plant, or acid. Students choose to fill each tank with either pond or tap water and select up to one (or “none”) objects to place in each tank. Once the tanks are set up, students can “run” the experiment and use the water measurement tools to see the results
	The Mesocosm Tool allows students to investigate how real-world contextualization interacts with the behavior of the variables that they combine in the pool. They consider how changing temperature, levels of nitrates, etc. interact over time. They configure up to four pools with up to two factors each. Once the pools are set up, student can “run” the experiment and use the water measurement tools to see the results
	The Tracer Tool allows students to understand the movement of matter in the environment. They can test how the spatial lay-out and topography play a role in the process. They can choose to place tracers of different colors in different places. The tool allows then to understand how the spatial terrain interacts with the movement of materials
	Buoy Sensor Data is collected over time in the pond. Students can access this data to understand changes in the pond over time that ultimately, they will realize, are relevant to understanding what happened to the fish. They access the buoy data by talking to a scientist at the edge of the pond (Dr. Hsieh) who has a tablet that enables them to access the information.

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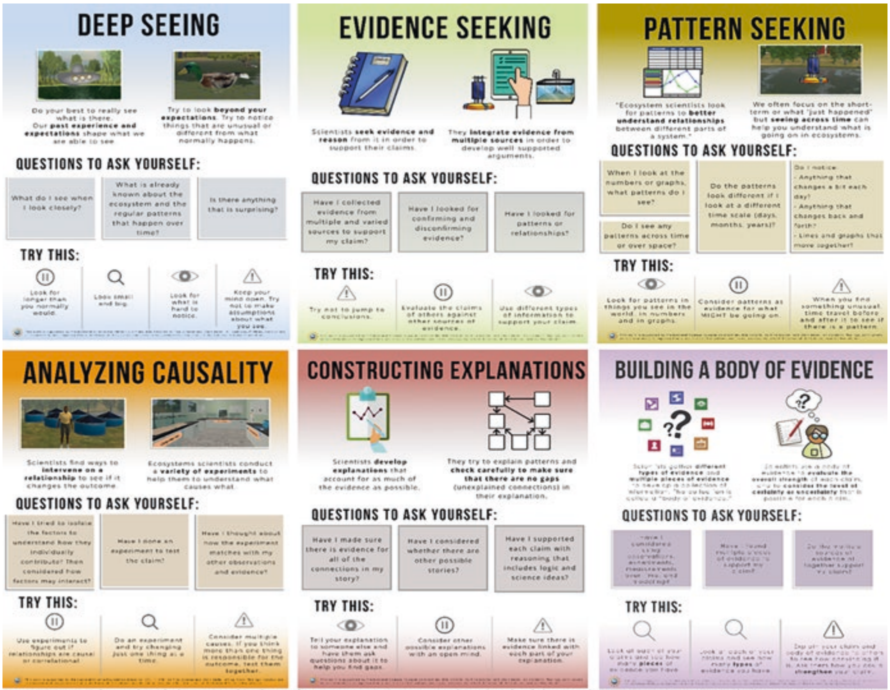
EcoXPT Thinking Move Posters Including a Body of Evidence Approach



DEEP SEEING

Do your best to really see what is there. Our **past experience and expectations** shape what we are able to see.

Try to look **beyond your expectations**. Try to notice things that are unusual or different from what normally happens.

QUESTIONS TO ASK YOURSELF:

- What do I see when I look closely?
- What is already known about the ecosystem and the regular patterns that happen over time?
- Is there anything that is surprising?

TRY THIS:

- Look for longer than you normally would.
- Look small and big.
- Look for what is hard to notice.
- Keep your mind open. Try not to make assumptions about what you see.

EVIDENCE SEEKING

Scientists **seek evidence and reason** from it in order to support their claims.

They **integrate evidence from multiple sources** in order to develop well supported arguments.

QUESTIONS TO ASK YOURSELF:

- Have I collected evidence from multiple and varied sources to support my claim?
- Have I looked for confirming and disconfirming evidence?
- Have I looked for patterns or relationships?

TRY THIS:

- Try not to jump to conclusions.
- Evaluate the claims of others against other sources of evidence.
- Use different types of information to support your claim.

PATTERN SEEKING

"Ecosystem scientists look for patterns to **better understand relationships** between different parts of a system."

We often focus on the short-term or what "just happened" but **seeing across time** can help you understand what is going on in ecosystems.

QUESTIONS TO ASK YOURSELF:

- When I look at the numbers or graphs, what patterns do I see?
- Do I see any patterns across time or over space?
- Do the patterns look different if I look at a different time scale (days, months, years)?
- Do I notice:
  - Anything that changes a bit each day?
  - Anything that changes back and forth?
  - Lines and graphs that move together?

TRY THIS:

- Look for patterns in things you see in the world, in numbers and in graphs.
- Consider patterns as evidence for what MIGHT be going on.
- When you find something unusual time travel before and after it to see if there is a pattern.

ANALYZING CAUSALITY

Scientists find ways to **intervene on a relationship** to see if it changes the outcome.

Ecosystems scientists conduct a **variety of experiments** to help them to understand what causes what.

QUESTIONS TO ASK YOURSELF:

- Have I tried to isolate the factors to understand how they individually contribute? Then considered how factors may interact?
- Have I done an experiment to test the claim?
- Have I thought about how the experiment matches with my other observations and evidence?

TRY THIS:

- Use experiments to figure out if relationships are causal or correlational.
- Do an experiment and try changing just one thing at a time.
- Consider multiple causes. If you think more than one thing is responsible for the outcome, test them together.

CONSTRUCTING EXPLANATIONS

Scientists **develop explanations** that account for as much of the evidence as possible.

They try to explain patterns and **check carefully to make sure that there are no gaps** (unexplained connections) in their explanation.

QUESTIONS TO ASK YOURSELF:

- Have I made sure there is evidence for all of the connections in my story?
- Have I considered whether there are other possible stories?
- Have I supported each claim with reasoning that includes logic and science ideas?

TRY THIS:

- Tell your explanation to someone else and have them ask questions about it to help you find gaps.
- Consider other possible explanations with an open mind.
- Make sure there is evidence linked with each part of your explanation.

BUILDING A BODY OF EVIDENCE

Scientists gather **different types of evidence** and **multiple pieces of evidence** to make up a collection of information. This collection is called a "body of evidence."

Scientists use a body of evidence to **evaluate the overall strength** of each claim, and to **consider the level of certainty or uncertainty** that is possible for each claim.

QUESTIONS TO ASK YOURSELF:

- Have I considered using observations, experiments, measurements, [illegible] and [illegible]?
- Have I found multiple pieces of evidence to support my claim?
- Do the multiple sources of evidence all together support my claim?

TRY THIS:

- Look at each of your claims and see how many **pieces** of evidence you have.
- Look at each of your claims and see how many **types** of evidence you have.
- Explain your claim and body of evidence to others to see how convincing it is. Ask them how you can **strengthen** your claim.

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Script for Body of Evidence Approach Thinking Move Video

Building a Body of Evidence Thinking Move:

Wow, how cool is it that we get to use the experiments in the lab now?! Experiments can help test whether a pattern is actually a causal relationship. This evidence is useful because it helps us construct causal claims about what's going on in the world.

But we can't always conduct an experiment. Here are some examples:

Imagine you wanted to study the impacts of fires on forest ecosystems. You wouldn't burn the forest down just to see the impacts. That would harm the ecosystem and the organisms that inhabit it! OR *imagine you wanted to increase the* CO_2 *in the forest to find out what the long-term impacts are. This experiment might hurt the organisms and could also take many years to conduct.*

When they can't conduct an experiment, scientists use something called the Body of Evidence Approach. A Body of Evidence Approach is when scientists look for multiple pieces of evidence and many different types of evidence in order to support their claim. Gathering multiple pieces and types of evidence from different sources reduces the uncertainty of the results.

But remember, a Body of Evidence Approach can be used even when we **can** conduct an experiment! Experimental results are just one of the ***many*** types of evidence that we can use to support our claims.

Remember that there are many types of evidence that we can collect in EcoXPT. Consider talking to people and other scientists, as well as using your observations, data and information you've collected from opportunistic experiments. Doing this will also help fill in some of the gaps you may have in your explanation!

In EcoXPT, use a Body of Evidence Approach, just like ecosystems scientists do. Be sure to use multiple types of evidence to support your claims. You can make sure that you are doing this by checking the evidence for the links in your Concept Map. Check to see that you're using multiple pieces of evidence and evidence from different sources, by clicking on the arrow between factors you've used to build connections.

When you're using the Building a Body of Evidence Thinking Move, remember to:

Use multiple pieces of evidence to support each claim.
Use multiple types of evidence.
Evaluate the overall strength of the evidence for each claim.
Consider the level of certainty or uncertainty that is possible for each claim.

Body of Evidence Worksheet

“I then decided to conduct an experiment. In one cage, I kept a tomato plant on its own. In the second cage, I kept a tomato plant and some beetles. After a week, I noticed that the tomato plant without beetles was compeletely normal and healthy, while the other tomato plant with the beetles in the cage had holes in its leaves from being eatern.”

What about Jasmine’s claim and its supporting evidence feels convincing and strong to you? Where does it feel like it could be improved, or where do you have questions about it?

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Which of the two statements above do you feel has a stronger Body of Evidence? Why?

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Which of the two statements above do you feel more certain about the findings? Why?

____

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Thinking About Different Types of Evidence Worksheet (Both Classes)

Name____ Date__________________

Thinking about Different Tpes of Evidence

Think about each type of evidence. Draw the symbol from the Notebook connected with each type of evidence from the world. Then answer the two questions about each type of evidence. How can it help you to understand what is going on in EcoXPT? How might it be wrong or misleading?

Symbol in Notebook	Type of Evidence	How can it help me to understand what might be going on?	How might it be wrong or misleading?
Observation	Observations or Things that I see		
Field Guide	Information that I read in the Field Guide and in the written information in the world		
People and Things	Things that characters in the world and videos tell me (scientists and other people)		
Data Graph	Patterns that I see in the graphs and numbers		
All Experiments	Experiments that I conduct in the lab		
	Experiments that I conduct in the world		

Name ___*Sample Responses*_______________________________ Date_________________

Thinking about Different Tpes of Evidence

Think about each type of evidence. Draw the symbol from the Notebook connected with each type of evidence from the world. Then answer the two questions about each type of evidence. How can it help you to understand what is going on in EcoXPT? How might it be wrong or misleading?

Symbol in Notebook	Type of Evidence	How can it help me to understand what might be going on?	How might it be wrong or misleading?
Observation	Observations or Things that I see	*It can help me to notice fine grain details; I might record something that seems irrelevant now but later as more information is known, it might be part of the causal story.*	*I might not know what something is or I might not get to look really well at it; I might mistakenly write down my interpretation of what I see instead of just what I observe and the interpretation could be wrong.*
Field Guide	Information that I read in the Field Guide and in the written information in the world	*Information from secondary sources can be really useful in gaining more information from experts and others who know more about a topic that I do; I can get details about things such as listings of ingredients on the fertilizer bag.*	*I have to think about where the information in a written source comes from. The information in the field guide probably comes from scientists and is probably well researched. I can probably trust the information. It might not tell everything about a species.*
People and Things	Things that characters in the world and videos tell me (scientists and other people)	*The characters in the world have noticed different things and give information. THere are a lot of scientists who tell about how they do their work and talk about how to think like a scientist.*	*I don't know if all of the characters give the right information or how much they know. Some of the characters I don't know much about, for instance, the dog walker or Tommy.*
Data Graph	Patterns that I see in the graphs and numbers	*The patterns can help me see how the variables change in relation to each other. I can see lots of different variables at the same time.*	*Even if two things move together, I still don't know if one thing causes another to change. There could be a causal relationship or it could just be a correlation caused by something else or it could be a coincidence.*
All Experiments	Experiments that I conduct in the lab	*I can focus on just the factors that I want and really see how certain things impact each other.*	*It is possible that in the real world other factors may influence the factors that I focused on and make them work differently. The lab is different from the real world because it leaves a lot of stuff out.*
	Experiments that I conduct in the world	*It is possible to see how things might work in the real world and how parts of the real world impact the outcome of the experiments. For example, tracers move according to how the texture of the land goes.*	*With a lot going on at once in the real world, it is hard to figure out the exact relationships between things.*

Supporting Materials for Body of Evidence Thinking Move

Thinking Moves Scientists Use	Try this:	Ask:
Building a Body of Evidence *Instead of focusing mainly on discrete pieces of evidence, scientists consider what the collection of evidence suggests in order to support a causal claim.* They gather multiple pieces and forms of evidence. They evaluate the strength and weaknesses of the collection of evidence. They consider their level of certainty and uncertainty about the claim based upon what the collection of evidence can support.	It is not always possible to conduct an experiment to test for causality. However, if the collection of evidence is varied (especially if it includes natural contrasts or opportunistic experiments), extensive and highly suggestive of causality, a causal claim may be warranted. Make sure that you consider the body of evidence through the same questions as you would for “Evidence-Seeking” above. Include information about the strengths and weaknesses of your body of evidence in your explanation. Include information about your level of certainty and uncertainty, as scientists do, when offering a causal explanation.	Have I included multiple and diverse pieces of evidence (including data from observations, patterns), experiments (including natural contrasts and opportunistic experiments) and trustworthy sources? Have I evaluated the body of evidence carefully (as per the “Evidence-Seeking” guidelines above)? Have I included information about the strengths and weaknesses of my body of evidence in my explanation? Have I included information about my level of certainty and uncertainty for specific claims, as well as what claims the body of evidence supports, in my explanation?

Accompanying Teacher Pedagogical Moves to Support Student Thinking Moves:
Building a Body of Evidence Approach:
Help students to realize ways that there are different kinds of information and that some are more useful in determining causality than others. Help students to evaluate the trustworthiness of claims by considering whether claims appear to predict outcomes. For instance, if a claim states that adding phosphates and nitrates should increase algae levels, is that what happens when they do? Help students think about other cases that are hard to test but the overwhelming evidence points in a certain direction. For instance, it is difficult to link behaviors like smoking to cancer but over the years, a body of evidence supported the finding of a causal relationship. Help students to think about instances that are hard to test, such as processes that take a long time to reveal outcomes or where there are many possible interacting causes. These are often cases when a Body of Evidence Approach is helpful.

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Learning from Opportunistic Experiments

Discussion Sheet

Experimentation is easier to conduct in some disciplines than others. Ecosystems scientists do conduct small scale experiments in a lab, but when they want to understand changes in the broader environment, they need to rely on a variety of approaches. One of these approaches is using "Opportunistic Experiments" or "Natural Experiments." They involve studying changes that happened either through natural processes or unintentionally by humans or other animals.

"Opportunistic Experimentation" or "Natural Experiments" are often used in cases where an intentional experiment would cause harm or would be unethical, for instance to an ecosystem or a population of people. For example, if you wanted to know if chemicals are harmful to a pond, scientists wouldn't fill one pond with the chemical and compare it to another pond without it. But if a chemical spill releases the chemical into a pond, they could study it and compare it to other ponds. Similarly, if scientists what to know the impact of environment on children, they can study identical twins but they can't send one twin to live in a different environment. However, if they find twins who were somehow separated at birth, they can study their differences.

In EcoXPT on Lesson Day 9, there is a scientist by a small woodland pond and she is studying what happened to the pond such that it turns bright green. She discovers that a farm worker moved a manure pile such that the runoff began entering the pond and explains this to the students.

Consider the following questions:

1. Did any of you meet a scientist on Day 9 at a small woodland pond that had turned green? If so, what did you learn from her?
2. What do you think opportunistic experiments are? Why are they so important in ecosystems science?
3. Ecosystems scientists adopt a "do no harm" approach. Do you think this means that they never conduct an experiment in which an organism dies? Are there any instances in which this might be justified?
4. What other examples of opportunistic experiments or natural experiments can you think of? Make a list together as a class.

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Uncertainty and Constructing a Best Explanation

Discussion Sheet

Scientists aim to construct the very best explanation that they can with the available evidence. Often it is not possible to definitively know the “right answer.” Therefore, it is important that scientists talk about uncertainty and the sources of scientific uncertainty in their work.

The focus is a little different than talking about your personal certainty or uncertainty. There are always things that we as people don’t know. Scientific uncertainty is more about what we do or do not have the data to support and even if it is possible to know something.

Scientific uncertainty is especially important when we are constructing explanations about the past. Think about fossil evidence, for example. We can use what is left behind to create the best story about what happened but since we can’t travel backwards to the time of the dinosaurs we will never know for sure. Even for more recent events that we did witness, there are often different perspectives and different sources of data on what happened. Recall the last time you had a disagreement with a friend. You probably both give a different explanation.

Even when you are present to observe something happening, there can be uncertainty about what happened in between the times you are there. For instance, in EcoXPT, you only visit the pond during the day and so it is hard to know what happens when you are not there. So when you take measurements, you have the day to day data but you don’t have the data points in between. When you collect data, you are guessing that there is a straight line between the data points, but you cannot be certain.

Sometimes new information causes scientists to revise their explanations. Revising explanations is part of how science works. An explanation can be the best one for a certain period of time and then new evidence might suggest an even better explanation. Even so, the old explanation may have been very helpful in the meanwhile.

It is common to hear scientists:

1. …express uncertainty. *(The data suggests that it might be due to this cause but we still have further questions about other possible causes.)*
2. …talk about how much certainty they have in a set of findings. *(We have a lot of certainty in these findings because we have seen this outcome so often.)*
3. …express certainty at some levels of analysis of a problem and not at others. *(We know how this chemical behaves in a lab but we don’t know what happens over time in the broader ecosystem.)*
4. …talk about certainty in some contexts but say that it is not generalizable to other contexts. *(We know that these findings are reproducible in these contexts but in other contexts with changes in variables such as temperature, moisture levels, etc. they may not be reproducible.)*

Consider the following questions:

1. In what ways is scientific uncertainty similar to and different from personal uncertainty? *(Think of examples when you didn’t know something because you didn’t have the information yet but it was knowable. Think of examples of when you didn’t know something because it was unknowable.)*
2. What are some instances when scientists might talk about uncertainty?
3. What does it mean to give the best possible explanation?
4. What are some places in EcoXPT where there are sources of uncertainty?

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Tina A. Grotzer is a senior researcher at Project Zero and faculty member at the Harvard Graduate School of Education. She directs the Causal Learning in a Complex World Lab. Her research focuses on how causal reasoning interacts with complexity and on developing supports for complex causal learning and public understanding of science. In addition to many research articles, her books include, *Learning Causality in a Complex World*, the *Causal Patterns in Science* Curriculum series, and chapters focused on developing deep understanding, issues of pedagogy and teaching to the Next Generation Science Standards. With colleague Chris Dede, she developed the EcoLEARN curriculum that leverages new technologies to teach complex ecosystems science concepts. She is a recipient of a National Science Foundation (NSF) Career Award and a Presidential Early Career Award for Scientists and Engineers (PECASE).

Emily Gonzalez is a researcher and project manager at Project Zero, a research center at the Harvard Graduate School of Education (HGSE). She previously earned her Ed.M. in Mind, Brain, and Education from HGSE. As a licensed teacher in the state of Massachusetts, Emily's experience also includes teaching and designing curriculum at the elementary school level. Emily has worked on various research projects at Project Zero including EcoXPT, 21st Century Excellence, and the Next Level Lab. Much of her work focuses on applying cognitive science to educational practices and instructional materials. Emily is also interested in examining the relationship between student agency and features of learning experiences, in hopes of encouraging more agentive learners for the future.

Eileen McGivney is a current PhD student, researcher, and instructor at the Harvard Graduate School of Education. Eileen's research interests include how people learn in immersive technology-enabled environments like virtual reality (VR). In particular, she asks whether technology-enabled experiences may change how young people see themselves, and their motivation to learn, through the authentic "hands-on" tasks and environments the technology affords, and how such experiences may affect learners with diverse identities and cultural backgrounds. She is currently studying the use of VR in remote high school and university courses, and is a researcher at Project Zero in the Next Level Lab and the EcoLearn projects. Previously, she conducted research on education policy in low- and middle- income countries, at the Center for Universal Education at Brookings in Washington, D.C. and at the Education Reform Initiative in Istanbul.

Chapter 10
Science Teachers' Construction of Knowledge About Simulations and Population Size Via Performing Inquiry with Simulations of Growing Vs. Descending Levels of Complexity

Billie Eilam and Seena Yaseen Omar

10.1 Introduction

The biology domain is all about complex systems, from the cell organelles to the biosphere different ecosystems. Understanding complex systems requires high-order system thinking relating to systems' multilevel structure cause and effect of components' interactions, system emergent behaviors, dynamicity or equilibrium (Eilam, 2012). Simulations were found to be effective tools for developing understanding of such multifaceted phenomena, as well as to facilitate users' scientific mode of thinking and inquiry (e.g., Charles & d'Apollonia, 2004; Greca et al., 2014; Hinton & Nakhleh, 1999; Jacobson et al., 2011; Resnick & Wilensky, 1998). Hence, simulations use in science teaching is highly recommended (Eilam & Reisfeld, 2017; Merchant, 2019). Yet, students' efficient use of simulations is challenging and little is known about what teachers themselves – who mediate the use of simulations to students – know and understand about simulations, how best to access and select simulations and how to use them effectively for performing an inquiry (Stinken-Rösner, 2020). For example, no study was found regarding the pedagogy of an effective acquisition of this high-order skill, as associated with the order of exposing students to simulations of different complexity (number of variables involved). Thus, an investigation of teachers' interactions with simulations while performing an inquiry in the biology domain, in particular, is called for. Such an investigation would facilitate an improved instruction of biological complex systems and may include, among other issues, the examination of the preferred order of using simulations of different complexity for instruction. It would provide pre- and in-service

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teachers' education programs with timely and relevant information for developing an effective pedagogical mode of instruction, as well as possibly facilitate the optimization of simulations pedagogical design for classroom use.

The use of simulations requires not only the understanding of how simulations function and their potential but also the application of many related cognitive and metacognitive skills. Skill acquisition requires learners to engage with problem solving and experience skill applications in many diverse situations (Anderson, 1981). Namely, to use simulations effectively, teachers have to experience inquiries with diverse simulations. The question asked is: While experimenting with different simulations, what should be the effective order of teachers' exposure to the different levels of simulation complexity? Complexity is defined here as the number of variables available for manipulation. The present chapter describes an investigation of Arab science teachers' engagement with three Simulation-Based Scientific Inquiries (SBSI) of ascending or descending levels of complexity, involving two, four and six variables. We focused on teachers' construction of knowledge about simulations' function and effective use, their affordances in teaching and learning, as well as on teachers' simulations- related beliefs. Most research focus on students' learning with simulations (van der Meij & de Jong, 2006), leaving a lacuna regarding teachers' experiences with simulations. No study was found regarding the influence of the order of using simulations of different complexities on teachers' successful learning processes and products but no information was given on how literature search was made such that we judge the reliability of the claim.

10.1.1 Simulations

Computerized simulations are defined as interactive dynamic models representing certain qualitative or quantitative components of any referent (e.g., a phenomenon, idea, process, system), enabling its abstraction, simplification, and explanation, as well as making predictions about its behavior (Khan, 2011; Landriscina, 2013; Stern et al., 2008). Simulation tools claim fidelity, accuracy and validity (Sauve et al., 2007). The core of simulation models is the ability to manipulate and control the variables composing the referent phenomenon in order to reveal their interrelations. Simulation models afford an immediate feedback regarding the manipulation effect, which expose the phenomenon recurring patterns of behaviors and its related principles. Simulation-related predictions improve students' epistemological beliefs about phenomenon, supporting the enhancement of relevant theories and the updating of knowledge about different referents (Lamb et al., 2018; Tasquier et al., 2016). Hence, experiencing problem solving and inquiry via the effective manipulations of simulation variables may facilitate high-order "systems thinking" (Gerard et al., 2011). Simulation's design and structure may promote and alleviate learning by enabling learners to control the speed of information presentation; to view the referent from different perspectives; to direct learners' attention toward core characteristics of the phenomenon; to simplify the referent complexity; to emphasize implicit borders between different events; or to use visual and dynamic illustrations of the referent (Hegarty, 2004).

10.1.2 Performing a Simulation-Based Scientific Inquiry

Simulations create a scenario-based learning environment, where students are engaged in problem-solving processes of real-world authentic problems, by interacting with the simulation components, applying their relevant prior knowledge and practical skills, and enacting a self-driven acquisition of knowledge. Depending on factors such as the content represented, the simulation design, or teachers' role, studying with simulations frequently shows positive effect on knowledge and skill/meta skills construction (e.g., complex concepts, deep learning, higher-order thinking, problem solving, inquiry, reflection). Moreover, simulations facilitate learners' ability to connect theoretical issues to real-world situations (Lamb et al., 2018; Vlachopoulos & Makri, 2017). However, in spite of these affordances, performing a SBSI (Simulation-Based Scientific Inquiry) is challenging due to both simulations' features and learners' characteristics (Eilam & Reisfeld, 2017). Simulations may cause a high cognitive load due to the large amount of representations and information presented simultaneously on the computer screen, impeding their processing (Watson et al., 2010). Performing a SBSI requires relevant prior domain knowledge as well as cognitive and metacognitive high order inquiry skills such as raising hypotheses, collecting or processing data (Gerard et al., 2011; Hmelo-Silver & Azevedo, 2006; Kornhauser et al., 2007).

Teachers' knowledge about simulations their understanding of its function as models of referents, and their beliefs about simulation classroom use, changes and develops along their professional lives while accumulating formal and informal experiences. Teachers' development may be influenced by factors such as their personal characteristics, modes of training, their interaction with their environment, the context in which they have constructed their knowledge, or their teaching practices (Scardamalia & Bereiter, 2006; Shulman, 1986; Tondeur et al., 2017). Research about teachers' visual and technological pedagogical content knowledge about simulation and their use is limited, but simulation prominence in science education requires teachers' high exposure to SBSI and many experiences with it (Greca et al., 2014).

Several studies examined the effect of different factors on students' performance in SBSI. For example, a study examined the effect of the types of relations between the values of physics variables on students' performance (i.e., unrelated, simple relation - a change in one variable value results in a change of another value, and complex relations – where a change in one variable value results in changes in some variables values). Findings showed that differences among groups were more salient while using simulations of high complexity, and best performance was evidenced in the most complex simulation (van der Meij & de Jong, 2006). Another study compared between students' performance along two consecutive SBSIs involving similar surface simulation elements (e.g., agents' color) and two different simulations. They have found that performance with the different simulations was higher than that with the similar simulations, and in particular in high achievers. They concluded that the latter were able to ignore superficial similarity and focus on the abstract characteristic of the biological phenomenon studied (Goldstone & Sakamoto, 2003). Other researchers examined differences in performance of students who were engaged in problem solving of three ill-structured and well-structured problems provided to them in different order. The two groups received well-structured problems as the second trial and ill-structured problems at the third trial. However, one group began the series with ill-structured and one with well-structured problem. Although the performance of those who experienced solving the ill-structured problem first, was lower than those experiencing the well-structured problem first, the students exhibited better performance while solving the third ill-structured one. The researcher concluded that a learning sequence that begins with ill-structured problems enables students to construct flexible knowledge and understanding and to adapt their use for application in future new situations. He termed the phenomenon "Productive failure" (Kapur, 2008, 2015). Pathak et al. (2008) examined students' performance while being engaged in a series of three SBSIs – complemented by guidance or lacking it. They found that students that have started the series without guidance exhibited a productive failure and were cognitively primed to better succeed in the third task. As presented here, there is still debate regarding the conflict between the productive failure phenomenon and the cognitive load notion. Findings regarding students with low domain knowledge did not support the productive failure notion (Toh & Kapur, 2017). These different studies call for more research on factors affecting SBSI performance.

In the present study we explored Junior high school teachers' SBSI performance using three agent-based simulation modeling adapted from the NetLogo computer language (Wilensky & Rand, 2015). All three simulations were in the domain of science, modeling the ecological complex system of population size, but involving two, four or six variables – defined as the simulation level of complexity. In addition to examining teachers' SBSI behaviors as well as their knowledge and beliefs about simulations, we focused on the effect of a descending or ascending order of simulation levels of complexity on teachers' performance – from two variables to six variables simulation and vice versa. We asked:

How does the order of performing three simulations of different complexity levels influence teachers'-

1. knowledge about simulations inherent characteristics?
2. knowledge and beliefs about an effective classroom SBSI?
3. domain and relevant representational knowledge?
4. SBSI performance?

10.2 The Study and Its Context

A mix method paradigm was applied, utilizing both the qualitative and quantitative methods' affordances (Johnson et al., 2007; Mayoh & Onwuegbuzie, 2015).

10.2.1 Participants

Thirty Arab teachers volunteered to participate in the study. They were mostly females with BA and MA degrees, who teach science in few Arab sector junior-high schools in the north of Israel. The group was highly heterogenous in their demographic characteristics, ranging from 1 to over 15 years of teaching experiences, mostly with four to ten previous SBSIs experiences but some with none, and more than half of them never receiving an explicit, well-planned program of theoretical and practical learning about simulations. The teachers were divided into two similar groups ($n_1 = n_2 = 15$). The first - Group A (GA) experienced the three provided simulations in an ascending order of complexity whereas the second – Group B (GB) experienced the same three simulations but in a descending order of complexity. All simulations represented in a similar manner the dynamic phenomenon of changes in population size, using different components of the complex ecosystem (e.g., grass, deer, growing rates) (Fig. 10.1).

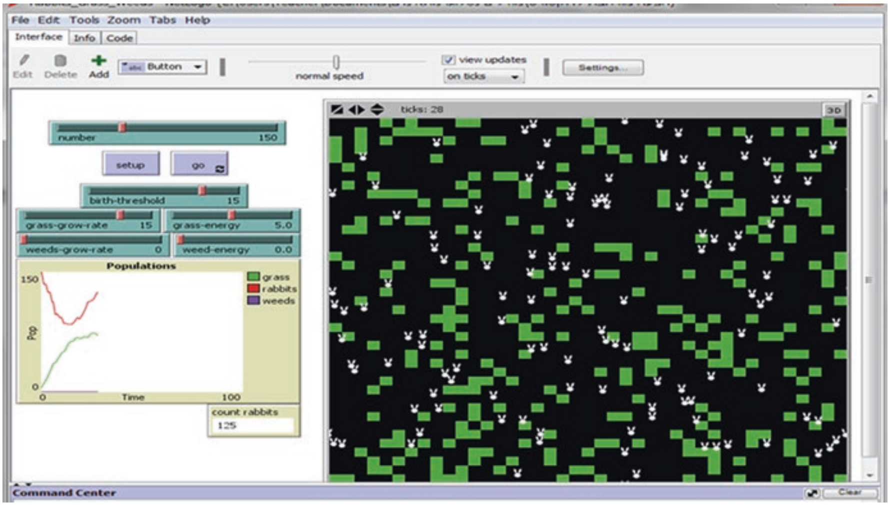

number 150
birth-threshold 15
grass-grow-rate 15
grass-energy 5.0
weeds-grow-rate 0
weed-energy 0.0
count rabbits 125
ticks: 28

Fig. 10.1 A Photograph capturing a screen view of the six-variable simulation, including The number of rabbits (range of 0–500); rabbits birth-threshold (range of 0–20); Grass growing-rates (range of 0–20); Grass energy (range of 0–10 energy units); Weeds growing-rates (range of 0–20); and Weeds energy (range of 0–10 energy units)

10.2.2 Data Collection

Data about the teachers' inquiry process and knowledge construction were collected using four main tools: (a) identical pre- and post-SBSI questionnaires for assessing teachers' theoretical knowledge about simulation and their characteristics, including 20 statements about simulations and 34 about simulation potential for classroom use and their selection. The duration of time between the pre- and post questionnaires and the high number of questions of the type used decreased the test effect, especially following the number of simulations performed (examples and experimental). Teachers were asked to indicate their extent of agreement with the different statements on a 1 to 3 range scale (e.g., "The simulation enables to predict relations between different represented variables"; "The use of simulations is appropriate for students having reading difficulties only"; "I search in the internet simulations for my teaching"). The 3 range scale was chosen due to the more general type of statement; (b) identical pre- and post-domain knowledge questionnaires for assessing teachers' knowledge of the topic of population dynamics and related visual representations. It was composed of five open tasks and one multiple choice task (e.g., "interpret the two presented graphs, explain each of them and compare between the meaning of their representations"); (c) observations, video-recordings of each teachers' computer screen and audio-recordings of teachers' think aloud while performing SBSI; and (d) post-inquiry semi-structured deep individual interviews with five teachers of each group (n = 10). The interview was conducted as an open dialogue between the teacher and researcher and has been audio-recorded. It was based on pre-prepared questions or issues that the researcher raised for discussion while often presenting a short video clip of interviewee's interactions with the simulation, for activating their memory. Our aim was to expose the interviewee's hidden considerations and the meaning of the specific phrasing they used for describing their ideas and explanations for different activities enacted during the inquiry (Beggrow et al., 2014). The tools were validated for their content by two disciplinary and simulation experts.

10.2.3 Data Analysis

Data analysis included the use of predetermined criteria for performing content analysis on teachers' responses to the open questions of the content knowledge questionnaires. Criteria were based on relevant canonic knowledge about ecosystems, food webs, food chains and population dynamics in particular. These criteria were applied for analyzing the open questions in the questionnaires. The grounded theory approach was applied for analyzing teachers' verbal and non-verbal SBSI performance as recorded by the video camera, and for the individual interviews recorded data. Scoring indicators lists were developed for various data features. Qualitative and quantitative (MANOVA and t-tests) comparisons were carried out between the scores gained in each of the three SBSIs and between the frequencies of teachers' verbal and non-verbal behaviors in each group, for assessing the extent of teachers' constructed knowledge and understanding along their experiences with the three SBSIs and to evaluate the effect of the order of exposure to a certain level of complexity on this constructed knowledge. The analysis of teachers' interviews yielded a deeper understanding of teachers' different moves along the inquiry and the considerations behind them.

10.2.4 Procedure

Three individual meetings have been conducted with each participant: (a) providing a full explanation about the study and teachers' tasks and filling up the pre-inquiry simulation and domain knowledge questionnaires; (b) explaining the NetLogo simulations and demonstrating the use of three simulations that were not used in the study itself. Teachers performing of the SBSI according to the group assigned order of complexity; (c) teachers filling up the post-inquiry simulation and domain knowledge questionnaires and 10 teachers being interviewed.

10.3 What Did we Learn About Teachers' Knowledge and SBSI?

A comparison between the different demographic characteristics of both groups revealed no significant difference, except for a small difference in the number of previous experiences with simulation reported. At least half of GB teachers (descending complexity) reported 4 to 10 prior experiences, whereas GA teachers (ascending complexity) reported only 1–3 ones. GA and GB knowledge of simulations and of the related domain was found to be similar as well. The similarity between the groups suggests that these factors did not intervene in performance or that if they intervene one can assume the intervention was roughly similar across groups.

10.3.1 Teachers' Knowledge About Simulations and their Function

Many diverse factors may influence teachers' knowledge, as it develops and changes alongside their life experiences, formal learning (e.g., teachers' in-service programs), classroom practical experiences, and/or informal and incidental experiences with simulations (Sevinc & Lesh, 2018). The pre- and post simulation knowledge questionnaires' scores calculated for teachers in both groups were found to be in the range defined here as having average knowledge about simulations (5 to 15 points out of possible 20 points). As expected, a significant growth in knowledge about simulations and their function was found for both GA and GB teachers, after experiencing the SBSI (GA – $Z = -2.307$, $p \leq 0.05$; GB - $Z = -2.419$, $p \leq 0.05$). However, this growth was similar in both groups, showing no order effect. Moreover, both groups teachers' responses exhibited similar difficulties. In particular, errors evolving from teachers' lack of understanding that simulations are models of a phenomenon were identified. Prior to the inquiry, teachers' knowledge about simulation and their function was characterized as at the lower part of the range defined as average level. Based on research about skills acquisition and in particular about the ability to perform an inquiry through simulation use, experiences with simulations alone usually contribute to learners' understanding of scientific models (Ruebush et al., 2009). Hence, we expected teachers' knowledge about simulations and their function as a model of phenomenon to grow after performing three simulation inquiries. However, in spite of the revealed increase in both groups teachers' knowledge after completing the inquiries, it still remained in the average level range only, as defined in this study. It seems that involvement in a short experience having little knowledge to begin with is not enough for acquiring this high-order skill. Researchers also suggested that teachers understand models as efficient tools for teaching scientific content rather than as tools for performing scientific inquiry (Henze et al., 2007). Teachers' responses were partial, general, and used the names of the different components of the simulation they experienced – stating facts, rather than principles of function (metacognitive knowledge) and ignoring the possibilities provided by the simulation for investigating the phenomenon it models. Teachers in both groups agreed with erroneous statements in the pre- and post-inquiry questionnaires, suggesting low understanding of the simulation features and function and a difficulty to construct a comprehensive mental model of it. For example, in spite of teachers' experiences with three simulations, they failed to perceive the simulation as representing only certain selected aspects of the referent rather than being identical to it and that one can control this interactive tool (e.g., stopping it or controlling its running speed).

10.3.2 Teachers' Pedagogical Knowledge and Beliefs About Teaching with Simulations

Teachers' pedagogical knowledge regarding simulation use in teaching, as expressed in the post-inquiry questionnaire (extent of agreement with presented statements) was similar between groups, did not change significantly and did not exhibit an order effect. GB teachers scored higher (although not significant), which may suggest the productive failure effect. It was not surprising to find that teachers' self-report about their own ability to locate a relevant simulation in different sources and use it for teaching, was not significantly different in the two groups. These teachers reported minimal experiences with simulations before the study and did not have the chance to experience classroom teaching after the study, and as is well-established, the construction of practical knowledge requires practice. Our finding corroborates reports (Donnelly et al., 2014; Opfer & Pedder, 2011) claiming that limited inquiry experiences that lacked explicit guided classroom experience are not sufficient for changing deep and entrenched beliefs. Changing deep beliefs requires an investment of time and efforts for performing a qualitative change and a reorganization of one's body of knowledge, but both possibilities were not available for teachers in this study. Teachers' responses suggest they mostly did not consider simulations affordances for teaching science but were predominantly influenced by superficial instructional pedagogies such as: simulations increase interest, facilitate misconceptions, hinder motivation, or that drawing information from text is easier than from simulations.

10.3.3 Teachers' Knowledge and Understanding of Population Dynamics and Related Representations

A comparison between GA and GB regarding teachers' domain and related visual representations knowledge before their SBSI experiences yielded no significant differences, ruling out prior knowledge as an intervening factor. However, a significant difference ($F_{(1,28)} = 8.893$, $p < 0.01$) was found while comparing the magnitude of the change ensuing in teachers' knowledge from the pre- to the post domain knowledge questionnaire in each group using MANOVA. Experiencing the simulations in an ascending order of complexity, GA teachers were able to construct more domain knowledge than GB teachers, who experienced the simulation in a descending order. An examination of the pre-post changes ensuing in scores for each of the six tasks separately showed that on most tasks scores of GA teachers improved more than those of GB. Hence, GA teachers were better able to construct some theoretical knowledge and understanding of the complex construct of population dynamics and to interpret more accurately the meaning of the related graphs. For example, before the SBSI most teachers described the graphs in a general manner ("At first there was a sharp rise in the number of individuals"). In teachers' post responses – more in GA responses – a shift was revealed toward more accurate and detailed interpretation including indication of units ("At first we see a sharp rise till the third generation from the value of 25 to 100 thousand"). Another example showed – again more representative of GA teachers – that teachers in the pre- simply described what they saw in the graph. This single graph presented a continuing increase in the rabbits population over time and a parallel increase in the fox population but only to a certain point in time, from which the population remained of constant size. The graph was interpreted by a GA teacher as "The number of rabbits is rising all the time and the number of foxes is rising over time, so there is a relation between the rabbit and the fox populations" - ignoring the change ensuing in the fox population. In the post this teacher wrote: "There is a constant increase in the number of rabbits, as compared with the fox population that first increases, but then their number remain constant. One cannot infer the kind of relation existing between the size of the two populations, because there is not enough data to identify it". Some even used the concept of "arriving at an ecological equilibrium". These representative examples suggest that many teachers in the post-inquiry questionnaires, but more the GA teachers, related to the tasks, and the graphs data in particular, more precisely than in the pre-inquiry questionnaires and their inferences improved. They examined the variables and the units on the graphs' axes more carefully, responded more accurately and in a focused manner, and raised broader inferences than in their pre-responses. Because the topic of ecology, including population dynamics, gained considerable importance in the Israeli curriculum in the last few decades, it is safe to assume that most teachers' prior knowledge on the topic has been activated by their engagement with the simulations, promoting their ability to grant meaning to the different simulation results. Moving from the easy simulation (2 variables) to the complex one (six variables) enabled GA teachers to better understand the growing complexity of the ecosystem inquired, whereas GB teachers exhibited some confusions and diffused responses that were too general to explain their arguments regarding the targeted issue. Indeed, personal experiences led to an improved domain understanding (Goldman et al., 2019).

10.3.4 Science Teachers' Inquiry Performance

The qualitative analysis of the transcripts of teachers' audio and captured screens videos, including teachers' behaviors, explanations and considerations, yielded three major themes, each with several subthemes (Fig. 10.2). The analysis of the transcripts of teachers' interviews yielded five major themes, somewhat overlapping with the themes revealed in their performance (Fig. 10.3).

In the next sections we describe our main findings concerning some of these issues as revealed in teachers' behaviors, considerations and notions.

10.3.5 SBSI Time Duration

Although the total time invested by teachers and the time invested in each simulation may attest to various explanations (e.g., teachers' motivation, interest, difficulties encounters, persistence, fatigue), it may still give us a clue regarding teachers' performance. Unsurprisingly, the time invested in the SBSI in both groups was significantly and positively related to the simulation complexity level, namely, the

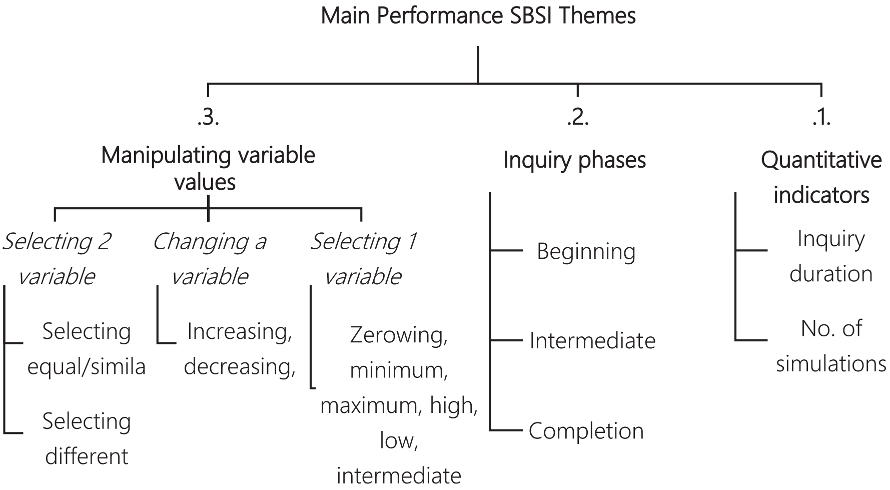


Fig. 10.2 Teachers varied verbal and non-verbal behaviors while performing an inquiry using simulations

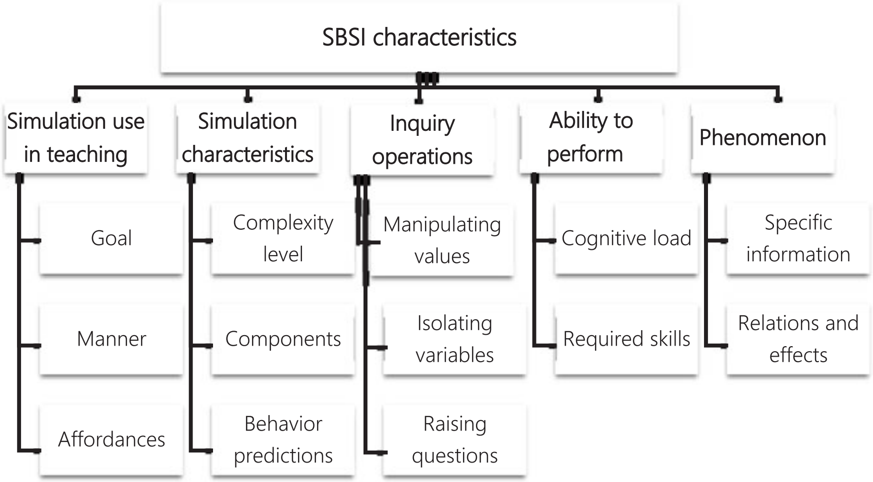


Fig. 10.3 Themes identified in teachers' interviews about their use of simulations for performing an inquiry regarding the "population size" complex system

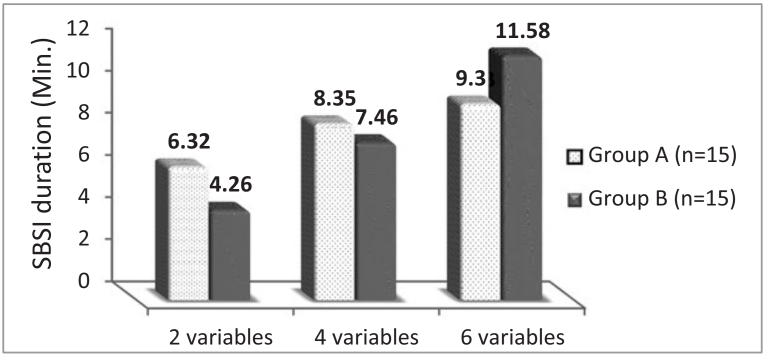


Fig. 10.4 The SBSI time (in minutes) consumed by each group teachers, for each of the simulations

more variables to manipulate – the higher the number of runnings performed, and more time consumed (Fig. 10.4). The total time invested in the SBSIs by both group teachers was similar. A significant difference between the two groups in the time consumed was found only for the 2 variables simulation – that was performed by GA as the first in the three simulations series, hence required significantly more time than in GB – that performed it as the third one, after "training" on two other more complex simulations ($t_{(28)=}3.186$, $p < 0.01$). Surprisingly, the time invested in the 6 variables simulation, by both group teachers, was not sig. Different, although this high-complexity simulation was performed as the first one by GB teachers. Probably, they abandoned this difficult task after a while, due to the high difficulty encountered.

As expected, a significant positive relation has been found between the simulation complexity level and the number of runnings enacted by teachers, with GA teachers enacting significantly more runnings than GB teachers, thus being engaged longer with the simulation and promoting their understanding of its function and of the phenomenon represented. It seems that the gradual increase in the simulation's complexity enabled GA teachers to first grasp the principle of manipulating a single variable value while keeping the other constant (low cognitive load) to reveal the potential relations among them, and that further manipulation of additional variables deepens the comprehensive understanding and enables the prediction of the phenomenon behavior. Beginning the inquiry with a large number of variables promoted GB teachers' trial and error moves that lack the consistency that usually enables the studying of the phenomenon.

10.3.6 Inquiry Phases

Teachers' performance may be described as including three phases for each simulation: (a) the initial phase defined as teachers' total moves from the moment they press the simulation button of "go" after setting the variable values, till they press the "setup" button – composing a single simulation running in each of the three simulations; (b) the intermediate phase defined as the "go" of the second running till the "stop" of the running performed before the last runnings of the final phase, including different number of running depending on the performer; and (c) the final phase defined as the last single simulation running from "go" to "stop" in each simulation. As mentioned above teachers performed different number of runnings in the second phase, which increased with the growing level of complexity. However, the main differences were found regarding teachers' manipulation choices of variables values, which influenced their ability to acquire the effective mode of SBSI and impeded knowledge construction.

The initial phase. Generally, starting with simulation 1 (2 variables) most GA teachers (73%) set equal/similar values, and more of them did so in simulation 2 (4 variables), with a bit more teachers setting different values in simulation 3 of the highest complexity. This behavior suggests teachers' gradual construction, organization and generalization of knowledge. Most GB teachers behaved similarly to GA teachers, but exhibited greater "boldness" (60%) in setting two different values in simulation 1 (2 variables) probably feeling more assured following their prior experiences with the simulations of higher complexity. Moreover, in simulation 2 (4 variables) all GA teachers chose to set one of the variables to zero while manipulating the other, attempting to reduce the number of variables and thus – the complexity of data, differently from GB teachers who mostly did not use the zero option. Hence, exposure to descending complexity level order affected variables' values setting, and in turn was expressed in the construction of a partly fragmented knowledge that hindered the ability to infer about the studied phenomenon characteristics and its involved relations.

The intermediate phase. In this phase, all teachers performed several runnings and value manipulations after the initial phase and till the final one. The first indicator for comparing SBSI performance between the two groups and across the three simulations is the average number of runnings carried out by each group teachers and the percentage of each group teachers who carried out a small number of runnings or a large one (Table 10.1).

Generally, all teachers' average number of runnings in simulation 1 and 2 (of lower complexity) was similar but increased in simulation 3 – of the highest complexity (six variables). However, this average was higher for GA teachers in simulation 1 and 2 and lower in the third simulation than the average number of runnings performed by GB teachers. This finding suggests an order effect. Whereas GA

Table 10.1 Average number of runnings performed by group A and group B teachers in each of the three simulations and the percentage of each group teachers who performed small/large number of runnings

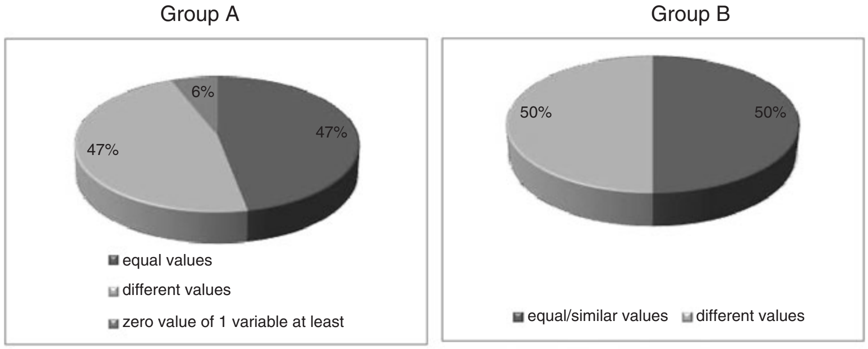
Sim. No.	1			2			3		
No. Run.	Ave.	1–4	5–8	Ave.	1–4	5–8	Ave.	1–4	5–17
GA (%)	~4	60	40	~4	67	33	~6	46	54
GB (%)	~2	93	07	~2	93	07	~8	33	67

teachers experienced a gradual ascending complexity, which prepared them for dealing with the highest complexity of simulation 3, GB teachers encountered the high complexity first, which required many runnings for making sense of the phenomenon behavior, after which a small number of runnings was required in simulations 2 and 1. Similar effects have been revealed for the percentage of teachers performing a small number of runnings, which consistently grew from simulation 1 to 2, but in simulation 3 a higher percentage of teachers performed a large number of runnings, differently from GB teachers, whose percentage performing a large number of running was the highest, dropping to almost all teachers performing 1 to 4 runnings in sim 1 and 2. Hence, the order effect was revealed in teachers' performance of the intermediate phase of the three SBSIs. GA teachers' performance fit the gradual ascending difficulty they encountered from simulation 1 to simulation 3, expressed in the duration of the time devoted to the experience, as well as the number of runnings performed in each SBSI. GB teachers exhibited a reduction in duration of time and number of runnings from the first simulation they experienced, which was the most complex one, to the second and third less complex simulations. Both group teachers exhibited high variability in their value manipulation behavior. The general view of each group performance over the three simulations is presented in Fig. 10.5 (a–f) below.

The final phase. No significant difference was found between the two group teachers' choices of variable manipulation. Generally, after several runnings (in each simulation initial and intermediate phases) more teachers "dared" to set different variables values. Mostly, GA teachers who experienced the ascending order of complexity set in this final phase of simulation 1 (two variables) different values (60%), in simulation 2 about 50% of them set similar values, and about 60% set in simulation 3 partly equal/similar and partly different variable values. GB teachers, who experienced the descending order of complexity, set in this final phase of simulation 1 (their third SBSI) different values (80%), in simulation 2 – partly equal/similar and partly different values (60%), and in simulation 3 - all similar values (60%). Hence, no order effect was revealed. It seems that all teachers required time for understanding how an effective SBSI function as a tool for inquiry and a model.

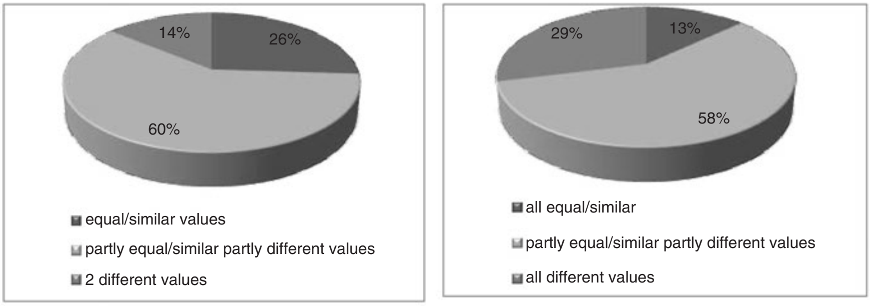
10.3.7 Teachers' Talk About Population Dynamics and SBSI Experiences

Almost all the two groups' teachers concluded a negative relation between the no. of deer and no. of tigers in simulation 1. However only about half of GB teachers, but most of GA teachers noticed the equilibrium existing regarding the populations size, and the tigers' death in extreme situations. In simulation 2, both group teachers' conclusions were similar. However, surprisingly, once again only half of the teachers could indicate equilibrium states of the populations as presented clearly in the graphs. This, in spite of their many correct theoretical explanations of the



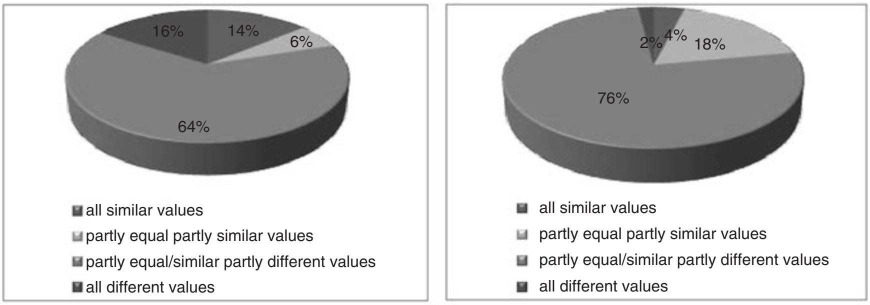
a GA teachers value setting in simulation 1

d GA teachers value setting in simulation 1



b GA teachers value setting in simulation 2

e GA teachers value setting in simulation 2



c GA teachers value setting in simulation 3

f GA teachers value setting in simulation 3

Fig. 10.5 (**a**–**f**) Teachers' values setting while performing the inquiry concept of equilibrium provided in the knowledge questionnaire and interview. This finding suggests that ecology teachers could gain a lot from SBSI experiences, transforming theoretical knowledge into practical one, identifying states in presented data. A smaller number of GB teachers concluded that the sheep fertility affects the number of wolfs as well, and the wolf's fertility affects the sheep number. This implicit relation requires some thinking and can't be inferred directly from observing the graphs simulations. Results for simulation 3 were somewhat different than those for the other less complex simulations. The difference between GA and GB teachers was expressed in the different conclusions they have arrived at, rather than in the number of teachers reaching a certain conclusion, suggesting confusion and an inconsistent mode of manipulation and thinking when the number of variables is high. This happened even when experiencing an ascending order of complexity. It seems that for the acquisition of the SBSI high-order skills, more practice with simulations is required that would allow for a deep understanding and appreciation of the simulations as inquiry tools and models of phenomena.

Some representative example of teachers' domain knowledge after their SBSI experiences are described next. A GA teacher explained: "an ecological equilibrium is required among populations. A state where the number of one population individuals rise too much, if the carnivores will multiply much more than the that of the devoured population, the latter would parish and the former would parish right after it and the equilibrium will be affected". Another GA teacher said: "now I understand that both populations influence the equilibrium". And yet another said: "In simulation 3 I thought that there is a relation, and that the reduction of the rabbits was related to competition and the two types of food available. But this was not so. As one food type contained more energy – the number of rabbits increased. A smaller number of GB teachers exhibited domain understanding. Both group teachers identified explicit relations between variables and the possibility to manipulate the simulation variables for revealing this relation characteristics: "I have discovered the answer by my own manipulations and repeated trials" or "you have to observe every piece of data you get and try to understand its meaning". Teachers noticed the difficulty encountered with the increased number of variables: GA teacher: "the last simulation was the most difficult – what should be changed? and what should be left constant? To change one variable or both". (GB teacher) "at first it was difficult, and I had to understand what it is and how does it work. But in the rest of the simulations it became easier." Many teachers of both groups recited the need for variables isolation, probably known from science experiments they carried out in their classrooms. Yet, although they indicated that only one variable should be manipulated while the other stay constant, many did not apply this principle in their SBSI, and in particular in the highly complex simulation 3, where they changed the values of few variables at the same time. Another related point is that teachers did not apply a metacognitive thinking regarding the performance of inquiry itself and the research question examined. Again, this may suggest some automatic application of an inquiry recipe, as is frequently reported regarding science classroom instruction, which seldom enacts an open inquiry. Teachers' relation to a simulation (the tool) was highly simplistic (e.g., "I change factors and observe the graph on the screen – all this together is the simulation"; "we exhibit reality through the simulation"; "You may repeat many times and it helps to understand the topic"). Such responses suggest superficial understanding based on explicit external characteristics and elements, rather than reflection and metacognitive considerations. An understanding of simulation as a model, affords the making of predictions regarding the represented phenomenon behavior. Only few teachers from the whole sample mentioned predictions ("I saw the relations to the prey, if the number of the carnivores goes up – the number of the prey decreases. I could also change – if the number of carnivores raises – and see what would happen in the future").

Some teachers characterized the simulation with properties that may be relevant to any learning aid such as the need to fit it to students' characteristics, it enables an easier understanding, etc. without indicating what in this tool enables these affordances. Many stated that before using it in the classroom, this tool, its function and use should be explained to students. A GB teacher indicated that students should be introduced first to two variables and only then complexity should be gradually increased.

To sum, it seems that most of the teachers' talk was situated in specific instances. In spite of their prior knowledge about ecosystems, they did not generalize the specific experiences gained into a thorough description of the ecosystem represented and its function - describing the "big picture". They were satisfied with indicating partial inferences regarding a specific relation or situation in a particular population. For example, none of the teachers mentioned food webs (vs food chains) as nature "means" for maintaining equilibrium among different population sizes. Granting a broad meaning to the fragmented knowledge they constructed required the investment of efforts while reflecting on their experiences and integrating these experiences' products. At a first glance it seems teachers did not have the motivation or the time to invest in metacognitive thinking and go beyond the direct inferences. However, it is also plausible that the task was quite challenging for them. Teachers reported almost no prior experiences with simulation inquiry or with teaching with simulations and no formal explicit learning of its principles and function. The analysis of teachers' actions suggested that teachers enacted frequently trial and error moves, which somewhat improved over the three SBSIs. Many findings were not significant, which probably resulted from the small sample, as expressed in their revealed consistent trend. This trend was almost always in favor of GA teachers (ascending order of complexity), whose knowledge and understanding of both the simulation and the phenomenon of size population improved more than that of GB teachers (descending order of complexity). The former mostly manipulated a single variable while keeping the other variables constant, enabling the examination of this variable' effect on other variables and the raising of inferences regarding the phenomenon inquired. Differently, the latter, who were challenged initially with six variables, applied mostly intuitive trial and error manipulation moves, changed few variables at the same time, and exhibited confusion.

Our findings suggest that a gradual increase in the number of the simulation variables enabled teachers to be more systematic in their approach and construct a more detailed and accurate mental model of both the simulations and the domain knowledge as expressed in their verbal and non-verbal responses, supporting relevant literature (Wen et al., 2018). Repeated experiences through the three simulations inquiring the same phenomena, strengthen this model and sharpened its conditional knowledge for an effective future use (Brucker et al., 2014; Bryce et al., 2016; Greca et al., 2014).

Interestingly, most teachers exhibited a correct knowledge about scientific inquiry, including the need for isolation of variables. This knowledge probably evolved from their formal and informal science education and their classroom practices with short-term, mostly two variables "recipe" experiments. However, they confronted real difficulty in transforming this knowledge into the practice of an open-ended dynamic simulation inquiry. Open-ended inquiries are rare in school context. Dealing with several variables in the more complex simulation was found to be a real challenge (Scanlon et al., 2011). Additionally, most teachers experienced difficulties to process the dynamic information involved in the simulation inquiry probably due to high cognitive load, which may have impeded their learning (Hegarty, 2004; Mayer, 2009; Scheiter et al., 2009).

Study limitations. Our relatively small and highly heterogeneous sample limited our ability to more clearly and significantly show the differences ensuing between the two study groups by applying more fundamental quantitative methods. However, the trends of the different aspects of the teachers' inquiry behaviors were consistent all through the study, supporting our inferences. This small heterogeneous sample also showed that in spite of the increase in their knowledge of the relevant biology, this knowledge still remained within the average range as defined in our study. It is possible that our range definition was too general to capture limited constructions of knowledge. However, this finding may also show the limited effect that a single experience with simulation inquiry, while having a deficient prior knowledge, may have.

10.4 Promoting System Thinking through the Use of Simulations – Few Recommendations for a Pedagogy and a Learning Environment As Well As Implications for Instruction and Learning

Several recommendations regarding simulations' potential to promote teachers' system thinking emerged from our study: (a) experiences with simulations should result in the construction of a broad mental representation and deep understanding of the multifaceted complex systems these simulations modelled. Such desired outcomes require time - time for processing and reflection after each simulation experience, time for being able to experience many diverse simulations about different aspects of the same/similar/other systems, and time for completing deficiencies in teachers' knowledge of the examined phenomenon; (b) multiple experiences with diverse simulations of different systems should promote teachers' deep understanding of the concept of modeling as simplistic static or dynamic representations of system-related phenomena. This goal may be achieved by applying to each simulation experience an explicit and directional guidance that elicit students' awareness of the affordances and weaknesses of each manipulation performed during an inquiry, and of its links to the inquiry outcomes. They should involve practical processes of well-structured problem solving, as required for high-order skill acquisition (Hmelo-Silver & Azevedo, 2006). Teachers should be engaged in a discussion that would lead them from the understanding of specific instances toward a generalization and a deep understanding the phenomenon as a whole. Such an explicit and directional guidance should also encourage teachers to examine the different alternatives available for performing an inquiry using simulations; (c) the described notions suggest teachers should apply self-regulation of their inquiry process. They should clearly define their goal and examine the contribution of each performed inquiry step to this goal achievement or its hindering effect; and (d), our study showed that teachers should be exposed to simulations in an order that consider these simulations' (phenomena's) complexity (number of variables involved), beginning with the less complex simulation of two variables and ascending to simulations of greater complexity. This principle enables teachers to independently learn some important aspects of the simulation functioning while dealing with the lower complexity, aspects which may be applied latter on for performing the more complex inquiry.

Even though simulations seem to be already an integral part of today's science education, teachers need to increase their knowledge of the nature of simulations, their affordances for teaching science, their ability to access and select appropriate simulations, and their effective use in classroom teaching. We should also consider teachers' needs by providing them more opportunities to experience relevant simulations in teacher education programs. Our findings showed that many teachers perceive simulation in a simplistic superficial manner, disregarding these representations' dynamic nature and its being a simplistic model of a phenomenon and its function, having a prediction power (Vo et al., 2015). In short, teachers have to develop simulations-related Visual-Technological and Pedagogical Content Knowledge. Special professional development courses that take in consideration the recommendations discussed above need to be designed to ensure such development. This is true in particular for promoting the understanding of ecological complex systems of these teachers' students and for the development of their high-order thinking in the course of constructivist learning (Basu et al., 2013; Jimoyiannis, 2010; Lee et al., 2016). Simulations can enable participation of all students, but may also create certain barriers for achieving success (Stinken-Rösner, 2020). Further research about the effective implementation, especially in science education, is called for.

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Chapter 11
Designing Complex Systems Curricula for High School Biology: A Decade of Work with the BioGraph Project

Susan A. Yoon

> In ordinary life, we are not aware of the unity of all things but divide the world into separate objects and events. This division is useful and necessary to cope with our everyday environment, but it is not a fundamental feature of reality. It is an abstraction devised by our discriminating and categorizing intellect. To believe that our abstract concepts of separate 'things' and 'events' are realities of nature is an illusion (Capra, 1975; pp. 274–275).
>
> We need to teach our children, our students, and our corporate and political leaders, the fundamental facts of life – that one species' waste is another species' food: that matter cycles continually through the web of life; that the energy driving the ecological cycles flows from the sun; that diversity assures resilience; that life, from its beginning more than 3 billion years ago, did not take over the planet by combat but by networking (Capra & Luisi, 2014, p. 356).

11.1 Developing a Coherent Understanding of Biological Systems

I was first turned on to complex systems ideas through the work of Fritjof Capra, Austrian-American systems researcher, best known for his work in ecoliteracy. The above quotes provide a glimpse into the epistemology that he has espoused for over four decades–that is, despite our predilections toward compartmentalizing phenomena, in reality, the world is a unified whole that is interconnected and interdependent. In order to have a sufficient understanding of how the world works, we need to consider in our knowledge development, how phenomena exist as systems. That is to say, for example, through ecological cycles, which enable constituent parts (or micro-level variables) to operate together to produce holistic systems (or

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macro-level structures). In Capra's brand of systems research, as is the case for me (and other organizations devoted to the study of complex systems, such as the Santa Fe Institute), a critical concept to understand is the notion of micro-level to macro-level emergence. And most complex systems researchers would agree that there is a hidden order that makes complex systems challenging to comprehend because mechanisms that fuel emergence are not readily observable to the naked eye. This has led to, as Kauffman (Kauffman, 1996) writes,

> The past three centuries of science have been predominantly reductionist, attempting to break complex systems into simple parts, and those parts, in turn, into simpler parts. The reductionist program has been spectacularly successful and will continue to be so. But it has often left a vacuum: How do we use the information gleaned about the parts to build up a theory of the whole? The deep difficulty here lies in the fact that the complex whole may exhibit properties that are not readily explained by understanding the parts. The complex whole, in a completely non-mystical sense, can often exhibit collective properties, "emergent" features that are lawful in their own right. (pp. vii, viii).

Some of these emergent features might be the wave-like movement of a flock of birds as they soar through the air, the synchronous flashing of a swarm of fire flies on a summer night, or the seemingly systematic marching of a group of ants lined up in a factory-style formation moving food back to the colony. These patterns that emerge from very simple rules that agents take up, such as the previous ant laying down a pheromone for the next ant to follow, are what drive complex systems researchers' interests in finding the wonderful hidden order that fuels the natural world.

Since the late 1980s, in an attempt to develop national science standards in the United States that culminated in the publication of *Benchmarks for Scientific Literacy* (American Association for the Advancement of Science, 1993), understanding natural and engineered systems has featured prominently in standards for K12 Science Education. The more recent adoption of the Next Generation Sciences Standards (NGSS Lead States, 2013) has also demonstrated the importance of learning about systems, most notably in the seven topics covered in the category of Cross Cutting Concepts, where they all, arguably, represent central systems mechanisms and states, for example through Patterns, Structure and Function and Stability and Change. However, a recent review of twenty years of empirical studies on complex systems learning in science education (Yoon et al., 2018) showed that while there has been a good deal of research on what students know about complex systems and how it can be supported, consensus is still needed in the field to identify essential curriculum content features (Fick et al., 2021). This may be the reason why complex systems curricula have not yet made it into the mainstream of instruction in any depth. Moreover, the same review revealed the need for more research on teacher learning and instructional supports and their relationship to student learning.

There is also the added challenge of developing a coherent scientific systems worldview. For Capra, the importance of such a development is paramount in the study of biology. With a coherent understanding, students would be able to connect separate topics with one another in a way that helps them to explain and predict outcomes of scientific events as well as to solve problems with seemingly disparate phenomena (Fortus & Krajcik, 2012). In terms of developing scientific knowledge, it stands to reason that recognizing relationships and patterns across curricular units would improve students' knowledge economies of scale as more information is added to their cognitive systems. Yet, research demonstrates that students face challenges in developing a coherent understanding of biology for multiple reasons. First, topics covered in standard biology curricula lack any kind of integration (Chiu & Linn, 2011; Chiu & Linn, 2014; Gilbert & Boulter, 2000; Klymkowsky & Cooper, 2012; NRC, 2012). Second, static images and representations of processes in textbooks obscure the dynamic nature of various phenomena (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010). Third, the preponderance of didactic instruction, few inquiry-based experiences, and an emphasis on rote memorization of content in biology classes has added to the issue that students come away from such learning experiences having only learned a set of disconnected facts (Anderson & Schonbom, 2008; Osborne, 2014).

Over the last 10 years, my colleagues and I have worked on an educational research project called BioGraph to develop units for high school biology content that are coherently connected through a complex systems lens. We have worked with teachers in professional development (PD) as first adopters, collaborators, and co-designers to improve the viability of full integration of BioGraph units into the standard high school biology curriculum. Using a graphical blocks-based programming language called StarLogo Nova, we have built agent-based simulations that model essential biology concepts such as protein synthesis and ecological communities that students use with accompanying curricular packets for investigations. A major learning goal is for students to understand that there are unifying characteristics of all biological phenomena that both fuel system dynamics (for example, cycles and perturbations) and define system structures and states (for example, initial conditions; equilibrium) (Yoon et al., 2016). Furthermore, in our PD workshops, teachers improve their own understanding of complex systems applications in science and science education and develop pedagogical content knowledge skills with complex systems curricula in a professional learning community (Yoon, 2018; Yoon, Anderson, et al., 2017a). The overarching research goal that we have sought to investigate is "How and in what ways can complex systems resources be integrated into the high school biology curriculum?"

In the remaining sections of the chapter, I will first detail our approach to designing for student learning (agent-based modeling) in relation to the curriculum and instruction framework that underpins the design of both student-facing and teacher PD activities. I will then discuss our approach to designing for teacher PD (development of social capital). Finally, I will discuss research findings, compiled from several empirical studies working with hundreds of high school students in approximately 30 classrooms that support the design decisions, modifications in the design, and lessons learned toward the goals of achieving high- quality learning and instruction of complex systems resources.

11.2 The BioGraph Curriculum and Instruction Framework

Figure 11.1 shows the curriculum and instruction framework that we have used to inform all project activities. The components point to four distinctive aspects in the development of our BioGraph resources: (a) Curricular relevance: why should it be learned?; (b) Cognitively-rich pedagogies: how does learning happen?; (c) Tools for teaching and learning: what is used to support instruction and learning?; and (d) Content expertise: what is the knowledge to be learned? More details about each of the framework components can be found in previously published work (see for example, Yoon et al., 2016; Yoon, Anderson, et al., 2017a). Here, I briefly describe our motivations in the design of each category.

11.2.1 Curricular Relevance: What Is Being Learned?

From the outset, we were interested in ensuring that the curriculum we developed would be usable by teachers in their high school biology courses and would have utility in supporting students' scientific skills, practices, and habits of scientific inquiry beyond their classroom experiences. When we embarked on the project's design in 2010, we used science education policy documents including local and state standards as well reports from other organizations that had gained some traction at the time in curriculum arenas such as the Partnership for twenty-first Century

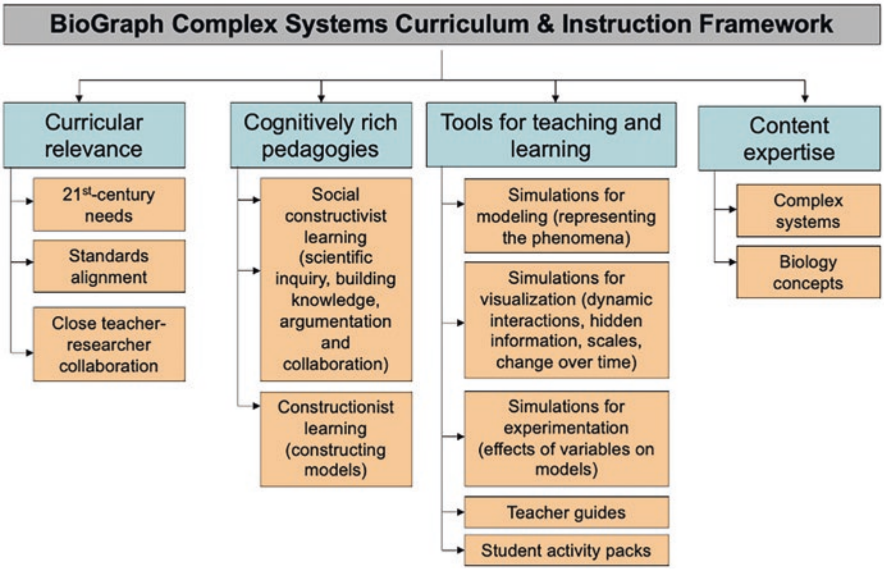


Fig. 11.1 BioGraph complex systems curriculum and instruction framework

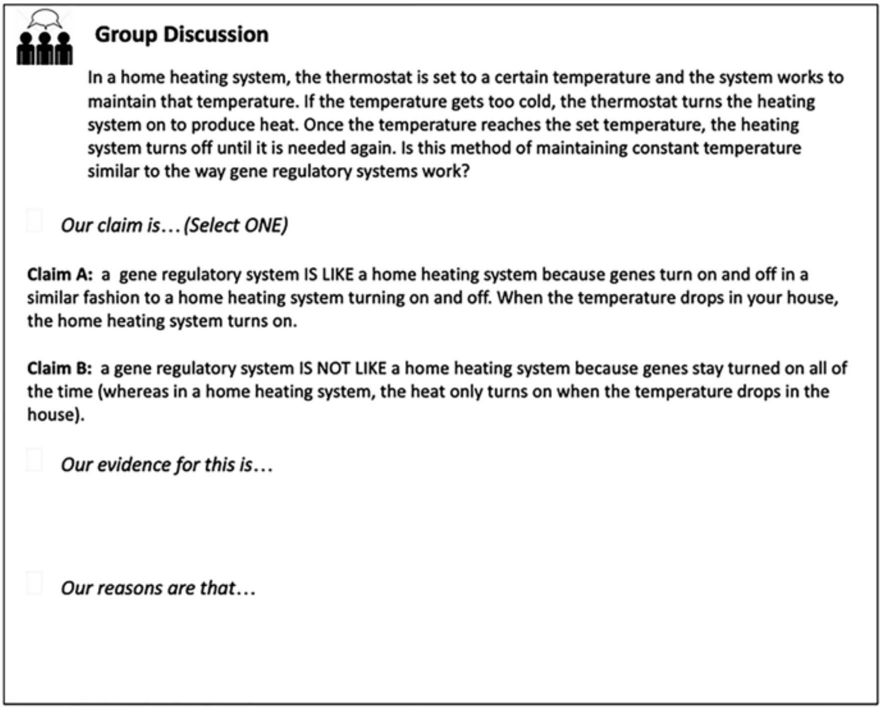
Learning (Partnership for twenty-first Century Skills, 2007) and the President's Council of Advisors on Science and Technology (President's Council of Advisors on Science and Technology, 2010). Emphases from these latter resources stressed critical thinking, collaboration, career skills, and the integration of technology. Just a few years later, with the introduction of the Next Generation Science Standards (NGSS Lead States, 2013), we worked toward providing experiences in three-dimensional learning that combined science and engineering practices and cross-cutting concepts with the biology content standards. It was clear that for curricular relevance to be realized in relation to classrooms in light of these policy mandates, teachers needed to have a key place as partners on the curriculum design team. We worked to improve the curriculum through design cycles with teachers as design collaborators for optimal implementation.

11.2.2 Cognitively-Rich Pedagogies: How Does Learning Happen?

The BioGraph curriculum is premised on two broad theories of learning: social constructivist and constructionist learning. The pedagogy is based in student-centered scientific inquiry exploration. With teachers as facilitators, students in teams of two or three generate hypotheses and questions, perform experiments (by manipulating the model parameters) to verify their hypotheses. They engage in argumentation through prompts that require them to select claims and provide evidence and reasoning to support the claims (see Fig. 11.2). The unifying theme of complex systems anchoring the various biology topics also provides the conceptual scaffold for developing their understanding. Furthermore, students learn how the simulation works through guided tours of the blocks-based coding language and are provided opportunities to modify existing code or construct aspects of the simulation on their own (see expanded explanation below). The idea is that through these hands-on activities, students begin to understand the underlying mechanisms that govern the behavior of system variables to produce the patterns that they see in the phenomenon under study.

11.2.3 Tools for Teaching and Learning: What Is Used to Support Instruction and Learning?

Instruction and learning about complex systems are supported through the StarLogo Nova computational agent-based modeling platform that combines programming based on graphical blocks (Figs. 11.3) with a corresponding simulation interface that allows students to dynamically interact with the programmed behaviors of system variables (Fig. 11.4) Students can simply drag and drop blocks of code, which



Group Discussion

In a home heating system, the thermostat is set to a certain temperature and the system works to maintain that temperature. If the temperature gets too cold, the thermostat turns the heating system on to produce heat. Once the temperature reaches the set temperature, the heating system turns off until it is needed again. Is this method of maintaining constant temperature similar to the way gene regulatory systems work?

☐ *Our claim is… (Select ONE)*

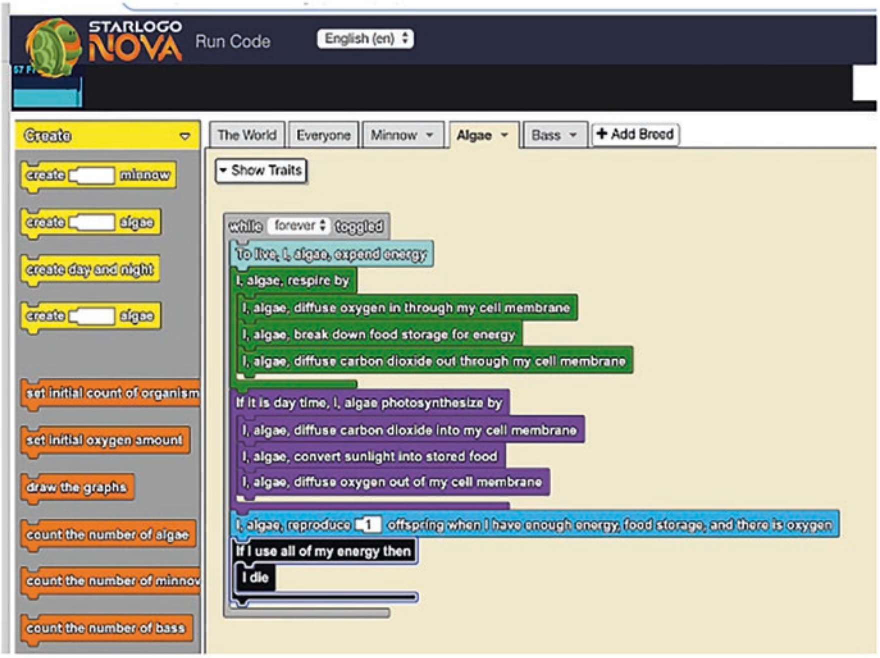
Claim A: a gene regulatory system IS LIKE a home heating system because genes turn on and off in a similar fashion to a home heating system turning on and off. When the temperature drops in your house, the home heating system turns on.

Claim B: a gene regulatory system IS NOT LIKE a home heating system because genes stay turned on all of the time (whereas in a home heating system, the heat only turns on when the temperature drops in the house).

☐ *Our evidence for this is…*

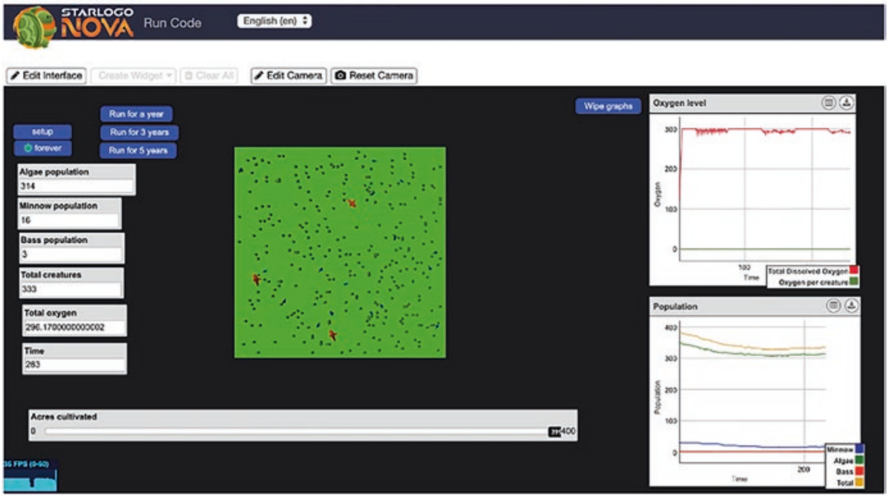
☐ *Our reasons are that…*

Fig. 11.2 Sample argumentation activity



```
while forever toggled
  To live, I, algae, expend energy
  I, algae, respire by
    I, algae, diffuse oxygen in through my cell membrane
    I, algae, break down food storage for energy
    I, algae, diffuse carbon dioxide out through my cell membrane
  If it is day time, I, algae photosynthesize by
    I, algae, diffuse carbon dioxide into my cell membrane
    I, algae, convert sunlight into stored food
    I, algae, diffuse oxygen out of my cell membrane
  I, algae, reproduce 1 offspring when I have enough energy, food storage, and there is oxygen
  If I use all of my energy then
    I die
```

Fig. 11.3 StarLogo Nova blocks-based coding sample



Algae population 314

Minnow population 16

Bass population 3

Total creatures 333

Total oxygen 296.1700000000002

Time 263

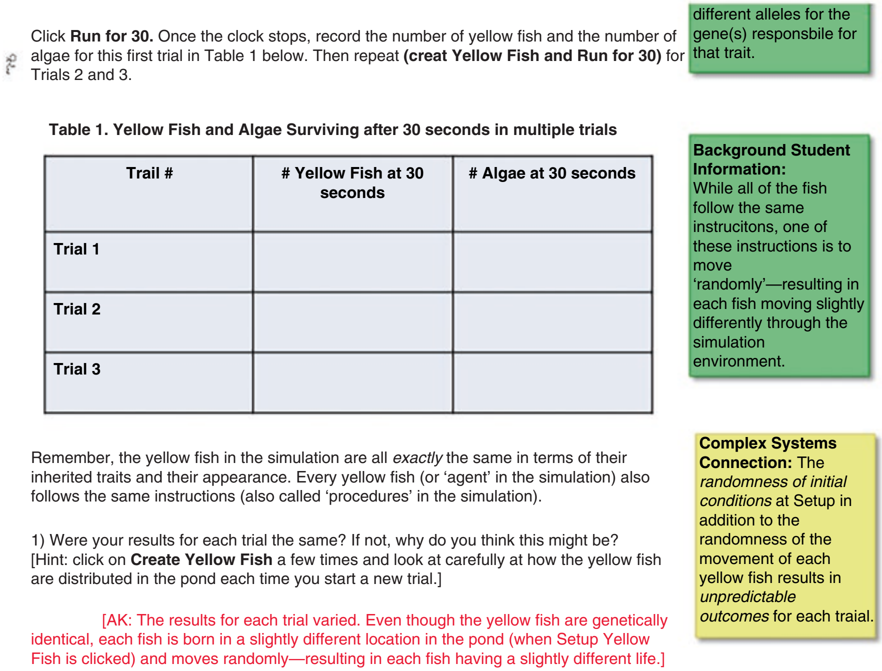
Acres cultivated 0 400

Fig. 11.4 StarLogo Nova simulation interface

are organized into categories that neatly stack together to execute commands. Throughout the BioGraph curriculum, students interact with models that visually represent system states and processes at different scales. Teacher guides and student activity packets have been developed to work hand-in-hand with the curriculum. They offer details of the learning goals of the curriculum, steps in the activities, formative questions, and information that tie together complex systems ideas, the biology topic, and how those phenomena are represented in the model (see Fig. 11.5 for teacher guide excerpt). They also make explicit connection to scientific practices such as conducting multiple data collection trials and aggregating data for greater accuracy and precision, controlling and changing variables, and observing visual and graphical patterns as system properties emerge.

11.2.4 *Content Expertise: What Is the Knowledge to Be Learned?*

The last category builds understanding of complex systems and biology content. We built short units that take two to three classes to complete in five common high school biology topics. These include sugar transport in cells, enzyme interactions, ecosystems, gene regulation and protein synthesis, and the development of genetic traits in evolution. The units can be taught in any order that best fits the school's curricular scope and sequence. In addition to the StarLogo Nova model and accompanying student activity packet for each unit, other resources include freely available videos and news stories that discuss systems ideas in the real world, vocabulary lists that identify common complex system features (for example, self-organization,



different alleles for the gene(s) responsbile for that trait.

Click **Run for 30.** Once the clock stops, record the number of yellow fish and the number of algae for this first trial in Table 1 below. Then repeat **(creat Yellow Fish and Run for 30)** for Trials 2 and 3.

Table 1. Yellow Fish and Algae Surviving after 30 seconds in multiple trials

Trail #	# Yellow Fish at 30 seconds	# Algae at 30 seconds
Trial 1		
Trial 2		
Trial 3		

Background Student Information: While all of the fish follow the same instrucitons, one of these instructions is to move 'randomly'—resulting in each fish moving slightly differently through the simulation environment.

Remember, the yellow fish in the simulation are all *exactly* the same in terms of their inherited traits and their appearance. Every yellow fish (or 'agent' in the simulation) also follows the same instructions (also called 'procedures' in the simulation).

1) Were your results for each trial the same? If not, why do you think this might be? [Hint: click on **Create Yellow Fish** a few times and look at carefully at how the yellow fish are distributed in the pond each time you start a new trial.]

[AK: The results for each trial varied. Even though the yellow fish are genetically identical, each fish is born in a slightly different location in the pond (when Setup Yellow Fish is clicked) and moves randomly—resulting in each fish having a slightly different life.]

Complex Systems Connection: The *randomness of initial conditions* at Setup in addition to the randomness of the movement of each yellow fish results in *unpredictable outcomes* for each traial.

Fig. 11.5 Sample from biograph teacher guide

feedback loops, and decentralization) and off-computer games that place students themselves in the role of agents in a complex system to see how information travels and gets transformed in the process. These additional resources are meant to demonstrate how complex systems ideas can be found in many different areas of the natural and social worlds such that students can make connections across content domains even outside of biology.

11.3 Designing for Teacher PD

11.3.1 Face-to-Face PD: Exploring Teacher Learning and Community Development

As previously discussed, a central aim of the BioGraph project has been to produce usable curriculum that is readily integrated into standard biology courses. To understand how this could be accomplished, we initially worked with a small group of 10 teachers as collaborators in PD activities to learn about their own content understanding challenges as well as implementation supports needed. Our initial efforts in designing PD experiences focused mainly on developing teachers' content and pedagogical content knowledge, which can be described as human capital (skills, knowledge and dispositions of the individual to accomplish a task). Described in more detail in various project publications (see for example, Yoon, Anderson, et al., 2017a; Yoon, Miller, & Richman, 2020a), the human capital PD design features are anchored in what we know about essential components of high-quality PD as best summarized in Darling-Hammond et al. (2017): (1) a focus on disciplinary content, both the concepts and associated pedagogies; (2) addressing how teachers learn through active learning and sense-making; (3) enabling collaboration among teachers; (4) using models of effective instruction; (5) offering coaching and expert support; (6) dedicated time for feedback and reflection on practice; and (7) sustained duration of PD participation. Similarly, Desimone and colleagues outline a set of core features of effective PD including content focus, active learning, coherence, duration, coaching and mentoring, collective participation, and the consideration of contextual variables (Desimone, 2009; Desimone & Garet, 2015; Garet et al., 2001).

Teachers first learned about BioGraph resources in a one-week intensive summer face-to-face PD workshop that ran for approximately 30 continuous hours and then participated in 10 hours of school year PD on Saturdays. Summer activities consisted of training in complex systems concepts, working in pairs to complete the curricular units as if they were their own students, reflection with each other and the research team examining likely pedagogical challenges such as accessing and working with the computational models, visioning and planning in terms of where the BioGraph resources would fit coherently into their Biology courses, and expert (research team support) to respond to issues of content and pedagogical understanding both during the PD and school year implementation. We considered active learning to be particularly important especially as the BioGraph curriculum is centered on the use of a computational agent-based modeling tool. Due to the well-documented, steep learning curve teachers experience in adopting new technologies in their classroom (Aldunate & Nussbaum, 2013; Ertmer et al., 2012), we emphasized exposure to computers (Mueller et al., 2008) and extensive training on computers (Pierson, 2011). To extend the PD experience beyond the initial adoption year, we worked with the same teachers over two years to continually develop their expertise–a time frame that has been shown to improve instruction with technology-enhanced inquiry science programs (Gerard et al., 2011).

In the second year of the PD experience, in addition to developing teacher's individual expertise, we worked more systematically to develop teachers' sense of a community of practice where resources and experiences could be shared between teachers and problems of practice examined and negotiated collectively. We discuss in Yoon, Anderson, et al. (2017a) that teachers wanted more collaborative experiences to learn from peers due to the fact that there are myriad instructional variables to navigate when teaching with our complex systems resources. We describe this second year as a focus on developing teachers' social capital (resources that can be garnered through social relations). Where previously, in our project, teachers were accustomed to accessing expertise from the research team, teachers had become increasingly more adept at using the curriculum in their instruction the second time around and were able to address classroom implementation issues more authentically than the research team although each teacher's experience was slightly different based on their student population. Thus, providing mechanisms for teachers to share their practice was a critical feature in growing the community. Valente (2012) discusses mechanisms that purposefully use networks to influence change in terms of bridging and bonding, that is, bridging between individual differences, and then solidifying those bonds made. We used four social capital categories discussed in Coburn and Russell (2008) and elaborated on in Yoon et al. (b; Yoon, Koehler-Yom, & Yang, 2017b) to inform our community building design. These are attending to:

Tie Quality: How many people teachers talked to in relation to the project implementation and frequency of these interactions.
Trust: How willing teachers were to share information with each other.
Depth of interaction: How related to the project the content of their interactions were especially as they addressed instructional and learning goals.
Access to expertise: How easily teachers were able to access the competencies and resources of other teachers and those found in other teachers' networks.

To improve tie quality, we used a strategy called *seeding interactions*, in which we connected teachers who were able to navigate through the BioGraph resources with relative ease to teachers who appeared to be struggling in their classroom implementation to serve as models and peer supports. During PD workshops, we reserved blocks of time for teachers to demonstrate strategies that they believed were successful in working with students. To develop increased trust among our teacher participants, we considered the important PD characteristic of active learning and sense making. Teachers worked in small teams during workshops on *targeted problems of practice* related to the project that they faced in their classrooms. They then worked together on solutions. The goal was to trigger supportive relational interactions through collective problem solving. In the category of depth of interaction, we grouped teachers who taught in schools that shared common student population characteristics to work on tailoring the curriculum to support increased learning. For example, several teachers in the group worked with large populations of second language learners and they created additional instructions for students to access the information in student activity packets. This *birds of a feather* strategy afforded teachers time to hold conversations that were consequential to the learning that was taking place in their situated contexts. Finally, we used a strategy called *expertise transparency* (Baker-Doyle & Yoon, 2011) to reveal the hidden expertise that resided in project participants, for example by asking teachers to conduct PD sessions in which they lead the other teachers through instructional sequences simultaneously performing a metacognitive think-aloud. For further details about our social capital strategies, see Yoon et al. (2018).

11.3.2 Online Asynchronous PD: Exploring How to Scale BioGraph Resources

Recently over the last few years, we have engaged in design and development of PD experiences to reach broader teaching audiences to scale the BioGraph resources. We decided to leverage existing infrastructures for large-scale dissemination of knowledge through the construction of a massively open online course (MOOC) in edX. In selecting this scale-up asynchronous mechanism, we were motivated by research that discussed a lack of high-quality teacher PD that implicated time and space as issues related to scale. For example, among the highest concerns articulated by teachers for improving practice has been the need for more and flexible time to access and process new information (Merritt, 2016). Other research has highlighted a dearth of access to professional peers and the geographic isolation for teachers (Peltola et al., 2017). This research has indicated that online PD has the potential to supplement local, in-person experiences, where anywhere, anytime access to resources can potentially mitigate time constraints. Some reports have also emerged that suggests online teacher PD experiences (if designed and translated into classroom instruction well) can produce comparable results to face-to-face PD experiences in terms of student learning outcomes (Fishman et al., 2013; Webb et al., 2017).

From our previous work, we understood the importance of building a collaborative community, in which teachers could negotiate issues of practice due to the myriad challenges in integrating computer-supported complex systems curricula into science instruction. This requires teachers to develop adaptive expertise that considers teachers' own knowledge and instructional skills, student learning characteristics, and contextual variables in conjunction with the biology and complex systems content and the technology applications (Yoon et al., 2019). Thus, when investigating the design features necessary to build an online asynchronous course for BioGraph teachers, using social capital strategies became the primary driver (see Yoon, Miller, & Richman, 2020a; Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, & Shim, 2020b; Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, & Marei, 2020c for a more in-depth review of the literature on MOOCs and teacher PD). Table 11.1 summarizes the design choices we made to promote teacher's social capital in our online course. The conceptual framework includes the categories of social capital (Coburn & Russell, 2008) and essential components of high-quality PD (Darling-Hammond et al., 2017). These were embedded in a course with seven online PD modules: (1) Introduction to the course, participants and facilitators; (2) What are complex systems; (3) Why modeling is a core scientific practice; (4) What is scientific argumentation and evidence-based reasoning; (5) How the curricular materials fit into the NGSS; (6) An examination of each of the simulations and corresponding biology units in detail; and (7) Conclusion to the course and framing for implementation. The activities spanned about 30 to 40 hours of participation.

Table 11.1 Design choices for building teachers' online social capital

Social capital category	Teacher PD characteristics	Online design strategies
Tie quality	Collaboration or collective participation Sustained duration	Online profiles to share professional and personal information, e.g., *write a post that describes your background (e.g., how long you have taught, unique skills or knowledge that might interest your classmates). After you have responded, use the forum to connect to a couple of other course participants by clicking "reply" to comment on their posts.* Discussion forum Collaborative prompts to seed interaction, e.g., *share one triumph in creating your model along with one unexpected moment. Then, leave some encouraging comments on other posts!* Six-week PD in edX with follow up Moodle participation
Trust	Feedback and reflection with peers Networked communities	Synchronous meetups (scheduled 3 hour-long meetups for participants to connect course names with a real person) Content and implementation prompts, e.g., requests to share tried and true resources
Depth of interactions	Disciplinary content Active learning and sense making	Demonstration videos and practice with technology Anticipating and discussing problems of practice, e.g., *imagine your own classroom, what challenges do you see happening with your student population around building computational models? Think through some strategies with others* Relationships to standard curriculum, e.g., argumentation Lesson planning with peers on module capstones
Access to expertise	Coaching and expert support	Videos with narration of expert teachers delivering classroom instruction Expert teachers as course facilitators Help forum with technical and pedagogical support from PD development team

11.4 Research Findings

To date, we have conducted 9 research studies that have sought to document the design of BioGraph resources and their impact with students and teachers. A full review of the research methods and findings from each study is beyond the scope of this chapter. However, we have generally found that both student and teacher populations have improved in their learning of complex systems in relation to biology content, and this improved learning has resulted from a change in curricular experiences using the BioGraph resources. Students have especially gained a better understanding of the domain of biology as a coherent set of concepts that can explain the natural world. Teachers have found great utility in these resources that are easily integrated into their standard biology courses and our efforts to move PD from a face-to-face mode to an online asynchronous mode has proven to be successful in terms of a scaling up mechanism that retains high-quality PD characteristics. In this section, I will briefly present selected findings to provide evidence for these claims.

In all of these studies, we have taken a mixed-methods approach to measuring project impact. We draw from multiple data sources that include for teachers, a post PD resource usability survey (rating statements such as, "The PD covered topics relevant to the grades that I teach"); pre- and post-content and pedagogical content knowledge surveys (rating statements such as, "My students use computer models to visualize scientific phenomena"), individual post-implementation interviews, classroom observations, and online PD collaborative discussions. We have collected a similar set of data sources for students that include, pre-post biology and complex systems content knowledge surveys (see the following section for complex systems knowledge survey); pre-post classroom experience surveys; focus group interviews; and video recordings of small group interactions. With respect to our study populations, in earlier design and development studies (Yoon et al., 2016; Yoon, Anderson, et al., 2017a), we worked with a small number of teachers (n = 10) to be able to investigate in some depth the extent to which project simulations and resources were usable in classrooms and produced the desired outcomes of both student and teacher learning. In later studies in which we aimed to scale up the intervention through online PD experiences (Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, & Marei, 2020c) data collection and analyses are based on a larger, more random group of teachers and classrooms. Here are results from selected data sources.

11.4.1 Students Improve in Biology and Complex Systems Understanding

As reported in Yoon, Anderson, et al. (2017a) students improved in their understanding of biology content as measured through 14 multiple choice questions compiled from state and national standardized science exams. Results from a paired t-test with a sample size of 346 students showed significant growth ($p < 0.01$) from pre-survey scores equal to 7.67 (SD = 2.36) to post-survey scores equal to 9.43 (SD = 2.47) with a Cohen's d effect size of 0.67.

We saw similar results in student's complex systems understanding. Students responded to the following open-ended question in pre- and post-surveys.

> Imagine a flock of geese arriving in a park in your town or city, where geese haven't lived before. Describe how the addition of these geese to the park affects the ecosystem over time. Consider both the living and non-living parts of the ecosystem.

Student responses were scored on a scale of 1 (not complex) to 3 (completely complex) for each of four different dimensions of complex systems understanding that included the predictable or random nature of agents in a system; systems processes being static or dynamic; order being centralized or decentralized; and linear versus non-linear emergent effects. Aggregated for a score of 12, a sample size of 361 students showed significant growth ($p < 0.01$) from pre-survey scores equal to 5.80 (SD = 1.23) to post-survey scores equal to 6.79 (SD = 1.29) with a Cohen's d effect size of 0.65. Although this research was a single group non-comparative design, the effect sizes of 0.67 and 0.65 are interpreted as medium effects (Cohen, 1988) and about 3.5 times larger than science learning gains in a whole year of learning as measured by several nationally normed tests (Bloom et al., 2008).

11.4.2 Students Understanding of Biology as a Coherent Set of Ideas Improves

In another study (Park et al., 2017) we sought to determine the extent to which students improved in their understanding of biology as a coherent set of ideas explaining the natural world. Students were asked the following questions in focus group interviews: (1) What do you think biology is? (2) Recall all the units you did using the simulations, which units did you cover and was there anything that these units had in common? (3) How do complex systems fit into biology? A large portion of the student sample articulated that complex systems concepts could be located in many biology ideas. For example, one student stated the following:

> I feel like the complex systems govern kind of the overarching patterns that we see from stuff that's really, really tiny like the organelles in your cell. Like ribosomes and enzymes functioning and in each of those cells go by another and form organs, each of those organs form complex systems, to form your body. Each individual body forms complex systems within a population and it just builds, and builds, and builds.

Here the student explained that multiple concepts in biology could be understood from a complex systems lens. Similarly, another student said:

> I mean all [of the units] just had like–it wasn't just sun hits plant, plant goes, yay. It was like the protein goes over here. Then the RNA reacts like this, and this hooks onto here, but if it hits here, then it does this. If it goes over there, then it does that. There were multiple factors all running around doing their own things and depending on how they interacted, when they bumped into each other mostly, the step would interact differently. Stuff would happen. They were all like that. (Focus Group ID 6, May 2014)

In the above quote, the student explained that all of the units showed how systems have multiple interacting agents, which randomly bump into each other, and depending on the ways in which they interact, different outcomes would occur in the system. Still, another student stated, "Everything is a complex system; if you think about it" (Focus Group ID 6, May 2014). All of these statements revealed that students came to understand biological content more coherently through a complex systems lens.

With respect to how the BioGraph resources supported their understanding, students pointed to the StarLogo Nova simulations and opportunities to modify the code as affordances in their learning experiences. The following quotes illustrate this point:

> The biggest thing that helps me understand biology was how everything in the simulation has a set of rules that it follows and how things move about randomly in complex systems. It's hard to get that from a diagram that your teacher might draw on the board or something like that. (Focus Group ID 9, May 2014)

> I like using the coding; when you use the coding to change the program… Because I could control what everything was doing and I saw like how when you took the tumble blocks in and out, I saw like [how] things worked. Like I could just know what they were suppose [sic] to do. (Focus Group ID 5, May 2014)

It has been clear in all of our studies examining student learning and participation with the BioGraph curriculum that they have gained a great deal in terms of understanding how concepts in biology are connected. Furthermore, in data not presented here, students have articulated enjoyment and interest using the resources, which no doubt has also contributed to their engagement in the project. In the next sections, I discuss findings from teacher data that showed equally successful outcomes.

11.4.3 Teachers Indicate High Usability in their Biology Courses

Results from a PD usability survey (sometimes referred to as a satisfaction survey) administered to teachers at the end of the PD workshop showed high evaluation and usability of the BioGraph resources. Teachers responded to 18 Likert-scale questions (1 = strongly disagree to 5 = strongly agree) in three categories of: overall course satisfaction (for example, *The course covered topics that are relevant to the grade(s) I teach*); module construction and delivery (for example, *The modules actively engaged those in attendance*); and usability of materials in teaching (for example, *The student worksheets given out during the course will be useful in my teaching*). All ratings for both face-to-face workshops (held in 2012 and 2013) and online workshops (held in 2018 and 2019) showed uniformly high ratings ranging from 4.42 to 4.98. Figure 11.6 shows a comparison of ratings across the four years.

What is notable about these numbers is that even as we worked with about 4 times more teachers in 2019 who took the online course, the rates of satisfaction, continued to be high, which bodes well from the perspective of our goals for delivering high-quality PD at larger scales.

11.4.4 Developing Teacher's Social Capital Is Key

Over the years, we have come to understand that developing teacher's social capital may be just as important as developing their human capital. Yoon et al. (2018) demonstrates that teachers in the face-to-face PD wanted to share their experiences with other teachers, characterized their experiences in terms of opportunities rather than

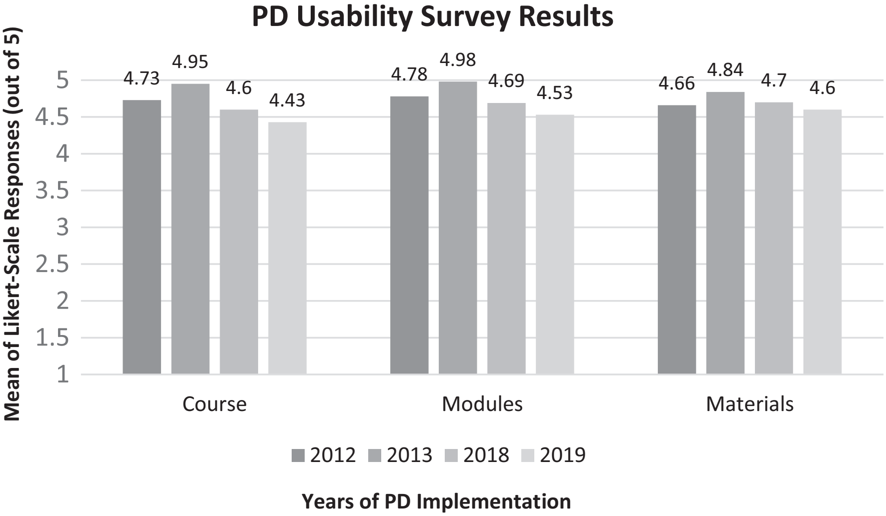


Fig. 11.6 Comparison of teachers' responses to usability of PD resources across 4 years

barriers to implementation, and generally improved in their beliefs about the utility of BioGraph resources to support their instruction. This happened after we launched our social capital PD activities such as seeding interactions and addressing targeted problems of practice. The following comment from one teacher in that study illustrates these ideas:

> I remembered another place where I talked about your simulation[s]. [I talked] with some other biology teachers and certain concepts and I told them that they should check your simulations out because I think they really do a great job…Maybe we were talking about ecosystems or evolution and how there's a real lack of web labs available for us to do and that your simulations…are able to support portions of our curriculum where it's hard for us to find activities to do.

Likewise, teachers' implementation confidence improved dramatically as a result of increased access to peers. Again, the following set of quotes from that study supports this claim.

> Certainly, familiarity was a big thing…I had resources from teachers and online that I didn't have the year before. There were videos that Lisa had put online that I was able to use…I had a lot of things, a whole repertoire of tools that were created [after] the first year that I was able to pull from and more were added. As we went to the PD a lot of teachers shared a lot of what they had created, simple little worksheets. I had all of that in place, all of the very helpful tools that I could use over the course of the year and that made it really easy.

> Again, having that second week of summer PD and really sitting down with the other teachers and figuring out, okay, "When did they incorporate it? What activities did they use? Did they have openers or closers?" So, I think that was the biggest thing; is talking to other teachers and spending that time

> I would say by practice and communicating with the group. That was probably the best set of examples for me. It just helped communicating with the other teachers and communicating with all of you doing the presentations on the complex systems.

Several studies investigating the impact of our social capital design in the online PD mode also shows the importance of sharing and reflecting on practice with others. In Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, and Marei (2020c), we saw high degrees of collaborative discourse that resulted from prompts designed to solicit interaction between teachers. In interviews, where we asked teachers to comment explicitly on their experiences in the four social capital categories (namely, tie quality, trust, depth of interactions, and access to expertise), teachers offered many positive comments. For example, in the category of access to expertise, one teacher said:

> I really, really liked watching the online implementations...with watching those videos of classrooms, I got to see what it was going to look like for my students, and I got to think about what I might have to modify for my particular group of kids.

11.5 Benefits of Computer-Supported Complex Systems Curricula and Lessons Learned

With respect to the overarching research goal of this project that I articulated in the introduction, which is “How and in what ways can complex systems resources be integrated into the high school biology curriculum?”, I have illustrated the benefits afforded to student learning about biology content knowledge and their ability to understand the domain in a more coherent way (a need articulated in science education research, such as in Chiu & Linn, 2014) through a computer-supported complex systems approach. This approach addresses further needs in science education research for dynamic visualizations (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010) that allow students to manipulate and modify simulations of biological systems and enables them to compare processes and structures that emerge through agent-based interactions. They also conduct experiments, collect and analyze data, and participate in scientific argumentation in sequenced activities to support their developing knowledge of how complex systems operate.

Over the course of our decade of work, the importance of working with teachers in PD activities as design collaborators must be greatly underscored. In addition to anchoring PD structures in what we know best about how teachers learn and participate in PD (for example, Darling-Hammond et al., 2017; Desimone & Garet, 2015), the following design features of our project have led to usable and impactful curricular and instructional resources:

1. Extensive and repeated training on computers.
2. A minimum of two-years of PD.
3. Focus on developing teachers’ human and social capital.

4. Concerted effort to develop a professional learning community to support teaching beliefs and confidence.
5. Developing high-quality PD at larger scales by utilizing the design features in 1–4 for asynchronous online experiences.

Importantly, this set of design features are critical to the teaching and learning of complex systems resources based upon the use of computational agent-based models that are deployed in real-world classrooms with myriad variables that teachers must negotiate if they are to be successful in supporting student learning.

Lastly, I believe that the BioGraph project instantiates well the complex systems epistemology articulated in Capra's (1975, 2014) quotes at the beginning of this chapter. That is, through curriculum, instruction, and PD activities that highlight the importance of the interconnectedness and interdependence of phenomenon (from micro to macro scales), we will be able to greatly improve teaching and learning in the domain of biology.

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Chapter 12
Lessons Learned: Synthesizing Approaches That Foster Understanding of Complex Biological Phenomena

Orit Ben Zvi Assaraf and Marie-Christine P. J. Knippels

12.1 Introduction

The aim of this book was to bring together international researchers that focus on fostering understanding of complex biological phenomena. We have diverse contributions, based on different conceptual frameworks related to systems thinking (Sect. 12.2), covering different biological topics, including different teaching and learning activities for various target groups.

In this final chapter we try to connect these different contributions, compare and analyze them from the perspective of system characteristics (Sect. 12.3), and search for overarching guidelines and pedagogical principles that emerge (Sect. 12.4).

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12.2 Perspectives and Frameworks

In defining and describing complex systems in biology the authors in this book emphasize different aspects and use various conceptual approaches and frameworks for understanding complex systems. Yoon (Chap. 11) and Mambrey et al. (Chap. 6) for instance, argue that the consideration of systems represents a holistic view instead of reductionistic, while traditional strategies for teaching biological systems still heavily rely on reductionist approaches, as highlighted in Dauer's et al. contribution (Chap. 4). Common to all complex biological systems is the presence of various components and multiple interactions between them. Biological phenomena manifest themselves at different levels of organization and interaction of individual elements at one level creates emergent structures and behaviors at higher levels. The mechanisms that fuel emergence are not readily observable to the naked eye, which makes biological systems challenging to comprehend. Yoon (Chap. 11) indicates that 'a critical concept to understand is the notion of *micro-level to macro-level emergence*'. Addressing this micro-macro problem is also the starting point in the studies of Schneeweiß and Gropengießer (Chap. 7) and Hammann and Brandt (Chap. 5) that focus on students' causal and mechanistic reasoning on different levels of organization. Overall, all contributions in this volume agree that complexity is inherent to biological systems and describe interventions and scaffold strategies to stimulate students' and/or (pre-service) teachers' understanding of complex systems. Various contributions refer explicitly to *systems thinking* as a higher-order thinking skill to help students make sense of complexity in biological systems. The authors use different frameworks or models to describe this skill and/or develop educational interventions to foster students' systems thinking.

In Chap. 2 for instance, Dor-Haim and Ben Zvi Assaraf use the *Systems Thinking Hierarchy* (STH) model developed by Ben Zvi Assaraf and Orion (2005). They suggested that thinking about and understanding a system can be categorized according to eight hierarchical characteristics or abilities, which are demonstrated by students in an ascending order. These eight characteristics compose the STH model (see Chap. 2). The STH model describes the skills systems thinking includes as the ability to: (1) identify the system components and processes; (2) identify relationships between separate components and processes; (3) understand the cyclic nature of systems and organize components and place them within a network of relationships and make generalizations; (4) understand the hidden components of the system and the system evolution in time (prediction and retrospection).

In Chap. 8, Torkar and Korfiatis, use the *Structure-Behavior-Function* (SBF) conceptual framework for understanding complex systems developed by Hmelo-Silver et al. (2007), where 'Structure' refers to the elements of a system; 'Behavior' refers to the role of each element in a system; 'Function' refers to the dynamic mechanisms that produce a response or outcome within a system. In a more recent study Hmelo-Silver et al. (2017) described systems thinking in terms of *Components-Mechanisms-Phenomena* (CMP) conceptual representation. This representation supports students to think about the components (C) of a particular phenomenon (P) and how they interact to result in a specific mechanism (M) of the phenomenon. So, the CMP reflects the mechanistic reasoning while the SBP representation '*guides students to broadly consider the relevant structures, observe their behavior and their functional role in the context of a complex system*' (Hmelo-Silver et al., 2017, p. 56). Torkar & Korfiatis prefer the SBF framework in their contribution on reasoning on the carbon cycle and climate change, since the nomenclature of the SBF framework helps the learners to focus on the processes taking place in a system.

These different frameworks illustrate (slightly) different emphasis on aspects of systems thinking. Boersma et al. (2011) argued that these differences in definitions are related to the implicit or explicit reference to three systems theories that systems thinking originates from, that is General Systems Theory, Cybernetics and Dynamical Systems Theories. The study of Boersma et al. (2011) showed that most science education studies focused on only some systems concepts in their definition, while they and Verhoeff et al. (2018) recommend focusing on the systems concepts of all three systems theories. In Chap. 3, Gilissen et al. build on these considerations, and they define eight system characteristics based on the systems theoretical concepts of these three systems theories and empirical studies (Gilissen et al., 2020a, 2020b): "systems have a *boundary*, consist of different interacting *components*, have an *input and output*, are regulated by *feedback loops*, are *dynamic* and are *hierarchical* (can be divided into different levels of biological organization). Moreover, an overarching characteristic can be identified, that is *emergence*. Systems have emergent properties which are suddenly appearing new qualities that emerge from the interactions between the components of the system" (Sect. 3.1.2). They also define guiding questions related to the different system characteristics which can be used to investigate a specific biological system from a systems perspective (see Fig. 3.1). Since these system characteristics (Boundary, Components, Interactions, Input and Output, Feedback, Dynamics, Hierarchy, Emergence) focus on the system concepts of all three systems theories, we will use these as a lens to reflect on the different contributions in this volume.

In the next section we will use these system characteristics to compare and reflect on a couple of contributions at a time that address comparable biological phenomenon in their educational interventions, such as the carbon cycle, ecosystems, plant and human physiology.

12.3 Analysis of the Contributions in Terms of System Characteristics

12.3.1 Understanding Complexity in the Carbon Cycle

The carbon cycle is addressed in two chapters in this book. In Chap. 2, Dor-Haim and Ben Zvi Assaraf, address it within the larger context of Earth systems, while in Chap. 8, Torkar and Korfiatis 'zoom in' on the specific mechanisms underlying the carbon cycle's complexity. Dor-Haim and Ben Zvi Assaraf's chapter presents an education project designed around Long Term Ecological Research (LTER), in which high school students are introduced to the work of scientists at LTER facilities and engage in the collection and analysis of data from ecosystems at a variety of locations and times. The LTER learning environment allows students to learn alongside professional scientists, exploring the dimensions of time and space – both of which are necessary to the understanding of ecological systems. Torkar and Korfiatis, in contrast, introduce an intervention program for pre-service teachers, which used concept maps, laboratory experiments and computer simulations to enhance their understanding of the structure, behavior and function of the carbon cycle and its connection with the greenhouse effect and climate change. The juxtaposition of these two chapters is interesting because the programs they describe complement and complete one another in several ways.

Both chapters emphasize the importance and efficacy of focusing on the *components* of complex systems, the *interactions* between them, and the *input and output* aspect of their complexity. Both studies found, for instance, that their learning intervention improved the students' understanding of the carbon cycle and the interconnections between biotic and abiotic elements in ecosystems. This was emphasized in the LTER program's outdoor and lab activities, in which the students collected data on a-biotic components (phenology, arthropods, plant litter) at various times throughout the year, analyzed it (following changes in the organic matter they gathered), and uploaded the data to the LTER station's computers. This allowed the students to identify the system components and the interactions between them, and to 'see' the matter transfer that occurred in the system during the year's cycle (food web, decomposition, and ecosystem function).

While this 'hands-on' outdoor method proved highly effective in demonstrating large-scale (habitat-level) system phenomena, many students in the LTER program still had difficulty understanding and explaining matter transfer between different reservoirs in the carbon cycle, and comprehending the system's different levels of biological organization (from the molecular to the biosphere level). For example, when describing the food web, they tended to limit their explanations to the macro level of organisms consuming one another, while omitting references to the micro-level transmission of carbon between these organisms.

This particular limitation could have benefited particularly from the approach employed in Torkar and Korfiatis' study, which used interactive computer simulations to support the students' understanding of the complex interactions in the system and to engage them with evidence and processes underlying the phenomenon being studied. Like the LTER program's outdoor activity, the simulation was used to explore the *interactions* between the different system *components*, but it focused more specifically on demonstrating the micro-level processes involved. The 'Greenhouse Effect' simulations, for example, allowed students to alter the various conditions of the greenhouse effect (like the concentration of CO_2, CH_4, H_2O; ice age atmospheric conditions, pre-industrial times atmospheric conditions) and study their impact on the Earth's temperature and climate.

Both chapters also emphasized the reliance of complex systems on *input and output* – exchanging "matter, energy and/or information with the environment". Torkar and Korfiatis related *input and output* to the 'Function' category of the SBF, which refers to the mechanisms that produce a response or outcome within a system. The global carbon cycle is made up of carbon reservoirs (stocks) and the transfer of carbon between them (fluxes). Therefore, in the case of the carbon cycle, *input and output* represent how the exchange of matter (CO_2) concentration can alter the function of the system (by increasing the Earth's temperature).

Both also emphasized the complex system's *dynamics* – referring to the ways in which the *input and output* of a system can change (regularly) over time (seconds, minutes, hours, days, months, years). Carbon, for example, may be transferred from one reservoir to another in seconds (e.g., the fixation of atmospheric CO_2 into sugar through photosynthesis) or over millennia (e.g., the accumulation of fossil carbon (coal, oil, gas) through deposition and diagenesis of organic matter). Torkar and Korfiatis found that the greatest improvement amongst their students concerned their ability to relate environmental problems to the increase in CO_2 concentration in the atmosphere and, consequently, to the increase in the Earth's temperature.

The time dimension was a central element of the LTER program, which revolved around the study of natural ecological systems. These include multiple bio-geochemical cycles (the carbon cycle, the water cycle, the nitrogen cycle etc.) that interact with one another in multiple ways over time. As the chapter shows, the students emerged from the program acutely aware of the role played by time in the behavior of complex systems. For example, they noted that in order to understand a phenomenon like desertification, we must trace and understand long-term trends and changes in the water cycle. These include long-term changes to the system's *input* (such as changing levels of precipitation and solar energy) and its *output* (evapotranspiration), which influence the level of plant litter in the ecosystem that decomposes into the soil. Desertification is a complex phenomenon that refers to the spread of desert conditions beyond desert margins, and the intensification of desert conditions within them. Parts of Israel are considered a semi-arid zone: a zone that can normally sustain dry-land agriculture and livestock raising activities with little additional input if stocking rates are held at adequate levels to sustain production. In the LTER program, desertification was examined through the phenomena of waterlogging, salinization, increased soil temperature and aridity and decreased soil organic matter.

Despite the wide range of interactions between Earth systems that were presented by the students following their experience in the LTER program, one system characteristic that was not represented at all was *feedback*. It would therefore seem advisable to integrate some explicit questions on this topic during the inquiry process to guide students toward the identification and comprehension of feedback loops. For example: Which feedback loops can be identified between the system components/within the system? Does the feedback lead to opposing changes within the system (negative feedback)? Does the feedback lead to enhancing changes within the system (positive feedback)? Such questions are important because understanding feedback loops is critical to understanding phenomena associated with the carbon cycle. Coupled carbon-cycle climate models indicate that less carbon is taken up by the ocean and land as the climate warms, constituting a positive climate feedback. Many different factors contribute to this effect: warmer seawater, for instance, has a lower CO_2 solubility, so altered chemical carbon reactions result in less oceanic uptake of excess atmospheric CO_2. On land, higher temperatures foster longer seasonal growth periods in temperate and higher latitudes, but also faster respiration of soil carbon. This would have been a useful context in which to acquaint the students with the concept of *emergence* – behaviors that occur at the system level and are derived from multiple interactions at different levels of organization.

In contrast to its absence in Dor-Haim and Ben Zvi Assaraf's chapter, the system characteristic *feedback* is strongly represented in Torkar and Korfiatis' portrayal of the students' activities in the Habitable Planet's Carbon Lab. In this computer simulation, the students explored questions such as – What happens to the carbon in the atmosphere due to changes in fossil fuel use and deforestation? By manipulating fossil fuel use, deforestation rate and melt of tundra, students were able to observe and compare carbon amounts in the lithosphere, hydrosphere, biosphere and atmosphere. This simulation thus allowed students to develop their understanding of the various feedback loops present in the carbon cycle components. For example, they could explore climate change's influence on flowering plants – changes in the timing of blooms and frosts in relation to how changes in the use of fossil fuels affect the relative amounts of carbon in the reservoirs. It is worth noting, however, that the term "feedback loops" does not seem to have been used explicitly by the students in describing these phenomena. More explicit scaffolding and definitions might therefore have served to improve their conceptualization of the specific concepts of *negative feedback* (namely, how feedback within the carbon cycle leads to opposing changes within the system), and *positive feedback* (how feedback leads to enhancing changes within the system).

One aspect of system complexity with which the students in Torkar and Korfiatis' chapter had more difficulty is the relationship between the biological elements of the carbon cycle and the social elements with which it intersects. Torkar and Korfiatis suggested that scaffolding students through discussion of their findings and concept maps is important in order to help students understand the socioeconomic aspects of climate change, and relate it to other environmental phenomena. We would further suggest looking and talking more explicitly about the concept of the system boundary – namely where one draws the lines that determine where a system ends. Students should be encouraged to consider – what are the borders of the environmental phenomenon I am addressing? What are its proportions? What is the context in which it exists?

In this sense, the program described by Torkar and Korfiatis could have benefited from aspects of the LTER program described by Dor-Haim and Ben Zvi Assaraf. Analysis of that program's results showed that it improved the students' ability to expand their perception of a system's *boundaries* from the local to the global – understanding that the earth as a whole is a complex system and that environmental phenomena can therefore influence one another across vast stretches of time and space. In the time dimension, this was reflected in the students' understanding that short-term research cannot accurately capture the changes that take place in the ecological system, and that many ecological processes, like changes in biodiversity, occur over many years, and must therefore be studied in the long-term. In the space dimension, the chapter focuses on the biosphere as a global system, showing the program's contribution to the students' understanding of the importance of conducting comparisons between phenomena in multiple locations around the world (for instance, studying the influence of fires on biodiversity in ecosystems in Israel vs. the U.S., which share the same latitude).

12.3.2 Understanding Complexity in Ecosystems

Exploring live ecosystems (an ocean, forest, or marsh) is an essential part of biology education. Learning about systems by directly interacting with and examining live ecosystems has advantages such as contextualizing learning in real, complex, world environments, engaging students in particular environments that are meaningful and relevant to them. However, live ecosystems contain a much larger number of components than individuals can address, as well as mostly implicit interactions and processes, occurring at diverse microscopic and macroscopic levels over time. Moreover, the variables in real ecosystems cannot be manipulated and controlled by students in order to observe the results (Eilam, 2012). Simulations address these limiting elements by creating a scenario-based learning environment in which students can engage in problem-solving processes based in facsimiles of real-world authentic problems.

Both the advantages and the limitations of using simulated environments to teach students about the complexity of ecological systems are exemplified in the chapters contributed by Grotzer et al. (Chap. 9), and Eilam and Yaseen Omar (Chap. 10) and Yoon (Chap. 11).

All three chapters describe the use of a simulated ecosystem to convey key concepts in complex systems. Both Yoon and Eilam and Yaseen Omar's chapter, for instance, employ a similar simulation, which is designed to highlight complex systems' dynamic equilibrium. It employs a simplified representation of various food webs/chains in an imaginary ecosystem to exemplify the mutual relationship of the organisms in that system. Grotzer et al.'s chapter uses its simulation, in conjunction with the "Body of Evidence Approach" (BOE), as a means of helping students think about causality in complex systems. Kamarainen and Grotzer (2019, p. 533) note that, "Moving from a correlational to a causal account involves epistemological assumptions in any discipline," and "presents particular challenges when phenomena involve multiple causes, time-lags, feedbacks, or thresholds as is the case in ecosystem science." Grotzer et al.'s chapter addresses these challenges by simulating a pond, and the effects of eutrophication on the biodiversity within that pond.

All three chapters reflect the usefulness of virtual environments in clearly defining a system's boundary, and of incorporating multiple hierarchy levels into the learners' inquiry process. The simulation in Grotzer et al.'s chapter sets a geographical boundary by depicting the ecosystem of two ponds. This geographical boundary is defined in terms of the edges of what is depicted in the world. This virtual world is presented to the students via the EcoXPT learning tool, through which the students can become familiar with the system's various hierarchy levels – from macro-level organisms such as fish to microscopic ones like zooplankton. Yoon and Eilam and Yaseen Omar's chapters limit the boundaries of the system they represent by artificially limiting its variables, using agent-based simulation modelling adapted from the NetLogo computer language to model changes in population size within increasingly complex ecological systems containing two, four or six variables respectively. The systems represented here also depict multiple levels of hierarchy, ranging from fluctuations in population size at the macro level to variations in the consumption of 'energy units' at the micro level.

All three chapters illustrate the ways in which simulations can be a highly useful means of representing the complex system's *dynamics* – the ways in which the input and output of a system can change over time. Yoon's study is part of a larger project in which a series of units were developed to support improved understanding of biology through a complex systems approach in the following topics: diffusion, ecology, enzymes, evolution, genetics, and modeling. Each unit takes 2–3 days of instruction, consisting of a simulation – an agent-based modeling platform called StarLogo Nova that combines graphical blocks-based programming with a 3-D game-like interface – and a student packet, which scaffolded students' learning about complex systems, scientific practices, along with biology content knowledge. This chapter builds upon Yoon's previous studies (Yoon et al., 2016, 2017) aimed at developing agent-based simulations represented in modeling tools such as StarLogo. These simulations allow students to visualize structures and mechanisms to view the evolution of systems over time. The simulations enable users to manipulate and construct facsimiles of scientific systems in which changes in initial conditions, random variation, decentralized interactions, and self-organized emergent behaviors (among other system characteristics) are investigated.

System dynamics are also directly tied to the main focus of the curriculum described in Grotzer et al.'s chapter, which is eutrophication – the introduction of nutrients into an aquatic ecosystem from sources such as untreated domestic sewage or industrial and agricultural wastewaters. The central question that was posed to the students: "Why did the fish die out? How can I look for patterns that suggest what might be going on?" requires them to address the changes that take place in the input and output of the pond's ecosystem over time. Thus, for instance, when students discover that a fish die-off had occurred on a certain day within the virtual world, the virtual tool allows them to travel in virtual time before and after the event to observe and collect data on population levels and water quality measurements. The unit's strategy of asking the students to move back and forth in the timeline of the simulation to determine how various phenomena may be influencing one another, and to assess whether various effects they noted were short or long-term, seems to have impressed upon the students a strong comprehension of the system's dynamics. Grotzer et al. (Chap. 9) note, for example, that students' explanations focused on causal dynamics that were central to the eutrophication scenario and successfully represented the complex causal factors involved in it.

Finally, dynamics are similarly central to the curriculum described in Eilam and Yaseen Omar's chapter, in which the simulation allowed learners to track and compare changes in the size of various species populations over time. The design of the simulation in this chapter was particularly well suited to encouraging learners to consider *feedback* as an element of system *dynamics*. In examining graphs that juxtaposed the rise and fall over time of species populations (such as grass/rabbits, rabbits/foxes, deer/wolves etc.), the learners were required to (a) identify the relationship between the variables as either positive or negative to predict each organism's chances of reproduction and survival, and (b) identify patterns of long-term dynamic equilibrium, in which both populations remain stable within a given margin, despite constant short-term fluctuations.

Though using a virtual system model carries many advantages, it also has some important limitations when it comes to system complexity. The scenarios presented in these chapters are necessarily defined by a much narrower range of possibilities and influences than are present in a 'real-life' ecosystem. In real aquatic ecosystems such as lakes, for example, sources of N and P loading include both external and internal nutrient loading (Ding et al., 2019). External nutrient loading into lake ecosystems happens through riverine inflows, agricultural run-off, and/or atmospheric deposition. Parts of the external nutrients are taken in by organisms to participate in the nutrient cycle of the lake ecosystem, and other parts are stored in sediment with particles settling down. Furthermore, bottom sediments of shallow lakes are typically recognized as large pools of nutrients. These legacy nutrients in sediment may return into the water column and cause internal nutrient loading by various pathways.

Grotzer et al.'s curriculum addresses this gap between virtual and the real-world ecosystem phenomena by providing students with evidence from scientific research. It includes lab-based and in-situ experiments and data as well as collecting all kinds of data in the virtual world (e.g., water quality measurements, temperature, population data). Comparisons between lab experiments and data from mesocosms allowed the students to perceive various ongoing processes of input and output (like the input of phosphate, sunlight, oxygen and the output of carbon, organic matter). The broader watershed is depicted and one of the tools that students use is tracers that they place in the watershed to understand how matter moves in the ecosystem. We suggest that units like the one described in Eilam and Yaseen Omar's chapter could benefit from a similar approach. Eilam and Yaseen Omar's chapter highlights the advantages of teaching complex systems according to a gradually ascending order of complexity. Incorporating comparisons with mesocosms could serve as a further outward progression of this ascent. We would further suggest that similar studies could expand upon this step significantly by also introducing evidence from research carried out in 'full sized' outdoor natural ecosystems, in order to illustrate the full breadth of an ecosystem's complexity, and the ways in which its boundaries can extend far beyond its local environment. For example, Grotzer et al. (2015) designed a learning environment that began with an EcoMUVE environment depicting the pond and surrounding land. Then they significantly expanded the world to include an additional pond, a nearby farm, as well as a golf course, housing development and a road.

12.3.3 Understanding Complexity in Plant Physiology

In Chap. 7, Schneeweiß and Gropengießer's demonstrate how a "zoom map" can be used as an explicit scaffolding strategy to foster students' comprehension of complex biological systems in plants by focusing on the interactions between and within the various levels of organization. Having shown a group of high school students in northern Germany pictures of two plants, and asked them: "Why are the leaves of the left plant upright and the leaves on the right wilted?" they demonstrated how the combination of the zoom maps with a yo-yo teaching strategy encouraged the students to provide a mechanistic explanation for the phenomenon that addresses it at multiple organization levels, such as organelle, cell, tissue, and organ.

The strategy described in this chapter highlights three aspects of system characteristics, namely *components, hierarchy, and interactions*. The first two of these three aspects are addressed in the first stage of the knowledge integration activity described in this chapter, in which the students work in groups to list the system's various components (or "entities") and sort them into the zoom map according to their place in the hierarchy. As Schneeweiß and Gropengießer note, students must be explicitly encouraged to consider the biological levels of organization in the system, and the zoom maps can be a useful tool with which to do so. Indeed, they found that, after learning with the zoom map, students considered more of the relevant system levels, and also considered deeper levels, such as those of the cell and the organelles. The system characteristic interactions arises out of this explicit consideration of the system's hierarchy, as the students are explicitly encouraged to reflect on how the system's various components interact, both horizontally within a level of hierarchy and vertically between one level and another. Thus, for instance, students can look for causal explanations by moving down the zoom map (reductionist framing, from the macro towards the micro), and for functional explanations by moving up (holistic framing).

While the strategy employed in this chapter seems to have successfully fostered the students' ability to address multiple layers of *hierarchy* in the system and seek explanations across multiple levels of organization, including those that cannot be seen with the naked eye, other key system characteristics were not as dominantly represented. Explicitly guiding students in the examination of a system's levels of organization could serve as an excellent basis for instruction on many other system characteristics as well, since "levels of organization can be formed, ordered, and related through different relationships—mainly, coevolutionary, matter-energy, and physiological relationships that can be ordered in a system of levels" (Schneeweiß & Gropengießer, 2019). However, the task that the students were assigned in this instance seems to have imposed several limitations that prevented these additional aspects from being incorporated into the conversation.

One possible expansion that could further increase the potential of the task described in this chapter is a more explicit incorporation of the topic of *feedback loops*. While there is no doubt that explicitly addressing the vertical and horizontal interactions between system components is an extremely useful tool for fostering mechanistic reasoning, feedback loops do not consistently conform to either the vertical or the horizontal interactions. Rather, feedback loops can incorporate multiple interactions – vertical and horizontal – which together produce a given positive or negative feedback. The water regulation in plants, for example, is achieved by the regulation of potassium cation concentration in the stomata. A stoma is composed of two guard cells that have different cell wall thicknesses, thanks to the structure of the cellulose microfibrils. The guard cells operate by active transport of potassium cations, in an enzyme-induced process. Closing the stomata under water stress conditions is extremely important, in order to save plant water. Potassium cations actively exit the guard cells, and as a result the osmotic pressure within the guard cells decreases, which causes the water in the guard cells to go out, and the stomata to close. This process incorporates *interactions* at *multiple hierarchy levels* (vertical) and between cells (horizontal).

This possibility was represented in neither the task instructions nor the students' work products. Understanding the function played by feedback loops in a complex system therefore requires explicit attention that uses the notion of vertical and horizontal interaction, but also introduces additional questions such as "Which feedback loops are present in the system? Does the feedback lead to opposing or enhancing changes within the system? (in other words, is the feedback negative or positive?)"

One aspect of the task that poses limitations is its delineation of the *system's boundaries*, which were defined on one side by the organelle (rather than, say, the water molecule), and on the other by the organism (rather than the habitat). Expanding the system's boundaries to higher and lower levels of organization would have facilitated an explicit discussion of input and output in the system – namely the ways in which the plant exchanges matter and energy with its environment, and how these are related to the condition of its leaves. More specifically, this would introduce the question of where the water in the plant's system comes from and where it goes (for example, moisture escaping the leaves into the atmosphere through evaporation, entering the plant from the soil through trichomes). Such an expansion of the system's boundaries would also make it possible to address the system's dynamics – the ways in which its input and output can change (regularly) over time.

The benefits of the expansion and explicit discussion of system boundaries are demonstrated, for example, in Dauer et al.'s chapter (Chap. 4). Like Schneeweiß and Gropengießer's chapter, this chapter also focuses on a teaching strategy designed to improve students' mechanistic understanding of phenomena in complex systems. In this case, the authors used a computer simulated modelling activity to promote university-level students' understanding of the cellular level of the photosynthesis process. Though Dauer et al.'s chapter declares that it will set the system's boundaries around the photosynthetic processes of LDR and CC reactions occurring within the chloroplasts of plant cells, the activity employed in their study does incorporate an expanded perception of the system's boundaries by addressing the environment in which the plant is located (in this case, a darkened room without a window), and asking the students to predict that environment's impact on its photosynthetic processes.

This chapter openly declares that its emphasis will be *primarily on specific system characteristics* – namely *interactions* and *input and output*. It explicitly addresses the issue of input and output by conceptualizing photosynthesis as one of multiple complex systems that make up the plant organism and asking the students to explore (1) how different aspects of the system can influence one another and (2) how the output of the system is influenced by input from without. Thus, their computational model of cellular-level photosynthesis was designed to highlight the interactivity of the two photosynthetic processes light-dependent reaction (LDR) and Calvin Cycle (CC), and to illustrate that levels of chemical and energy inputs (water, carbon dioxide, and sunlight) determine functional outcomes like the production of oxygen and sugar molecules.

This activity could potentially be expanded even further by introducing a comparative element – addressing, for instance, different metabolic cycles for carbon fixation in different types of plants. This would reinforce the interactive relationship that often exists between an organism and its environment, and how the internal processes addressed in this simulated model are influenced by that relationship. The examples presented in this chapter are of C3-type plants, whose enzymatic systems for example differ from those of C4-type desert plants. These differences increase the efficiency of the latter type's photosynthesis in drought conditions, which are the conditions addressed in the chapter. Comparing the houseplant in the current example to an example of plants that are adapted to arid environments could provide an additional context in which to explore the mechanisms addressed in the students' task, thus emphasizing how these microscopic processes relate to macro-level ecological phenomena.

12.3.4 Understanding Complexity in Genetics and Human Physiology

The three chapters in this book that addressed complexity in the context of genetics and human physiology approached the topic from three different perspectives. In Chap. 5, Hammann and Brandt highlight the relationship between the gene and the environment, emphasizing the importance of perceiving and understanding interaction at all levels of the system's *hierarchy*. To understand how organisms function, biologists switch constantly between different levels of biological organization – from the molecular to the ecosystem level and back (Knippels & Waarlo, 2018). Thus, understanding complexity in genetics requires an integrated understanding of the relationship between genes and protein synthesis and between protein synthesis and an organism's phenotype, as well as how these micro level elements interact with the organism's environment. In Chaps. 3 and 6, on the other hand, Gilissen et al., and Mambrey et al. focus, inter alia, on the human body as a complex system, in which homeostasis represents the *emergence* aspect of that system. In contrast to ecological systems, physiological systems are characterized by self-regulation to maintain equilibrium states (Mayr, 1997). Homoeostasis is a fundamental biological principle defined as the ability of every living organism to maintain – through various biochemical, physiological, and behavioral mechanisms – a stable internal environment within defined boundaries; an internal environment different from its surrounding external environment (Mor & Zion, 2019). These chapters explore homeostasis in the human body through the specific mechanism of glucose regulation. The studies described in Chaps. 5 and 6 did not focus directly on teaching complex systems, but rather on the assessment of biology students' conceptualization of physiology as a complex phenomenon. Both chapters emphasize systems thinking as the ability to recognize and describe systems in their full complexity, and to analyze and predict system behaviors based on constructed mental models. The representations used in these chapters are tools with which students are invited to model complex systems – in Hammann and Brandt's case genetics and trait formation, and in Mambrey et al.'s case the regulation of blood sugar in humans, and food web.

Both of these chapters (5 and 6) suggest their model as a potentially useful advance organizer for knowledge integration, which should help students build an integrated understanding of complex phenomena and avoid fragmented knowledge. Hammann and Brandt's chapter introduces the Gene-environment interplay model, which focuses on multiple and interactive causation by making explicit the following four aspects: (1) the relationship between gene and gene product, (2) the relationship between gene product and trait, (3) the impact of the environment on the relationship between gene and gene product and (4) the impact of the environment on the relationship between gene product and trait. The chapter then uses this model to characterize high school students' reasoning via a trait formation task addressing gene-environment interplay for variation of eye color in fruit flies. Furthermore, the authors suggest to use the teaching learning strategy *tracing trait formation* in conjunction with model building activities because the gene-environment interplay model can help students structure their responses to trait formation tasks.

Mambrey et al.'s chapter discusses models of systems thinking including a model developed by Wellmanns and Schmiemann (2020), which takes the form of a flowchart that explicitly depicts negative feedback loop mechanisms that determine the systems behaviors of blood glucose regulation. The students' systems thinking was assessed via 'thinking aloud reasoning tasks,' in which students were asked to use the model to explain the components, processes and relationships involved in the regulation of blood sugar levels in humans. The model is designed to provide students with explicit prompts that encourage students to acknowledge additional, hidden aspects of the system. In the case of blood glucose regulation, certain processes (such as insulin secretion by the pancreas, depletion of glucose for energy production in cells) are explicitly depicted in the model as a result of either an increased or a decreased value, and negative feedback loop mechanisms are explicitly represented as characteristic features. Meanwhile, other system properties, such as the continuity of processes, self-regulation and knowledge about mechanisms as well as time delays, remain implicit and must be integrated by the learners.

Both chapters used their models to investigate high school students' complexity reasoning. In the context of genetics, Hamman and Brandt's chapter addresses the issue of complexity via the distinction between causal reasoning and the more complex concept of "mechanistic reasoning." Krist et al. (2019, p. 161), define mechanistic reasoning in science contexts more specifically as a particular type of causal reasoning that involves the explanation of (a) the sequential stages, from input to output, of the underlying causal events leading to a phenomenon; and (b) how and why one or more factors behave to give rise to a phenomenon. In other words, while causal reasoning is 'knowing *that*,' mechanistic reasoning is 'knowing *how*.' In genetics, causal reasoning is the ability to describe that both genes and the environment are involved in the formation of traits, while mechanistic reasoning goes beyond causal reasoning by including the ability to explain how genes and the environment contribute to the formation of traits, in which causes and effects must be spatially and temporally distinct. Mechanistic reasoning, thus, focuses on entities (for example, genes, gene products, different environmental factors) and activities (for example, gene expression, protein-protein interaction). Mechanistic reasoning, essentially, builds on causal reasoning, but it is cognitively more demanding.

Defined thus, mechanistic reasoning encompasses many of the characteristics of system complexity. As Haskel-Ittah and Yarden (2018) note, for instance, understanding a mechanism means understanding the characteristics of its entities (its *components*), the relationship between them (their *interactions*), and how they are organized (their *hierarchy*). For example, the mechanisms by which genes affect traits include genes with specific DNA sequences, proteins with specific structures, other substances that interact with the proteins, certain kinds of cells that are affected by the proteins' activities, and so on. The relationship between these entities may be, for instance, that a gene encodes a protein or that the protein binds with another substance, affecting the cells in a certain way (processes that involve *input and output* of information).

In the context of this task, mechanistic reasoning required that the students' answers incorporate (a) interactions between physiological and environmental factors; (b) interactions between physiological and genetic factors and (c) interactions between physiological, genetic *and* environmental factors. As Hamman and Brandt note, "When we asked students to explain what the eye color of fruit flies depended on and when we encouraged them to trace trait formation, we expected mechanistic reasoning relating the phenomenon visible at the level of the organism (variation in eye color) to the physiological level (biochemical pathway of brown eye pigment synthesis) and the genetic level." Ultimately, Hamman and Brandt found that, despite their extensive background in genetics, only 13% of the 47 students in their sample showed molecular mechanistic reasoning about gene-environment interplay while completing the task. They conclude that significant numbers of students did not infer the genetic mechanism because of lacking knowledge integration, and that the crucial gap in the students' understanding seems to be that enzymes act as mediators between genes and traits.

Mambrey et al.'s chapter focused on the students' representation of system properties that were not explicitly shown in the model they provided. Most particularly, it addressed students' portrayal of the biological system's *feedback loops* and their role in maintaining system equilibrium. The chapter noted three key implicit aspects of the model's representation that were crucial to students' understanding of the system's complexity: (a) the system's *dynamics* – referring to the fact that many processes in the system run continuously (for example, glucose is continuously broken down for energy supply, even if one does not exercise for a while); (b) the system's continuous *self-regulation* (for example, negative feedback processes must always be active to maintain homeostasis); (c) the *causal-mechanistic* relations between system elements (being able to explain *how* one element causes another, rather than merely stating that a causal relationship exists). On the whole, Mambrey et al.'s analysis of the thinking-aloud protocols indicated that the students had difficulty integrating these three implicit elements into their descriptions of the system's behavior. For example, one student identified the causal relations that were explicitly represented in the flowchart, but did not use that representation as a starting point for explaining any further transport or effect mechanisms. This, Mambrey et al. point out, means that the student did not integrate any implicit relation property, such as that cause and effect are linked via numerous mechanisms, and that the effects occur with time delays.

Like Hamman and Brandt, Mambrey et al. attribute the students' difficulties to insufficient integration of content knowledge. Both chapters emphasize content knowledge's role in complexity conceptualization. Hamman and Brandt argue that knowledge fragmentation leads to inert knowledge, suggesting that inert knowledge is the most likely explanation for the finding that the students did not infer the genetic mechanism and did not interrelate it to the physiological and environmental mechanisms. Similarly, Mambrey et al. provide several examples in which lack of integration of content knowledge appears to have hindered students from gaining a deeper understanding of the phenomenon they describe. This lack of integration, they note, is a critical obstacle, because "*if students do not integrate their content knowledge about the basal metabolic rate, they will not conclude that the negative feedback mechanisms are continuously active [and] if students do not integrate content knowledge about molecular structures and processes, they will not be able to provide causal-mechanistic relations*" (Mambrey et al., Chap. 6).

Both chapters illuminate the difficulties that are currently associated with students' comprehension of the complexity of the (human) body as a system, and the consequent limitations of the models they employ in eliciting descriptions of that complexity from students. In response to these limitations, both chapters also emphasize the importance of providing students with additional scaffolding in this area. Mambrey et al. suggest that modelling should be adjusted to compensate for the students' difficulties. Since implicit system properties in physiological representations currently constitute a significant learning barrier, we must provide students with representations (such as interactive simulations) that explicitly represent both system organization and system behavior. Hamman and Brandt further argue for the use of deliberately targeted knowledge integration tasks in schools. Indeed, in a previous study, Heemann and Hammann (2020) analyzed the German high school science curriculum and concluded that, though the science education curriculum ought to provide students opportunities to reason mechanistically in order to broaden their understanding of the different types of gene-environment interplay, the majority of the tasks they had analyzed failed to do so.

In Chap. 3, Gilissen et al. argue that learning processes must be accompanied by explicit scaffolding for systems thinking. Awareness of the universal system characteristics can be helpful to understand biological systems in various contexts: the system characteristics can be used as a perspective or lens through which to see biology in a more coherent way (Verhoeff et al., 2018). In Gilissen et al.'s chapter Lesson Study (LS) was used to design and evaluate lessons on systems thinking in collaboration with teachers. The chapter reports about two Lesson Study (LS) cycles, in which a team of teachers collaboratively designs, performs, observes and evaluates a lesson in different steps, the so-called research lessons.

In order to promote students' understanding of the complexity of glucose regulation, the intervention consisted of learning and teaching activities, such as: (a) visualization of the blood glucose regulation of a person over one day with a seesaw in a roleplay, in which the case student had to draw the fluctuating glucose level in a graph, while the other students played the role of control center and the alpha and beta cells in the pancreas; (b) explanation of the glucose fluctuations; (c) describing the system characteristics *feedback* and *dynamics* for the context of glucose regulation; and (d) recognition of dynamic behavior.

The teachers indicated that the LS system trajectory gave them insight into ways to foster students' systems thinking, but also let them experience the difficulty of fostering such a higher-order thinking skill as systems thinking by students. They experienced that visualization can improve student understanding, as well as assist students to recognize the applicability of the system characteristics more easily in new contexts. The teachers developed a finer-grain sensitivity toward system characteristics and the relationships between them, noting, for example, that feedback is already an example of an interaction, that the interactions between different components can be a feedback-loop, that there is a relation between the boundary and the input and output, and that the boundary is the place where selection of the input and output takes place. Gilissen et al.'s chapter thus connects between the content knowledge of the system phenomena and the pedagogical strategies through which the system characteristics of those phenomena can be scaffolded for students.

12.4 Pedagogical Guidelines and Scaffold Strategies

The previous sections showed the diversity in approaches and biological topics addressed by the researchers aiming to foster students and (student) teachers' understanding of complex biological phenomena. Every setting and case have their specific intervention and the authors used and proposed a variety of pedagogical approaches. In this section we discuss overarching pedagogical guidelines and scaffold strategies that emerge from the various contributions to foster understanding of complex biological systems:

1. Modelling
2. Authentic inquiry approach
3. Cross-level reasoning
4. Use of system language

It is important to note that these pedagogical approaches and educational activities are not implemented in isolation. Most contributions in this volume implemented a range of teaching and learning activities to stimulate students' understanding of complex biological phenomena, since each activity can emphasize different system characteristics and skills. So, the *richness of the learning environment* is important in order to promote meaningful learning by explicit teaching in concrete biological contexts. Explicit teaching means that knowledge must be actively constructed by the knower in order to be meaningful and useful (Zohar & Peled, 2008). In the next sections specific characteristics of the various educational interventions to foster understanding of complex biological phenomena will be discussed.

12.4.1 Modelling

Almost all contributions made use of some form of modelling in their intervention. This might not be surprisingly, since modelling is simultaneously a tool that fosters reasoning about complex systems for students and an outcome that makes students' reasoning visible to educators, as Dauer et al. explained in their chapter. The studies in this volume made use of more qualitative pen and paper modelling activities, such as concept mapping, drawings and the 'zoom-map' or more quantitative modelling activities such as (interactive) computer simulations, or a combination of both.

12.4.1.1 Qualitative Pen and Paper Modelling Activities

Qualitative modelling activities are a way to visualize a complex biological phenomenon or problem. These external representations, such as concept maps and drawings, are tools used to model complex systems and can support students in exploring various system characteristics.

The studies of Dor-Haim and Ben Zvi Assaraf (Chap. 2) and Torkar and Korfiatis (Chap. 8) for instance, made use of *concept maps* in their intervention as a learning activity for the students as well as a means to assess their learning outcome. Both studies asked the students to create a concept map at the beginning of the intervention and at the end. Mapping is a means of eliciting the relationships that each student perceives among the concepts. As such, a concept map is a graphic organizer that provides a visual representation of a student's knowledge and thoughts (Novak & Gowin, 1984). A key principle in planning education about complex systems is representing the conceptual framework explicitly, and helping students to represent their mental models explicitly. In the study of Torkar and Korfiatis (Chap. 8) the pre-service teachers were asked to construct a concept map of the carbon cycle and its "links" with climate change and redesign their map during the last lesson. Through the use of concept maps they identify the student teachers' fragmented knowledge of the components of the carbon cycle and their interrelationships, and could identify the learning gain at the end of the four-lesson intervention.

Dor-Haim and Ben Zvi Assaraf (Chap. 2) used a similar approach, although their intervention ran over a whole school year and included five field trips which provided access to natural ecosystems. Their students worked with scientists at a Long-Term Ecosystem Research site. Moreover, next to concept maps they made use of a *drawing task* (before and after the intervention) to determine students' level of systems thinking. Each student was given a picture describing an ecosystem and were asked 'What did the painter forget to paint?' prompting the students to draw some of the missing components and their interrelations in the ecosystem. This tool was developed by Ben Zvi Assaraf and Orion (2005) to explore students' perceptions of the hidden dimension of the hydrosphere system (e.g., processes which take place under the surface), and the dynamic characteristic of ecological systems. Dor-Haim & Ben Zvi Assaraf's intervention contributed to students understanding of the *dynamic characteristic* of ecological systems.

So, external representation of mental models, by means of concept maps and drawing tasks, is a helpful approach to both teaching and assessing students' understanding of the multilevel structure that characterizes complex biological phenomena. These visual modalities have been positioned by researchers as a potential key resource for reasoning in science classrooms, fostering a constructive learning process (Ainsworth et al., 2011; Boulter & Buckley, 2000; Tytler et al., 2020).

The study of Schneeweiß and Gropengießer (Chap. 7) integrates concept mapping and the yo-yo learning strategy (Knippels, 2002; Knippels & Waarlo, 2018) into a new graphic organizer, the *zoom-map*. Since biological phenomena manifest themselves at different levels of organization (*hierarchy*), relating concepts and processes on one level as well as between levels of organization is crucial for understanding the phenomenon. The zoom-maps builds on the idea of zooming in and out ('yo-yo'), by presenting students worksheets that provided representations (photographic images and illustrations) of the phenomenon at all relevant levels of organization, asking them to explain 'Why the leaves of the left plant are upright and the leaves on the right wilted?'. A key aspect was that students had the opportunity to investigate the phenomenon themselves since they needed to develop conceptions based on experiences with the phenomenon. In this case students were provided with external representations of entities and their properties at all relevant levels of organization (including the micro-levels) and were handed two models intended to represent the mechanism students had to explain (a balloon in a net, one inflated and one limp). The intention of the zoom-map was to guide the process of explaining the phenomenon. Schneeweiß and Gropengießer's chapter showed that the zoom-map encouraged learners to make levels of organization and the interrelation of system elements explicit and fostered their causal-explanations across levels of organization.

In Chap. 6, Mambrey et al. used an image of a food web and made students think-aloud to get an insight in their systems thinking skills and ways of reasoning when they were seeking to understand food web ecosystems. This think-aloud task also revealed students' learning difficulties while verbalizing the *interrelations* in the food web. Their study showed that students failed to *identify implicit system properties*, such as the indirect effects in ecosystems. For example, understanding that if population A acts on population B and population B acts on population C, then population A should also have an effect on population C. Moreover, students have to understand that each species represents a population rather than an individual. So, students need representation knowledge as well as system-specific content knowledge to understand *system dynamics*. In a second context they used a flowchart of glucose regulation, since the negative *feedback loop* mechanisms are explicitly represented in this physiological system. However, implicit system properties (characteristics), such process continuity, self-regulation and causal-mechanistic relations, challenge students' understanding of this homoeostatic system representation. Mambrey et al. therefore emphasize the importance of explicitly addressing implicit system properties that arise from system representations in learning settings by using prompts, sequencing and simulations.

Such a first sequencing and prompting is shown in the study of Gilissen et al. (Chap. 3). In the second lesson of their intervention they described a sequence of teaching and learning activities in the context of glucose regulation. In the first activity students had to visualize the glucose regulation of a person over one day with a seesaw in a roleplay, and draw the fluctuating glucose level in a graph. This is a way of *visualizing the dynamic character* of the system and let students reason about the *feedback loops* (homeostasis of blood glucose levels) in this complex physiological system (visual-spatial display) (Gilissen et al., 2020b). Next the students were prompted to explain why there is an increase or decrease in the glucose level they have drawn in the graph, followed by an assignment in which the students had to describe the system characteristics, feedback and dynamics for the context of glucose regulation. At the end the teacher evaluated the different causes of fluctuations in the graph and asked the students for examples of other biological systems which show dynamic behavior.

The use of these different qualitative modelling activities all aimed at *visualizing* complex systems, by drawing concept maps, food webs and graphs, and discussing the biological phenomenon in small groups makes students' systems thinking skills (and the flaws) tangible. So, these are helpful tools that can support students in exploring various system characteristics as well as provide instructors insight in students' systems thinking skills. Most contributions used a sequence of teaching and learning activities and made use of various representations and modelling activities, for example concept maps and drawings (Chap. 2) or concept maps and computer simulations (Chap. 8). This is in line with the proposed guideline based on Cognitive Flexibility theory of Spiro et al. (1988) described and used in the study of

Dauer et al. (Chap. 4), '*to provide multiple representations*'. By providing various presentations of the same concepts in new contexts different aspects of the biological phenomenon can be brought out, allowing students to navigate the system and identify gaps in a representation of a system and construct deeper understanding. This might also contribute to the problem Mambrey et al. (Chap. 6) encountered that system properties are often not explicitly integrated in the representation, since models (used in education) are a simplification of the complex biological phenomenon focusing on certain characteristics of the system. The use of various representations, focusing on (different) system characteristics, might be fruitful.

These qualitative modelling activities are all static representations that have limitations in visualizing certain aspects of the complex biological phenomenon, or system. For example, *emergent* phenomena cannot be represented in general but arise through the underlying mechanisms and interactions of system components. In the next section we discuss contributions that made use of computer-based simulations in fostering systems thinking.

12.4.1.2 Computer Based Modelling Activities

As Eilam and Yaseen Omar explained in Chap. 10, "*computerized simulations are defined as an interactive dynamic model representing certain qualitative or quantitative components of any referent (e.g., a phenomenon, idea, process, system), enabling its abstraction, simplification, and explanation, as well as making predictions about its behavior*" (Khan, 2011; Landriscina, 2013; Stern et al., 2008). The core of simulation models is the ability to manipulate and control the variables composing the referent phenomenon, hence, to reveal their interrelations. Simulation models afford an immediate feedback regarding the manipulation effect, which expose the phenomenon recurring patterns of behaviors and its related principles.

In Chap. 11, Yoon builds on this core principle of the ability to manipulate and control variables, and interact with various elements within the system. In her contribution she builds on her previous studies (Yoon et al., 2016, 2017) aimed at developing agent-based simulations represented in modeling tools such as StarLogo Nova (as part of the BioGraph project) that combines graphical blocks-based programming with a 3-D game-like interface, and a student packet scaffolding students' learning about complex systems and scientific inquiry. These simulations allow students to *visualize* structures and mechanisms to view the evolution of systems over time (*dynamics*). The simulations enable users to manipulate and construct replicas of scientific systems in which changes in initial conditions, random variation, decentralized interactions, and self-organized emergent behaviors (among other system characteristics) are investigated. All of the units described in the chapter ask students to respond to *argumentation prompts* that require students to state a claim, and provide evidence and reasoning to support their claim. A major learning goal in this project was for students to understand that there are unifying characteristics of all biological phenomena that both fuel system *dynamics* (for example, cycles and perturbations) and define *system structures and states* (for example, initial conditions; equilibrium) (Yoon et al., 2016). Agent-based modeling empowers learners to model at the micro-level to understand how macro-level phenomenon emerge in complex systems. It allows students to observe patterns generated by entities' activities at multiple levels of organization, and explore how their virtual interventions at one level (such as RNA) influence behaviors on other levels (like ribosomes and cells). So, agent-based models are dynamic, visual, learning environments that give learners the freedom to select and apply various settings and conditions and then observe the impact of their decision in real time. Since students can construct models based on what they believe is happening within the system this tool makes students' understanding visible. Students' hands-on activity of modifying existing code or constructing aspects of the simulation helped them to understand the *underlying mechanism* that directs the behavior of the system variables to produce the patterns they see in the biological phenomenon.

Comparable results were reported by the other contributions in this volume that used computer-based simulations (Chaps. 4, 8, 9, and 10). The contribution of Torkar and Korfiatis (Chap. 8), for instance, made use of two computer simulations in the context of ecology. 'The Habitable Planet's Carbon Lab' to study the carbon cycle, and a PhET simulation 'Greenhouse Effect' in which students could change various conditions (such as concentration of CO_2, CH_4, H_2O and ice age atmospheric conditions) and study their impact on the earth's temperature and climate. In both simulations the learners could select and apply various conditions and study their effect over time. This helped students to understand the relationship between the increase in atmospheric CO_2 concentration and the rise in global temperature, as such making the *system dynamics underlying mechanisms* explicit.

Dauer et al. (Chap. 4) designed a computational modeling assignment according to the five themes of cognitive flexibility theory of Spiro (1988): avoiding oversimplification, providing multiple representations, relating complexity to a clear context, and de-compartmentalizing concepts by explicitly connecting concepts. In this modelling assignment, in the context of photosynthesis, students had to manipulate models of interaction between light-dependent reactions and the Calvin cycle, interpret the resulting simulation graph, and apply knowledge of photosynthesis across levels of organization. Student learning was scaffolded by asking how each *output* was affected by the availability of the *inputs*, such as water, carbon dioxide, and sunlight. As highlighted in Sect. 12.3.2, the contribution of Grotzer et al. (Chap. 9) showed the usefulness of computer simulations in clearly defining a system's *boundary*, and incorporating multiple levels of *hierarchy* into the learners' inquiry process. In these studies learning was scaffolded by the use of prompts, such as science related thinking moves, so we will discuss the pedagogical value of these contributions in more detail in the next section.

Thus, computer-based simulations provide a rich context for inquiry; by providing the learner the opportunity to manipulate settings and conditions various system characteristics can be investigated. Simulations help students in understanding the *dynamics of biological systems over time* and can challenge learners to reason between biological levels of organization. Learning environment designed around agent-based modeling gives its students a clear distinction between the micro and macro levels in the system and an ability to understand how macro-level phenomenon *emerges* from micro-level interactions.

The flip side of the use of computer-based simulations can be that it may cause a high cognitive load due to the large amount of representations and information presented simultaneously on the computer screen, which might hinder their processing (Watson et al., 2010). Eilam and Yaseen Omar (Chap. 10) showed in their study that teachers exposed to an ascending order of complexity in the simulations were better able to predict the behavior of the biological phenomenon in the simulation than teachers that worked with descending order of complexity in the simulations. They also recommend training teachers in the use of computer-based simulations since they have to develop visual-technological and Pedagogical Content Knowledge.

12.4.2 Authentic Inquiry Approach

As emphasized earlier the modelling activities discussed in the previous section are not taught in isolation. Most contributions build on a more social constructivist (and constructionist) view on learning and made use of student-centered approaches in which collaboration and argumentation is fostered, and scientific (authentic) inquiry and reflection are emphasized.

Particularly pertinent to complexity is the feature ‘active and inquiry-based learning’, which concerns students’ engagement in ‘authentic science learning’, offering them the opportunity to understand and apply science in familiar physical contexts, with the potential to collect ‘real data’ in a natural environment. The studies of Dor-Haim & Ben Zvi Assaraf (Chap. 2) and Grotzer et al. (Chap. 9) for instance, explicitly used scientific inquiry activities in their approach to build understanding of complex system behavior. The curriculum of Dor-Haim & Ben Zvi Assaraf ‘s study in the context of ecology was based on a series of outdoor activities in which students, under the guidance of scientists from a local Long-Term Ecosystem Research (LTER) station, engaged in scientific inquiry at the LTER research site as well as in selected areas near their schools. The use of an authentic environment, which offered learners direct experience with concrete natural phenomena and materials in a real, authentic scientific context, allowed students to draw upon that experience in order to construct and integrate their knowledge of abstract concepts. The LTER’s extensive outdoor learning experiences were, most likely, central in the development of the students’ understanding of ecological complexity and enabled them to reach a high level of systems thinking. Dillon et al. (2006) also claim that implementing outdoor phenomenon that illustrate, in a concrete and authentic manner, the processes which are the focus of learning, increases the chances for significant learning.

Grotzer et al. (Chap. 9) build on the idea of complexity of ecosystems as well as the complexity of scientific research into ecosystems, in which ecosystem scientists use varied data sources and draw upon accumulated evidence to explain system concepts. They engaged their students in a problem-based learning curriculum and used the ‘Body of Evidence’ approach (BOE) as a means of helping students think about causality in complex systems. This included a set of science-related thinking moves, such as evidence seeking, pattern seeking and constructing explanations, encouraging the learners ‘to collect evidence from multiple sources, look for corroborating evidence of different types (including perceptual evidence, patterns in data and graphs, numerical information and testimony from trusted others) and to assess the validity and reliability of the sources of evidence’. The students who engaged in the BOE approach were better able to include both evidence and reasoning and build a compelling body of evidence in support of each claim, compared to the students that only engaged in the problem-based curriculum (without BOE).

Also Yoon (Chap. 11) used a scientific inquiry exploration approach in her intervention. Student teams needed to generate hypotheses and perform experiments to verify the hypotheses. They engaged in argumentation through prompts for debating empirical evidence gathered from the simulations. The prompts required them to select claims and provide evidence and reasoning to support the claims. Based on their previous studies, they drew connections between four main areas of benefit for student learning: (a) student-centered scientific investigations; (b) interaction with computer models; (c) development of evidence-based reasoning skills through argumentation; and (d) multiple resources for developing complex systems understanding (e.g., models).

So, these studies build on fostering scientific reasoning in order to understand complex biological phenomena, as well as the use of authentic real-life tasks such as the outdoor learning environment. Having direct experience with authentic scientific activities and creating scientifically authentic explanations provide learners the opportunity to acquire greater knowledge of the various working processes in the way of scientists and to develop scientific research skills (Achiam et al., 2016). Studying the complexity of a natural system it is not easy, and success necessitates interdisciplinary understanding informed by the integration of different disciplinary backgrounds. Professional development that incorporates outdoor science activities using an interdisciplinary approach could improve teachers’ disciplinary knowledge and skills and aid them in the daunting task of conveying complexity, and answering research questions based in real natural complex systems (Guerrero & Reiss, 2020).

12.4.3 Cross-Level Reasoning

Most contributions addressed in their interventions the importance of cross-level reasoning. Inherent to complex biological phenomena is that they manifest themselves at different levels of organization. These levels are generally defined by part-whole relationships with emerging phenomena at higher levels being linked with structures and processes at the next lower level. In understanding complex biological phenomena, it requires the learner to connect concepts and processes at one level of organization (horizontal coherence) as well as interrelate concepts at different levels of biological organization (vertical coherence). Looking for causal explanations means moving down (reductionist framing); moving up aims at providing functional explanations (holistic framing) (e.g. Verhoeff et al., 2008, 2018; Jördens et al., 2016; Knippels & Waarlo, 2018). This macro-micro challenge is emphasized and addressed by different authors in this volume. In Dauer et al.'s study (Chap. 4) for example, students had to apply knowledge of photosynthesis across levels of organization in context-rich problems focusing on observed plant physiology and conditions in their environment. By challenging their students to reason between molecular, cellular and organismal level of organization, they showed emerging systems thinking abilities.

The contribution of Schneeweiß and Gropengießer (Chap. 7) specifically addresses the hierarchical character of biological systems. Schneeweiß and Gropengießer present a tool that fosters cross-level reasoning, called the 'zoom-map'. The zoom-map is a new graphic organizer that combines the yo-yo teaching and learning strategy (Knippels, 2002) with concept mapping, and guides learners in the process of explaining and prompts them to consider the relevant entities and their relationships, as it makes levels of organization explicit. The zoom-map draws on the metaphor of 'zooming', in bringing an object closer to see more detail or stepping back to get an overview. The zoom-map is a fruitful scaffold strategy that fostered students' causal explanations across levels of organization (see also Sect. 12.4.1.1).

Causal reasoning is addressed in various contributions in this volume as an important skill for understanding complex biological systems. Hammann and Brandt (Chap. 5) take this a step further and distinguish specifically between causal and mechanistic reasoning in their study in the context of genetics. As they explained, causal reasoning is 'knowing *what*', the ability to describe which entities/causal agents are involved, such as being able to describe that both genes and the environment are involved in the formation of traits. Mechanistic reasoning also includes the ability to explain *how* genes and the environment contribute to the formation of traits, so focusing on entities (for example, genes) and activities (for example, gene expression) (Craver & Darden, 2013; Machamer et al., 2000). Hammann and Brandt focused on the core idea of genetic literacy, the gene-environment interplay. They asked students to explain what the eye color of fruit flies depended on encouraged them to trace the formation of the trait 'from gene to trait', expecting mechanistic reasoning relating the phenomenon visible at the level of the organism (variation in eye color) to the physiological level (biochemical pathway of brown eye pigment synthesis) and the genetic level. However, only few students acknowledged enzymes as mediators between genes and traits. So, students had problems to recognize that protein biosynthesis is the process connecting genes and gene products, although this was covered in the curriculum. They indicated that the materials did not prompt students to think in different levels of organization explicitly, and that the researchers did not explicitly prompt the students to use their genetics knowledge at the different levels of biological organization. Therefore, they suggest using 'tracing trait information' as a teaching and learning strategy in combination with the gene-environment interplay model of trait formation (see Fig. 5.1, Chap. 5). The model visualizes relationships between gene, gene product, trait and environment, and can prompt students to think on different levels of organization when tracing the trait information.

Visualizing the levels of biological organization of the biological phenomenon under study can be helpful for students. As Schneeweiß and Gropengießer (Chap. 7) did this explicitly with their zoom-map by providing representations (photographic images and illustrations) of the phenomenon at all relevant of organization, Grotzer et al. (Chap. 9) made students familiar with the ecosystems' various hierarchical levels from macro-level organisms such as fish to microscopic ones like zooplankton, by presenting them in the virtual learning tool.

12.4.4 Use of System Language

The contributions in this volume showed that in fostering learners' systems thinking skills, stimulating cross-level reasoning and the use of various (agent-based) modeling activities are advisable. Moreover, since systems thinking is a higher-order thinking skill that learners should be able to use in diverse biological contexts it is important to pay attention to the use of system language (e.g. Gilissen et al., 2020b; Hmelo-Silver et al., 2007; Jordan et al., 2013; Tripto et al., 2016, 2018). With systems language is meant making implicit or explicit use of system characteristics when reasoning about complex biological systems. This may help the learner to recognize that system characteristics are universal and can be applied to all complex biological phenomena. In order for students to reason about complex systems they need knowledge about meta-linguistic features of system characteristics (Zohar & Peled, 2008).

Gilissen et al. (Chap. 3) for instance, explicitly introduced teachers and students (Gilissen et al., 2020b) to eight system characteristics and formulated guiding questions per characteristics that can help students to address a complex biological problem or phenomena. The system characteristics were also visualized in a Tangram, in that way the teacher could refer to the system characteristic (or a specific characteristic under focus) during different topics taught in the school year. Yoon (Chap. 11) made use of vocabulary lists that identify common complex system features (for example, self-organization, feedback loops).

In explicitly using system language during instruction and encouraging students to use system language can foster students' knowledge about meta-linguistic features of system characteristics and help them in developing systems thinking skills.

12.4.5 Summary

Overall, we can summarize that the different studies in this volume showed that it is important to use rich learning environments that promote active learning and cross-level reasoning in order to promote understanding of complex biological phenomena. To engage learners in meaningful learning, it is important to provide multiple representations and modelling activities from more qualitative pen and paper activities such as drawings, concept maps and zoom-maps, to more dynamic interactive computer simulations. Conceptual models make students' systems ideas visible to themselves and to others. The modelling activities are ways to visualize complex systems, and to explain and predict biological phenomena (Bielik et al., 2021). They are helpful tools that can support students in exploring various system characteristics as well as provide instructors insight in students systems thinking skills.

Different modeling approaches highlight distinct features of phenomena and systems. A diverse range of modelling activities and representations were presented in this volume and each activity can emphasize, (or is more or less suitable to emphasize) different system characteristics. Dynamics and emergence, for instance, might be better addressed in agent-based computer simulations, while the zoom-map might specifically address hierarchy and cross-level reasoning. So, the instructor or educational researchers into systems thinking should be knowledgeable about the activities they choose, being aware of the limitations and making sure to provide multiple representations and activities to address all. The richness of the learning environment is of importance. Combining hands-on activities in the lab with simulations and outdoor learning, for instance, allows learners a direct interaction with components and processes of the system. Organizing the learning in a sequence that starts from the more concrete authentic context and gradually shifts to the more abstract levels, aids the learner.

As indicated in Chap. 1 and Sect. 12.2 the studies in this volume (and in the brother research field) use different perspectives and frameworks (such as the STH, SBF, CMP models) to foster understanding of complex systems, as such emphasizing slightly different system characteristics. We took the approach to reflect on the different contributions based on the eight system characteristics defined by Gilissen et al. (2020a, b) in Chap. 3 since they cover the systems concepts of three systems theories (General Systems Theory, Cybernetics and Dynamical Systems Theories) and insights from systems biologists: boundary, components, interactions, input and output, feedback, dynamics, hierarchy and the overarching characteristic: emergence. Based on their studies they formulated guidelines that can foster students' systems thinking (Gilissen et al., 2020b, 2021a), which seem also in line with the guiding steps formulated in the contribution of Dauer et al. (Chap. 4) based on the Cognitive Flexibility Theory of Spiro (1988): to avoid oversimplification, establishing a clear example context, provide multiple representations and de-compartmentalizing concepts by explicitly connecting them across a curriculum.

Suggested guidelines to foster students' systems thinking based on Gilissen et al. (2020b, 2021a):

- Get students acquainted with the system characteristics that are related to the three systems theories in a well-known biological context;
- Start with a central complex problem or question which covers different levels of organization;

- Let students visualize a complex biological problem or phenomenon into a systems model;
- Assist students to reason within and between levels of biological organization step-by-step;
- Make students explicitly aware of the use of the system characteristics in various contexts;
- Focus on one or two system characteristics specifically to deepen and/or improve students' understanding of these characteristics in relation to the others.

We hope these guidelines, as well as the other pedagogical activities suggested here, will be helpful for researchers and instructors to further address understanding of complex biological phenomena in their practices. One final element that must be acknowledged as critical to the implementation of all of these strategies is preservice and in-service preparation for teaching complexity in biology education.

Systems thinking is essential for a deeper understanding of many topics in science, so studies that address the teachers' role in incorporating systems thinking in the classroom is of importance. In the introductory chapter to this book (Chap. 1), Housh, Hmelo-Silver and Yoon suggest that teacher preparedness with an intentional focus on systems thinking is a crucial component in successfully conveying concepts in complexity to learners. Teachers' own understanding of systems and their acquisition of pedagogical content knowledge is critical to whether and how students understand the use of models and other epistemic practices in STEM. Yoon et al. (2018) emphasized the need for further research on the relationship between teachers' understanding of complex systems and their classroom instruction. Such research would need to ask how professional development may develop in-service teachers' understanding of complex system activities and what contents must be learned as a prerequisite for successfully passing this understanding on to students.

In Chap. 3, Gilissen et al. used Lesson Study as a teacher professional development approach (Lewis et al., 2006). Teachers and researchers collaboratively design, perform, observe and evaluate lessons. This approach made teachers think more in-depth about the design of a lesson and how they can embed systems thinking in their daily classroom practice. It also illustrates how expertise from educational practice can be combined with expertise from educational research. Moreover, they determined the viability of the above proposed guidelines in the context of a professional development activity with pre-service, in-service and teacher educators (Gilissen et al., 2021b). The teachers indicated that the guidelines helped them to embed systems thinking in their lesson designs and that the professional development activity fostered a better understanding of systems thinking as pedagogy. These studies show the importance of involving practitioners in the development, implementation and evaluation of educational materials to bridge the gap between empirical research and daily practice.

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