Mapping biological ideas: Concept maps as knowledge integration tools for evolution education

by

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Abstract

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Many students leave school with a fragmented understanding of biology that does not allow them to connect their ideas to their everyday lives (Wandersee, 1989; Mintzes, Wandersee, & Novak, 1998; Mintzes, Wandersee, & Novak, 2000a). Understanding evolution ideas is seen as central to building an integrated knowledge of biology (Blackwell, Powell, & Dukes, 2003; Thagard & Findlay, 2010). However, the theory of evolution has been found difficult to understand as it incorporates a wide range of ideas from different areas (Bahar et al., 1999; Tsui & Treagust, 2003) and multiple interacting levels (Wilensky & Resnick, 1999; Duncan & Reiser, 2007; Hmelo-Silver et al., 2007). Research suggests that learners can hold a rich repertoire of co-existing alternative ideas of evolution (for example, Bishop & Anderson, 1990; Demastes, Good, & Peebles, 1996; Evans, 2008), especially of human evolution (for example, Nelson, 1986; Sinatra et al., 2003; Poling & Evans, 2004). Evolution ideas are difficult to understand because they often contradict existing alternative ideas (Mayr, 1982; Wolpert, 1994; Evans, 2008). Research suggests that understanding human evolution is a key to evolution education (for example, Blackwell et al., 2003; Besterman & Baggott la Velle, 2007).

This dissertation research investigates how different concept mapping forms embedded in a collaborative technology-enhanced learning environment can support students' integration of evolution ideas using case studies of human evolution. Knowledge Integration (KI) (Linn et al., 2000; Linn et al., 2004) is used as the operational framework to explore concept maps as knowledge integration tools to elicit, add, critically distinguish, group, connect, and sort out alternative evolution ideas. Concept maps are a form of node-link diagram for organizing and representing connections between ideas as a semantic network (Novak & Gowin, 1984). This dissertation research describes the iterative development of a novel biology-specific form of concept map, called Knowledge Integration Map (KIM), which aims to help learners connect ideas across levels (for example, genotype and phenotype levels) towards an integrated understanding of evolution.

Using a design-based research approach (Brown, 1992; Cobb et al., 2003), three iterative studies were implemented in ethnically and economically diverse public high schools classrooms using the web-based inquiry science environment (WISE) (Linn et al., 2003; Linn et al., 2004).

Study 1 investigates concept maps as generative assessment tools. Study 1A compares the concept map generation and critique process of biology novices and experts. Findings suggest that concept maps are sensitive to different levels of knowledge integration but require scaffolding and revision. Study 1B investigates the implementation of concept maps as summative assessment tools in a WISE evolution module. Results indicate that concept maps can reveal connections between students' alternative ideas of evolution.

Study 2 introduces KIMs as embedded collaborative learning tools. After generating KIMs, student dyads revise KIMs through two different critique activities (comparison against an expert or peer generated KIM). Findings indicate that different critique activities can promote the use of different criteria for critique. Results suggest that the combination of generating and critiquing KIMs can support integrating evolution ideas but can be time-consuming.

As time in biology classrooms is limited, study 3 distinguishes the learning effects from either generating or critiquing KIMs as more time efficient embedded learning tools. Findings suggest that critiquing KIMs can be more time efficient than generating KIMs. Using KIMs that include common alternative ideas for critique activities can create genuine opportunities for students to critically reflect on new and existing ideas. Critiquing KIMs can encourage knowledge integration by fostering self-monitoring of students' learning progress, identifying knowledge gaps, and distinguishing alternative evolution ideas.

This dissertation research demonstrates that science instruction of complex topics, such as human evolution, can succeed through a combination of scaffolded inquiry activities using dynamic visualizations, explanation activities, and collaborative KIM activities. This research contributes to educational research and practice by describing ways to make KIMs effective and time efficient learning tools for evolution education. Supporting students' building of a more coherent understanding of core ideas of biology can foster their life-long interest and learning of science.

Dedication

To my parents, lifelong learners and travelers who always encouraged me to ask more questions.

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Quotes

Nothing in biology makes sense but in the light of evolution (Dobzhansky, 1973).

Science is built up of facts as a house is of stones, but a collection of facts is no more a science than a pile of stones is a house (Poincaré, 1968).

Isolation in all forms is the thing to be avoided; connectedness is what we should strive for (John Dewey, 1938; cited in (Westbury, 2006) (p. 278).

CHAPTER 1: INTRODUCTION

I. Goal of the Dissertation

This dissertation research investigates how different concept mapping forms embedded in a collaborative technology-enhanced learning environment can support students' integration of genetic diversity and evolution ideas using human case studies.

This research contributes to educational research and practice by describing ways to make concept maps effective and efficient learning tools for evolution, identifies pivotal cases to make evolution accessible, and evaluates design principles for a collaborative technology-enhanced evolution curricula implemented in real classrooms.

Biology is a historically fragmented science and is therefore often taught as isolated sub-fields. As a result, many students leave school with a fragmented understanding of biology that does not allow them to connect their ideas to their everyday lives (Wandersee, 1989; Mintzes et al., 1998; Mintzes et al., 2000a).

One of the most central ideas of biology, the theory of evolution, has been found difficult to understand as it incorporates a wide range of ideas from different areas (Bahar et al., 1999; Tsui & Treagust, 2003) and multiple interacting levels (Wilensky & Resnick, 1999; Boggs, Watt, & Ehrlich, 2003; Catley, Lehrer, & Reiser, 2005; Duncan & Reiser, 2007; Hmelo-Silver et al., 2007). Understanding evolution ideas is seen as central to building an integrated knowledge of biology (Blackwell et al., 2003; Thagard & Findlay, 2010). Research suggests that understanding human evolution is a key to evolution education (for example, Blackwell et al., 2003; Besterman & Baggott la Velle, 2007). Research suggests that learners can hold a rich repertoire of co-existing alternative ideas of evolution (for example, Jungwirth, 1977; Brumby, 1984; Clough & Wood-Robinson, 1985b; Hallden, 1988; Lawson & Thomson, 1988; Bishop & Anderson, 1990; Tamir & Zohar, 1991; Settlage, 1994; Demastes et al., 1996; Jensen & Finley, 1996a; Evans, 2008). Evolution ideas are difficult to understand because they often contradict existing alternative ideas (Mayr, 1982; Wolpert, 1994; Evans, 2008) [See chapter 2: Students' Alternative Ideas of Evolution]

An integrated understanding of evolution requires connecting ideas across different levels, for example non-observable underlying genetic processes and observable selection processes and distinguishing alternative ideas. Research suggests that students have difficulty connecting ideas across different levels (Hmelo, Holton, & Kolodner, 2000; Marbach-Ad, 2000b; Penner, 2000). The connections between ideas that constitute the theory of evolution are often hidden to learners, which also may be a basis for difficulties (Bishop & Anderson, 1990; Hmelo et al., 2000; Marbach-Ad, 2000a; Penner, 2000).

This dissertation research explores the use of concept maps as Knowledge Integration (KI) (Linn et al., 2000) tools to elicit existing ideas and connections, add new ideas, critically distinguish ideas, and sort out alternative ideas. Concept maps are a form of node-link diagram for organizing and representing connections between ideas as a semantic network (Novak & Gowin, 1984). This study describes the iterative development of novel scaffolded biology-specific forms of concept maps, called Knowledge Integration Maps (KIM) that aim to help learners connect ideas across levels towards an integrated understanding of evolution. This dissertation research describes the iterative development of a case study on human evolution to a pivotal case in a technology-enhanced curriculum. The curriculum includes scaffolded inquiry activities using dynamic visualizations that allow learners to investigate the relationships between genetic and evolution ideas.

II. Dissertation Overview

The dissertation consists of three consecutive studies that investigate iterations of concept maps as knowledge integration tools embedded in a technology-enhanced evolution curriculum developed by the author [See table: Dissertation studies overview]. The curriculum used the web-based inquiry science environment (WISE) (Linn et al., 2003; Linn et al., 2004) [See chapter 3: WISE].

Table 1: Dissertation studies overview

	Study 1	**Study 2**	**Study 3**
WISE module	Meiosis – the next generation: Diversity for Survival	Space Colony: Genetic Diversity and Survival	Gene Pool Explorer: Mechanisms of Microevolution
Concept map activity	Concept map generation	Concept maps Critique + Generation	Concept maps: Critique or Generation
Structure of concept map activity	Forced choice; No given levels	Forced choice; Three levels (DNA/ Cell/ Organism)	Forced choice; Two levels (genotype/phenotype)
Purpose of concept map	Concept map as posttest assessment tool	Concept map as learning tool: Generation and critique; Concept maps as pre/post-assessment tool	Concept map as learning tool: Generation or critique; Concept maps as pre/post-assessment tool
Case Study	Human parents expect a baby and wonder which of their traits might get inherited	Human settlers need to decide if high or low genetic diversity is better for survival	Human lactose intolerance
Guiding Question	Can phenotypic traits of a baby be predicted? Why are no two babies alike (except identical twins)?	What are the sources of genetic diversity? Under which circumstances is genetic diversity beneficial?	Why can some adults digest milk while others cannot?
Main Ideas	Genetic Diversity, Human Evolution, Inheritance, Meiosis, Mitosis, Cell Cycle, Chromosomes, Cell Division (Meiosis and	Genetic Diversity, Human Evolution, Mutation, Inheritance, Recombination, Meiosis, Adaptation, Fitness,	Genetic Diversity, Human Evolution, Gene Pool, Natural Selection, Genetic Drift, Mutation, Inheritance,

	Mitosis)	Chromosomes, Cell Division (Meiosis)	Adaptation, Fitness
Inquiry activity	BioLogica Dragon Genetics	BioLogica Dragon Genetics + Biology in Motion: Evolution Lab	Allele A1
Technology	WISE 2 (web-based)	WISE 2+3 (client-computer based)	WISE 2 (web-based)

A. Overview Study 1: Concept maps as generative assessment tools

Study 1 aims to answer the general research questions: “How does the WISE evolution module *Meiosis - the next generation* help students integrate their evolution ideas?” and “How can concept maps be used to assess gains in knowledge integration of evolution ideas?”

Study 1A investigates concept maps as a generative assessment tools to elicit alternative ideas of evolution. The study compares the concept map generation and revision process of biology experts and novices (students) using a talk-aloud protocol.

Study 1A aims to answer the research questions:

1) How do biology novices and experts differ in their concept map generation and revision process?
2) How do novices of different academic performance levels differ in their concept map construction?
3) How does verbal reasoning (talk aloud) match with concept map construction?

Study 1B investigates the implementation of the first iteration of the WISE evolution curriculum, titled *Meiosis – the next generation: Diversity for Survival*. Building on the findings of study 1A, the study compares the two generative assessments - concept maps and essays - as posttests to capture students’ understanding of given genetic, cell biological, and evolution ideas. Generation activities can promote learning (van Amelsvoort, Andriessen, & Kanselaar, 2005). By generating, students articulate and represent their knowledge, apply their representations to solve scientific problems, realize gaps in their knowledge, reorganize ideas, and strengthen connections among ideas. The generation effect of giving explanations (to oneself or others) has been found more beneficial for learning than receiving explanations (Chi, 2000a; Chi, De Leeuw, Chiu, & LaVancher, 1994). Based on the Knowledge Integration framework, a new concept map analysis rubric has been developed that focuses on evaluating connections between core ideas. The WISE module *Meiosis - the next generation* focuses on the sources of human genetic diversity through mutations, meiosis, and recombination through independent assortment of chromosomes, crossing over, and random fusion of egg and sperm cell. The curriculum aims to connect ideas of meiotic cell division to the greater picture of human genetic diversity and evolution. The WISE evolution curriculum incorporates a dynamic visualization, BioLogica Dragon Genetics (Concord Consortium, 2006), intended to facilitate students’ making conceptual connections across different levels (genetics, cell biology, and evolution) and between different phenomena (observable and non-observable). The dynamic visualization allows students to explore the connections between genotype and phenotype by manipulating the chromosomes of a virtual organism. The curriculum was carefully designed using scaffolded Knowledge Integration principles (Linn et al., 2004) to elicit connections between evolution ideas.

Study 1B aims to answer the research questions:

1) How did students' integration of evolution ideas change after using the WISE module *Meiosis - the next generation*?
2) How do the generative summative assessments methods concept mapping and essays differ in describing students' understanding of the connections between evolution ideas after the WISE module *Meiosis - the next generation*?
3) How can quantitative and qualitative concept map analysis methods (concept map topology, concept map accuracy score, and concept map convergence score) be used to distinguish different levels of knowledge integration?
4) How does the dynamic visualization BioLogica support knowledge integration of evolution ideas?

B. Overview Study 2: Knowledge Integration Maps as learning tools: Generation and critique

In addition to using concept maps as assessment tools, the second study embeds concept maps as collaborative knowledge integration tools. Study 2 extends the concept map generation activity with a subsequent revision and critique step to foster students' critical reflection and revision of their concept maps. Instead of using concept maps as a one-shot posttest activity as in the first study, students were given the opportunity to critique and revise their concept maps. Asking students to critique has been found to support the development of more coherent and generative criteria (Lehrer & Schauble, 2004). Critique activities require students to use or develop criteria to reflect, elaborate their ideas, revise their ideas, and self-monitor their learning progress, which supports the development of skills for lifelong autonomous learning (Chi, 2000b). In traditional classrooms, students are often given only limited opportunity to apply critique as scientific knowledge is frequently taught as given facts and delivered by textbooks or teachers who represent authority (Shen, 2010). Generation and critique activities can encourage students to actively use dynamic visualizations and facilitate integration of ideas from the visualizations (Buckley, 2000).

To elicit cross-connections between different levels, a novel form of concept map, called a Knowledge Integration map (KIM), has been developed that divides the drawing area into biology-specific levels: DNA, cell biology, and organism. Students were instructed to place ideas in the corresponding level and generate connections within and across levels. Similar to study 1, students generated paper-and-pencil concept maps from a given list of genetic, cell biology, and evolution ideas. After the generation phase, students reviewed and revised their maps by comparing them against another map: One group compared their concept map against an expert-made concept map while the other group provided feedback for a peer-generated concept map. Students were required to develop their own criteria for their critique.

The second iteration of WISE evolution module, titled *Space Colony: Genetic Diversity and Survival* (Schwendimann, 2008), extends the focus on human genetic diversity by adding a scaffolded inquiry activity about the effects of low and high genetic diversity on survival. After learning about the different sources of genetic diversity, students explore the chances of survival of two different groups of human space colonists that differ in their genetic diversity. Students are asked to make decisions which group of settlers should be chosen based on evidence gathered from inquiry activities.

The goal of study 2 is to evaluate the effects on student learning through a technology-supported learning environment with multiple interactive visualizations and critique-enhanced concept maps designed to support a more coherent understanding of evolution.

The general research question of this study is: How did students' integration of evolution ideas change after collaboratively generating and critiquing KIMs embedded in an inquiry-focused technology-enhanced learning environment?

This study investigates different ways to help students connect different biology ideas to form a systemic view that allows understanding of real life phenomena. In this study, students could build a more coherent understanding of biology by using a dynamic computer-based inquiry activity followed by KIM generation and two different critique activities.

The specific research questions this study addresses are:

1) Did the two treatment groups differ in their integration of evolution ideas after using the WISE module *Space Colony*?
2) How did students in each treatment group place the given ideas into the corresponding level in their KIMs?
3) What connections did students in each treatment group generate in their KIMs?
4) How did students in each treatment group generate criteria when critiquing expert or peer KIMs?
5) How did students use the critique activity to revise their KIMs?

C. Overview Study 3: Knowledge Integration Maps as learning tools: Distinguishing generation and critique

Following the iterative process of design studies, study 3 builds on the findings of study 1 and 2. Findings from study 2 indicated that a combination of generating and critiquing KIMs supported students' knowledge integration but was also time intensive. As time in science classrooms is very limited, study 3 aims to reduce time demands by distinguishing the learning effects from either generating or critiquing Knowledge Integration Maps. These findings will allow the design of more efficient concept mapping activities. Instead of reviewing peer maps that vary widely in quality, students in the critique group received a pre-made KIM with deliberate commonly found alternative ideas, introduced as the creation of a fictional student. The number of given ideas was reduced to limit complexity and time requirements. Study 3 used a revised version of Knowledge Integration Maps that distinguish two biology-specific levels: Genotype and phenotype. It was hoped that these levels allowed for a clearer distinction of ideas than the three levels in the second study. To facilitate concept map revisions, an electronic concept mapping tool, Cmap (Canas, 2004), was used instead of a paper-and-pencil format.

The third iteration of the WISE evolution curriculum, titled *Gene Pool Explorer*, uses a revised case study that aims to be more accessible and familiar to students than the space exploration in study 2. Study 3 uses human lactose intolerance as a case study to illustrate the connections between genetic changes and phenotypic traits. Human lactose intolerance is an observable real-life phenomenon many students have personal experience with. Based on the Hardy-Weinberg theorem [See chapter 2: History of Modern Evolution Theory], students explore the effects of mutation, natural selection, migration, and genetic drift in guided inquiry activities. The module introduces the population-genetics idea of "gene pool" to support students' understanding of evolution as changes in allele frequencies in a population from one generation to the next, instead of directed changes in individuals. Genetic drift is compared to natural selection to illustrate that evolutionary change does not necessarily lead to adaptations. Understanding both natural selection and genetic drift might help address alternative non-normative ideas that evolution always leads to perfect adaptations. The module focuses on adding and eliciting the connections between genotype ideas (for example mutation, allele, gene pool) and phenotype ideas (natural selection, adaptation, fitness).

This study examines students' learning from a technology-enhanced evolution curriculum that includes critiquing or generating KIMs that distinguish between genotype and phenotype ideas.

The general research question of this study is: How do students integrate evolution ideas through critiquing or generating concept mapping activities embedded in an inquiry-based technology-enhanced learning environment?

Specific research questions:
A) Overall changes in students' knowledge integration of evolution ideas
1) How does the WISE module *Gene Pool Explorer* change students' integration of evolution ideas?
2) How does the WISE module *Gene Pool Explorer* help students to integrate evolution ideas across contexts (plants and humans)?

B) Changes in knowledge integration of evolution ideas of treatment groups
3) How do treatment groups (critique and generation) differ in generating KIMs after the WISE module *Gene Pool Explorer*?
4) How do treatment groups (critique and generation) differ in cross-links between genotype and phenotype level ideas in their KIMs after the WISE module *Gene Pool Explorer*?
5) How do treatment groups (critique and generation) differ in qualitative changes of connecting ideas in their KIMs after the WISE module *Gene Pool Explorer*?
6) What variables can track changes in students' evolution ideas in KIMs?
7) How do treatment groups (critique and generation) differ in integrating core evolution ideas in their KIMs after the WISE module *Gene Pool Explorer*?
8) How do treatment groups (critique and generation) differ in changes of the topology of their KIMs after the WISE module *Gene Pool Explorer*?

9) How do treatment groups (critique and generation) differ in critiquing KIMs after the WISE module *Gene Pool Explorer*?
10) Is generating or critiquing KIMs a more time efficient knowledge integration activity to learn about evolution ideas?

III. Importance of Learning Evolution

Science education is of central importance to the economic success of a country to educate the next generation of scientists. The 2007 *Rising Above the Gathering Storm* review found the U.S. K-12 education in mathematics and science ranking 48th worldwide (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007). The report urges the government to focus on improving science education in the U.S. to remain globally competitive. "Improving science literacy and advancing scientific achievement in the United States will form the essential foundation for addressing national security, innovation and economic growth, and environmental stewardship, among many other critical challenges of the 21st century. Education can be the engine to lift all of America's diverse populace to greater understanding of the world around us, higher personal capacity and deeper civic engagement" (Futter, 2008).

The 21st century has been dubbed the "Age of Biology" (Maltsev, 2006). At present, there is probably no other field in science that produces as many new findings as biology (Graf, 2000). Advances in biotechnology, genomics research, and computational biology are expected to develop cures for diseases that are currently incurable, and future genetically engineered bio-products will contribute significantly to solving the global hunger problem.

Biology, and especially evolution and genetics, is a rapidly advancing field and science education has to try hard to keep up to date. Genetics is a relatively new science and has progressed at an unprecedented rate since the discovery of the structure of DNA only 50 years ago. A robust understanding of genetics and evolution is essential for being able to participate in meaningful debates and make informed political and personal decisions as a citizen, for example about genetically modified plants, biodiversity protection issues, stem cell research, and cloning.

Evolutionary theory is considered the "central and unifying theme of the discipline of the discipline of biology" (Muller, 1959), the "most fundamental idea of the discipline" (Rutledge & Mitchell, 2002), or as the evolutionary biologist Dobzhansky expressed it: "Seen in the light of evolution, biology is, perhaps, intellectually the most satisfying and inspiring science. Without that light it becomes a pile of sundry facts - some of them interesting or curious but making no meaningful picture as a whole" (Dobzhansky, 1973) (p. 129). Science for all Americans (Rutherford & Ahlgren, 1991) states: "The modern theory of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment". Ferrari notes that the power of evolutionary theory is that it provides an explanation for a wide range of biological phenomena over many scales and contexts (Ferrari & Chi, 1998). The universality of evolution theory makes it the central idea of biology (Bishop & Anderson, 1990). The U.S. National Science Standards identify evolution as a unifying theme to structure K-12 biology instruction (National Research Council, 1996). The Benchmarks for Science Literacy (American Association for the Advancement of Science (AAAS), 1994) outline K-12 biology education that starts with ideas of diversity and extinction and then gradually adds more abstract ideas like mutation and natural selection. The authors of Project 2061 write: "The modern theory of evolution provides a unifying principle for understanding the history of life on earth, relationships among all living things, and the dependence of life on the physical environment. While it is still far from clear how evolution works in every detail, the idea is so well established that it provides a framework for organizing most of biological knowledge into a coherent picture (American Association for the Advancement of Science, 1989). For a literature review of the centrality of evolution, see Wiles (2010).

Evolutionary theory influences both individuals and societies, from how to interpret human behavior to spiritual questions of the purpose of our existence (Brem, 2003). Evolution addresses fundamental questions such as: Where did I come from? Why am I structured in this way? What is the history of my world? The scientific conceptions of the answers to these questions involve the theory of evolution, a controversial and difficult topic in the teaching of biology (Cummins, Demastes, & Hafner, 1994). Without understanding evolution, biology becomes just a collection of factoids ranging from the internal plumbing of the digestive system to cute just-so stories about the daily lives of birds and bees (Linhart, 1997). "Evolution is the unifying framework that puts biology knowledge in context" (Mayr, 1988a; Mayr, 1993). Ernest Mayr proposed that biological phenomena must be explained on multiple levels: Proximate explanations describe the genetic development that lead to an organism's behavior, while ultimate explanations describe organisms' evolutionary history. [For further discussion: See chapter 2: Multiple explanations: Proximate and Ultimate]. Teleological reflections on ultimate explanations, like "Where does it come from?", "What is good for?", or "Why does a trait persists?" are defining characteristics of the field of biology. The truly outstanding achievement of the principle of evolution by natural selection is that it provides us with an ultimate cause that makes the invocation of final causes unnecessary—that is, teleological forces leading to a particular end (Mayr, 2000) [See appendix chapter 1 for further discussion].

CHAPTER 2: LITERATURE REVIEW

I. Literature Review Introduction

This literature review chapter discusses relevant research to reveal why students often struggle to understand evolution, and how concept maps can be used as knowledge integration tools to learn evolution:

The "Knowledge Integration" chapter explores how the knowledge integration perspective helps biology students construct more coherent and connected networks of evolution ideas [See chapter 2: Knowledge Integration].

The "Concept Mapping and Learning Evolution" chapter discusses the development of concept maps as biology-specific knowledge integration tools for evolution education [See chapter 2: Concept Mapping and Learning Evolution].

The "Evolution Instruction" chapter reviews different approaches of evolution instruction and the design of human evolution as a pivotal case [See chapter 2: Evolution Instruction].

The "Students' Ideas of Evolution" chapter provides an overview of learners' alternative ideas of evolution [See chapter 2: Students' Ideas of Evolution].

A. Knowledge Integration

1) Integrating Evolution Ideas

More than 150 years after Charles Darwin published his seminal work *On the Origin of Species by Means of Natural Selection*, people are still divided over understanding evolution. While the theory of evolution is firmly established in the scientific community, large parts of the general population across the world, from young children to college-educated adults, struggle with evolution ideas. Surveys consistently report that approximately 40%-50% of the US public rejects evolution (42% for Pew, 45% for Gallup) (Bishop & Anderson, 1990; Evans, 2008; Keeter & Horowitz, 2009). There has been little change in the percentage of the US public who reject the idea of evolution in the past two decades (Gallup, 2008). Rejection of evolution is not only a persisting issue in the United States but also in several European countries (Graebsch & Schiermeier, 2006), Scottland (Downie & Barron, 2000), Canada (Wiles, 2010), Australia (Sutherland, 2006), and several muslim countries (Clément, Quessada, Laurent, & Carvalho, 2008; Hameed, 2008; Clement & Quessada, 2009). Both among people who believe in or reject evolution, the level of understanding evolution is often low (Jakobi, 2010). Many people show mixed reasoning using both normative and non-normative ideas of evolution (Evans, 2005). Understanding evolution ideas is seen as central to building an integrated knowledge of biology by many scientists and science educators (Blackwell et al., 2003; Thagard & Findlay, 2010) [See chapter 1: Importance of Learning Evolution]. Despite the importance of evolution ideas for scientific literacy, understanding evolution ideas has been found difficult by science education researchers across the world, for example (Blackwell et al., 2003; Sinatra et al., 2003; Anderson, 2007; Deniz, Donnelly, & Yilmaz, 2008; Evans, 2008; Hokayem & BouJaoude, 2008).

"Evolution is a complex, abstract construct that stands on the top of a tower of complex, abstract constructs" (Good et al., 1992) (p. 12). The process of integrating ideas towards a deep understanding of the modern theory of evolution can be compared to the construction of a house [see figure 1: Repertoire of alternative evolution ideas]. Builders (learners) hold a rich repertoire of alternative stones (ideas related to evolution) from which they can choose, some normative and others non-normative. The idea that learners are not "blank slates" but hold a rich repertoire of alternative ideas (Ausubel, Novak, & Hanesian, 1978; Piaget, 1978; Vygotsky, 1978; Posner, 1982; Strike & Posner, 1992) is the foundation of the grand theory of constructivism.

Constructivism emphasizes that knowledge is actively constructed by the learner through connecting new ideas to prior existing ideas. Effective teaching and learning needs to address learners' existing ideas and scaffold building connections between new and existing ideas. Within science education, it is widely accepted that prior existing ideas are a key element that influences learning, as summarized by Clifton and Slowiaczek (1981): "Our ability to understand and remember new information critically depends upon what we already know and how our knowledge is organized."

Science education researchers have identified a wide variety of alternative ideas of evolution that are present prior to formal instruction. Evolution is a prime example for constructivist learning as students hold a rich repertoire of well-established alternative ideas of why something changes in nature [See chapter 2: Students' Ideas of Evolution]. Integrating ideas towards a deep understanding of evolution consists of the processes of eliciting existing stones, adding new stones to the repertoire, and then building a set of criteria that allow students to select stones to be used and connected for the construction of the building. These are the basic principles in the process of knowledge integration (Linn, 2008; Linn & Hsi, 2000; Linn et al., 2004) [See chapter 2: Knowledge Integration].

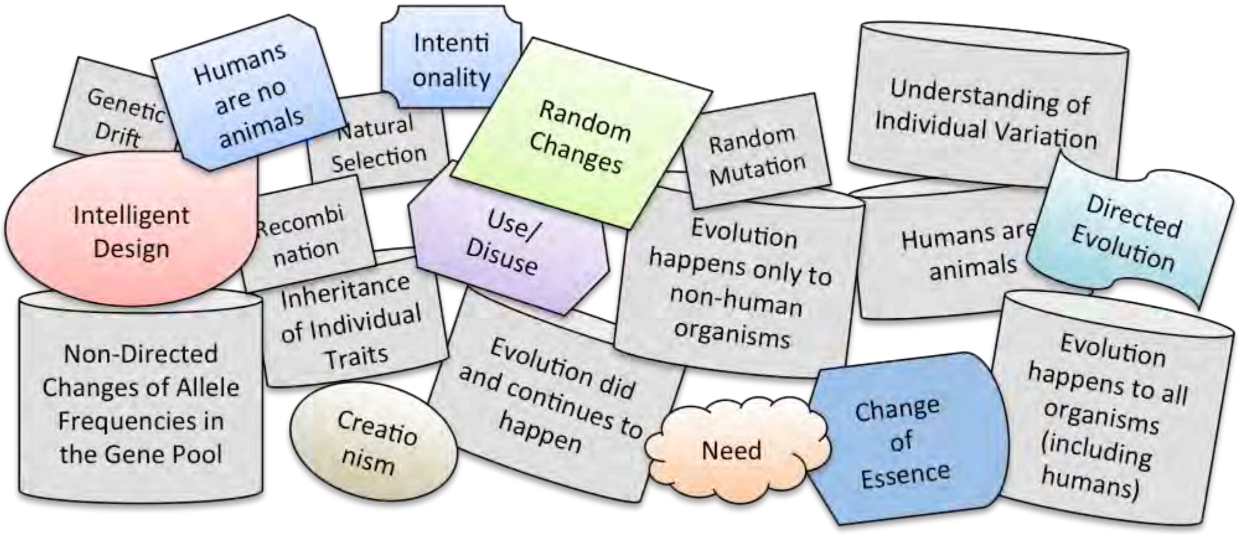


Figure 1: Repertoire of alternative evolution ideas [© by Beat A. Schwendimann]

First, the repertoire already contains a rich collection of alternative stones from which the builder can choose [See figure 2: House building analogy]. Builders need to elicit which alternative stones are already available in the repertoire. Learners are not "blank slates" but can hold a rich repertoire of alternative ideas related to evolution (Jensen & Finley, 1996a), such as anthropomorphism, teleology, Lamarckian evolution (Bishop & Anderson, 1990; Brumby, 1984; Clough & Wood-Robinson, 1985b; Demastes et al., 1996; Evans, 2008; Hallden, 1988; Jungwirth, 1977; Lawson & Thomson, 1988; Settlage, 1994; Tamir & Zohar, 1991), and religious ideas (Matsumura, 1998). Many curricula do not elicit existing ideas and the connections between ideas and levels [See chapter 2: Evolution Ideas on Different Levels], which might contribute to the current situation that many students leave school with a very fragmented knowledge of biology (Mintzes et al., 1998; Mintzes, Wandersee, & Novak, 2000b; Wandersee, 1989) that does not allow them to use biological ideas in their everyday lives.

Second, builders need to add new (normative) stones to their repertoire. The modern theory of evolution consists of a large number of abstract ideas (Cummins et al., 1994) from different disciplines, including the theory of natural selection, inheritance, genetics, paleontology, population genetics, systematics, and advances in mathematical modeling [See chapter 2: History of Modern Evolution Theory]. Each discipline focuses on different levels and developed its own terminology, which sometimes differs from the vernacular use [See chapter 2: Difficult Use of Terminology]. Integrating evolution ideas requires adding many abstract ideas to one's repertoire, for example natural selection (for examle, (Brumby, 1984; Bishop 1986; Bishop & Anderson, 1990; Greene, 1990; Settlage, 1994; Ferrari & Chi, 1998)), adaptation (for example, (Clough & Wood-Robinson, 1985b), genetics (Kargbo, Hobbs, & Erickson, 1980; Hallden, 1988; Demastes, Good, Sundberg, & Dini, 1992; Jensen & Finley, 1995; Lewis & Kattmann, 2004), inheritance (for example, (Kargbo et al., 1980), origin of new traits (Bishop & Anderson, 1990), common descent of organisms (Cummins et al., 1994), distinctions between species and individuals (Hallden, 1988), conceptions of deep time (for example, (Keown, 1988;

Renner, 1981; Cummins et al., 1994), viewing humans as animals (Cummins et al., 1994), nature of science (Rudolph & Stewart, 1998; Scharmann & Harris Jr, 1992; Sandoval & Reiser, 2004), non-directed nature of evolution (Cummins et al., 1994; Mayr, 2000), and genetic drift (Maret & Rissing, 1998; Winterer, 2001; Staub, 2002; Young & Young, 2003).

Third, builders need to form criteria that allow selecting stones for the building construction [See chapter 2: Critique]. Once selected, the builders need to connect the stones with each other. More normative stones and more connections between them lead to a stronger construction (higher explanatory power of integrated knowledge). Only carefully selected and well-connected stones can support the roof of the house, an integrated understanding of the modern theory of evolution. The roof needs to be supported by several pillars on the same level, each pillar representing a set of connected ideas. Integrated knowledge of evolution requires a connected understanding of evolution ideas.

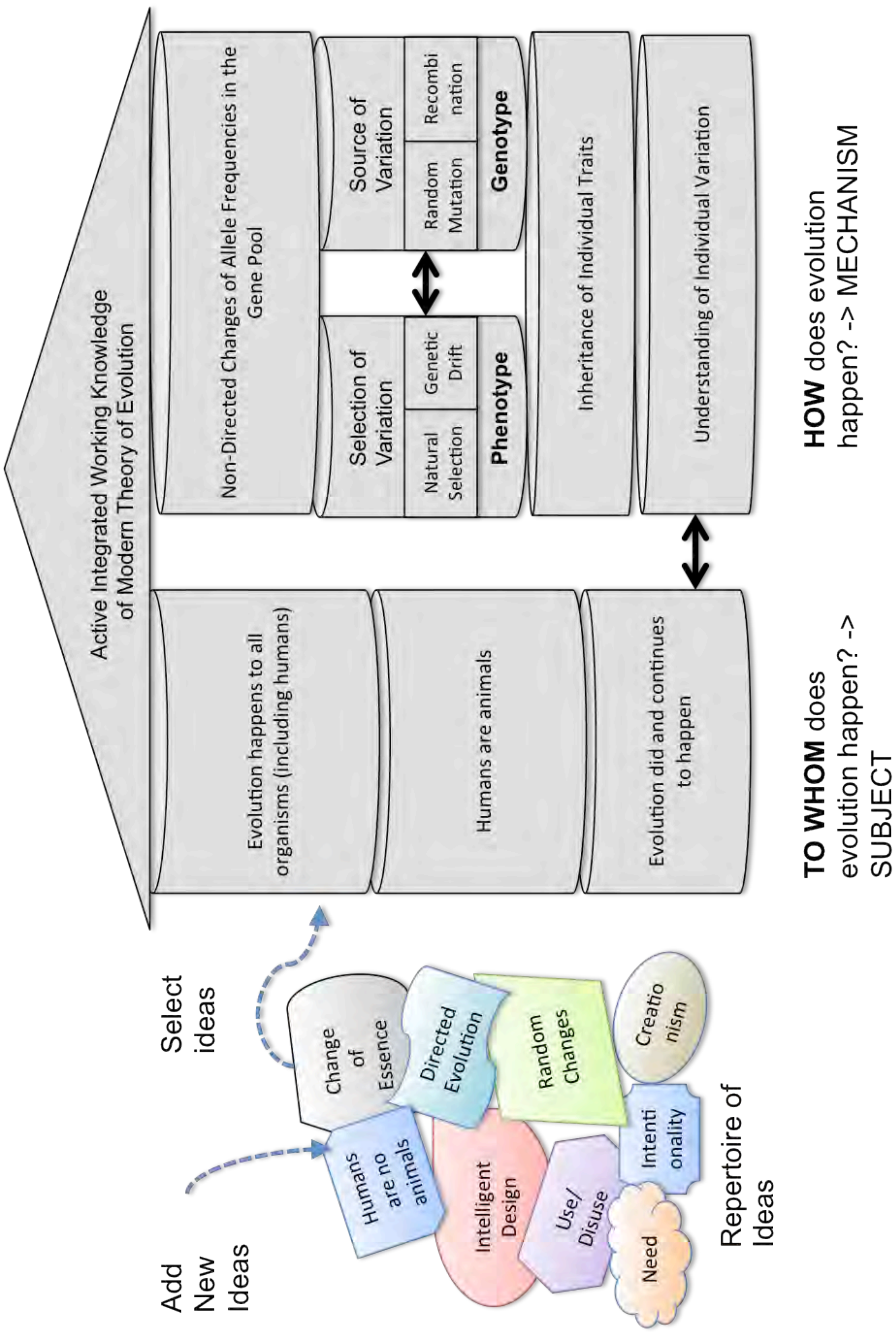


Figure 2: House building analogy. The figure illustrates a house built from normative ideas of evolution. [© Beat A. Schwendimann]

To understand evolution, students need to learn about two basic questions: "TO WHOM does evolution happen?", and "HOW does evolution work?". In the house building analogy, these two questions are represented by two separate but directly related columns: The TO-WHOM and the HOW column.

First, understanding TO WHOM evolution happens requires understanding that humans are animals and share common ancestors with all other life forms (see TO WHOM-column).

Second, the HOW-column contains ideas about the mechanism of evolution. The center stone of the HOW-column consists of the interplay between the sources of genetic diversity (mutations and recombinations) and selection processes (natural selection and genetic drift) (see HOW-column)

Knowledge integration aims to support learners to build an understanding of evolution that they will actively use to explain biological phenomena across a variety of contexts, make informed decisions, and continue to become autonomous lifelong learners who add new biological ideas to their repertoire (American Association for the Advancement of Science, 2001). A Knowledge Integration learning environment aims to provide learners with a variety of scaffolded opportunities to build criteria to distinguish ideas. By frequently revisiting and selecting alternative ideas, builders can learn to select normative ideas of evolution over non-normative ideas more frequently and in different contexts. When builders select non-normative stones over normative ones, the constructed understanding will be only partial and less strong. The building is never quite finished. The construction of the building is dynamic and the builder should be encouraged to frequently revisit to add or replace stones and add or change connections between stones. In addition to adding and removing stones, builders can also change the shape of stone (change meaning of ideas).

Novice builders tend to select different stones when creating houses for situations (contexts) that look different on a surface level. More expert builders learned that different situations are based on the same underlying ideas and that they can use the same powerful normative ideas for different houses. Additionally, builders tend to prefer re-using the same old stones that they have used many times before. When adding new normative stones to the repertoire, builders need help to learn using new unfamiliar stones by integrating them into a number of buildings in different contexts. That way the builders realizes the strength of the new stones and continues selecting and using them autonomously.

The house analogy does not aim to imply a particular sequence for instruction. For example, instruction about to-whom evolution happens can begin with the pivotal idea of human evolution [See chapter 2: Human Evolution as a Pivotal Case]. Using humans as a case study might help learners recognizing individual variation between individuals, and building connections between genotype and phenotype levels. Introducing a gene pool view of evolution might help students understand evolution as change in the proportions of individuals possessing those traits in a population instead of gradual change within individuals. Learning about the nature of science can and should be combined with learning the mechanisms of evolution.

One goal of knowledge integration is to help builders select and connect the same normative stones in different contexts. Builders need scaffolding to elicit available stones and connection between them, add new normative stones, generate a set of criteria, and sort out the stones. Inquiry-activities allow builders to test the (explanatory) power of different stones and gather evidence in favor of new normative stones. The builder learns to use normative stones more frequently than non-normative stones. More frequent use of normative ideas of evolution in different contexts can be seen as an indicator for increased knowledge integration.

Nehm (2007) identified three core challenges for the field of evolution education: First, to understand the interrelationships among cognitive, affective, social, cultural, epistemological, and metaphysical variables that influence integrating evolution ideas (Posner, 1982; Demastes, Good, & Peebles, 1995; Cobern, 1996; diSessa, 2002; Brem et al., 2003; Anderson, 2007; Park, 2007; Sinatra, Brem, & Evans, 2008); Second, to design, implement, and evaluate curricula that foster integration of evolution ideas; and third, to increase overall belief in evolution (Alters, 1997; Pigliucci, 2002; Scott, 2005).

This study describes the development and implementation of a novel technology-enhanced evolution curriculum that aims to support students' eliciting, adding, critiquing, and sorting out of ideas through scaffolded inquiry-activities and concept mapping activities.

2) Knowledge Integration

This research views learning as the process of integrating ideas through the cognitive processes of eliciting, adding, connecting, critiquing, distinguishing, sorting out, refining and applying ideas in a broad range of contexts (Bransford, Brown, & Crocking, 2000; Linn & Eylon, 2006; Piaget, 1971a; Smith, 1994; Vygotsky, 1962). To encourage students to build and revise connections between related ideas, this study uses the knowledge integration (KI) framework, which focuses on making connections among ideas (Computer As Learning Partner: Revised Annual Report*,* 1995; Linn, 1996; Linn, 2008; Linn & Hsi, 2000; Linn et al., 2004; Linn, Lee, Tinker, Husic, & Chiu, 2006).

Conceptual change research indicates that learners hold a rich repertoire of dynamically connected co-existing, and often conflicting, alternative ideas about the world around them (Davis, 2003; Davis & Linn, 2000; diSessa, 2000; Linn, 2002; Slotta, 1995; Songer, 2006) rather than internally consistent scientific theories, and that students often fail to connect ideas from one context to another (diSessa, 1988). Piaget showed that even an infant's mind contains complex cognitive structures (Piaget, 1971b).

Research suggests that in order to form coherent understanding of evolution, students need to add and distinguish new ideas and connections to their existing repertoire of ideas rather than replacing existing ideas (Demastes et al., 1995; Linn, 2008; Strike & Posner, 1992). Rather than seeing existing old ideas as obstacles that need to be replaced, knowledge integration seeks to add new ideas, and through application in different contexts, help students develop criteria to distinguish when ideas are relevant (Linn, 2008). Prior ideas are not simply exchanged for a new idea because ideas are embedded in a dynamic network where they define and constrain each other (Demastes et al., 1995; diSessa, 2002; Park, 2007). Adding new evolution ideas to one's repertoire is influenced by existing alternative ideas, view of the biological world, development of evolutionary theory, epistemological commitments (the nature of knowledge, the nature of learning, and the nature of conceptions), metaphysical beliefs, and emotional aspects (Demastes et al., 1995; diSessa, 2002; Kinchin, 2000b; Park, 2007). The knowledge integration approach encourages adding new normative ideas through carefully designed instruction that supports students to revisit their initial ideas, such as powerful pivotal cases (Linn, 2005)[See chapter 2: Human Evolution as a Pivotal Case].

Conflicting alternative ideas can co-exist because they are often contextualized (Davis, 2004; Smith, 1994). For example, Demastes (1995; 1996) found that some students show compartmentalized knowledge of evolution (learned at home vs. in science class). Students can hold multiple alternative ideas at the same time, for example “mutations are random” and “individuals change out of need”.

Newly added normative ideas are often used less frequently and in fewer contexts (Computer As Learning Partner: Revised Annual Report, 1995; diSessa, 1988)[See chapter 2: Integrating Evolution Ideas: House Building Analogy: Figure 2]. Alternative non-normative ideas remain in the repertoire because they are often more concrete and were previously applied in multiple contexts for long periods of time. Kuhn’s seminal work on change in scientific thinking (Kuhn, 1962) revealed that even scientists, who define themselves as rational reasoners, often prefer their well-established ideas over new ideas even when faced with contradicting evidence (also see (Lakatos, 1970; Lakatos & Musgrave, 1970)). On the other hand, new scientific ideas are often introduced in a single context (for example in a formal school lesson using a single example) during a short period of time. Studies found that even experts often continue to hold both non-normative and normative ideas and use them in different contexts, for example scientific (‘process-based, e.g. heat flow is a change in kinetic energy) or everyday life context (‘substance-based’, e.g. heat flows out of the room’) (Slotta & Chi, 2006). To achieve more integrated knowledge, new normative ideas need to be connected to existing ideas, ideally across different contexts. Only then will new ideas be actively used in different contexts.

Processes that encourage knowledge integration include eliciting students’ existing ideas (for example by explaining or predicting generation activities)[See chapter 2: Generation], adding ideas to build understanding (for example through dynamic population genetics inquiry activities), helping learners refine and sort their repertoire of ideas (for example by asking for explanations about how the molecular view relates to their observations), and developing criteria for distinguishing ideas depending on context (for example by critiquing concept maps generated by peers) [See chapter 2: Critique]. Research suggests that students should frequently revisit and revise their ideas and the connections between them. Ideas should be presented in various formats and contexts, for example text, pictures, dynamic visualizations, symbolic representations, or everyday situations (Linn et al., 2006). By engaging students in knowledge integration processes, they can learn to self-monitor their learning progress and take an active role in refining their knowledge. Developing self-monitoring skills for their own understanding can help students to become lifelong learners for biology-related topics.

By applying scientific ideas in different situations, for example through scaffolded inquiry activities in the context of everyday life situations, students can experience the explanatory power of new ideas and appreciate the relevance. More frequent usage of normative alternative ideas can be seen as an indicator for increased understanding of evolution ideas in different contexts.

(i) Elicit and Distinguish Ideas

(a) Generation

This dissertation research uses generative concept mapping activities to elicit students' existing ideas, add normative ideas, connect ideas with one another, and help students distinguish and sort out ideas. Generating artifacts, such as explanations or concept maps, can promote conceptual learning (van Amelsvoort et al., 2005). Osborne (1983) described learning science as a generative process. Slamecka and Graf (1978) found that learners could remember self-generated words better than when they were simply presented the words to be read. This "generation effect" has been well documented in a variety of different settings. For example, Foss (1995) reported evidence that generating summaries when studying texts can improve recall of ideas. Chi (1994; 2000a) found that generating explanations of a text or diagram, whether for oneself or for others, can be more effective for learning than receiving explanations. By generating explanations and concept maps, students articulate and represent their knowledge in new forms, apply their representations to solve scientific problems, realize gaps in their knowledge, and reorganize ideas. Using concept maps repeatedly as an embedded learning tool may allow learners to collect and connect ideas from different contexts. Traditionally, most concept mapping activities consist of generation from scratch. On the other hand, generating concept maps from scratch is often time-consuming and cognitively demanding.

(b) Critique

Critique is an essential step in the knowledge integration process of distinguishing alternative ideas. This dissertation research explores an alternative to generating concept maps from scratch: Critiquing and revising a provided concept map with deliberate flaws might provide more scaffolding to promote knowledge integration of evolution ideas.

Students can hold rich repertoires of alternative ideas of evolution [See Students' ideas of evolution]. Critiquing, distinguishing, and sorting out alternative ideas are essential steps of knowledge integration [See Knowledge Integration]. Critiquing is the process of creating a set of criteria, applying criteria to compare one's own or others' alternative ideas against each other, reflecting on how those ideas apply to different ideas, and selecting supported ideas based on evidence (Shen, 2010). Critique activities require students to use or develop criteria to reflect, revise their work, and self-monitor their learning progress (Chi, 2000b) that can foster the development of metacognitive skills for lifelong autonomous learning. Critique activities encourage the elaboration of ideas and conjectures. Asking students to critique has been found to lead to the development of coherent and generative criteria (Slotta & Linn, 2000).

Critique is often applied in collaborative settings. In science, peer critique is a central aspect of science (Ford, 2008). Scientific knowledge is collaboratively constructed by the scientific community, which evaluates each other's theories and findings (Wenger, 1998). Learners' views of the nature of science influence their willingness to critique (Schwarz & White, 2005; Tabak, Weinstock, & Zvilling-Beiser, 2009). Many students seem to hold the objectivist view that scientific knowledge is discovered and static (Marcum, 2008) rather than consisting of constructed tentative models. When scientific ideas are understood as immutable products there is little reason to critique. Karl Popper (1962) posited that scientific ideas are falsifiable which consequently leads to revising or rejecting of ideas when faced with contradicting evidence. Linn and Eylon (2006) noted that critique activities can engage students to ‘‘question scientific claims and explore the epistemological underpinnings of scientific knowledge" (p. 536).

From a situated learning perspective, critique activities in the classroom can mimic what professionals do in their communities (Lave & Wenger, 1991). Critiquing peer work can provide a driving force for revising one's own work (Lehrer & Schauble, 2004). The social process of reaching agreement is critical in shaping one's ideas (Clark & Sampson, 2008; Enyedy, 2005).

In science education, collaboratively critiquing ideas requires learners to argue, negotiate, and make informed decisions (Berland & Reiser, 2009). Finding common ground can be a driving force for critique. To reach such common ground, students need to pose questions, make revisions, accept propositions, defend against criticism, and improve their criteria (Shen & Confrey, 2007). Brown and Campione (1996) showed that elementary students can form communities of learners that constructively share resources and review each other’s work. Students need authentic opportunities to develop criteria to distinguish valid alternative ideas based on evidence and scrutinize the reliability of sources (Cuthbert & Slotta, 2004; Davis & Kirkpatrick, 2002). DiSessa (2002; 2004) found that students are able to develop their own criteria to critique representations. A meta-study by Falchikov and Goldfinch (2000) found that student-generated criteria work better for peer assessment than using a set of given criteria.

However, students have little opportunity to critique (Clark & Slotta, 2000; Grosslight, Unger, Jay, & Smith, 1991; Shen & Confrey, 2010). Students can a) critique their own ideas, b) a peer’s ideas, c) common alternative ideas, or d) expert’s ideas.

a) Critiquing one’s own ideas: Research has shown the difficulty of critiquing one's own work, for both experts and novices (Guindon, 1990). People tend to discount ideas that contradict their existing ideas (Chinn & Brewer, 2001; Kuhn, 1962; Schauble, Glaser, Duschl, Schulze, & John, 1995). For example, students as well as professional engineers often stick to their initial design strategies and resist alternative ideas (Cuthbert & Slotta, 2004).

b) Critiquing a peer’s ideas: Analyzing a peer’s work may be easier than evaluating expert generated work. Critiquing peer work can help to motivate students to improve their own work and better understand what might be refined. Comparing one’s own ideas against those of a peer, can help students to value their own ideas while developing criteria to critically review them. However, critiquing peers can be socially difficult as students tend to give overly generous or overly critical feedback (Hoadley & Kirby, 2004) [See study 2].

c) Critiquing common alternative ideas: Providing students common alternative ideas can serve as a starting point for critique [See chapter 2: Students’ Alternative Ideas of Evolution]. Critiquing and revising concept maps with deliberate flaws are partial solutions that require a completion strategy (Chang, Chiao, Chen, & Hsiao, 2000; Sweller, Van Merrienboer, & Paas, 1998; Van Merriënboer, 1990). Giving all students the same artifact equalizes conditions for all students, compared to a peer-critique activity where each student receives very different ideas from peers. Critiquing a generic students’ work (instead of a real classmate) could reduce discrimination issues. When giving peer critique, students are often too generous or too critical due to personal bias. On the negative side, having to compare, critique, and select ideas from three different sources (for example two collaborating group members and a given concept map) could increase cognitive load in some students. [See study 3].

d) Comparing one's own ideas to expert ideas could help students identify gaps in their understanding and non-normative ideas. Previous studies using expert-made concept maps often presented the maps to students as a form of summary to be studied (O'Donnell, Dansereau, & Hall, 2002). In these settings, students did not actively generate their own connections or critically evaluate presented propositions. Expert work should not be presented as absolute solutions but as one of many possible solutions. A meta-analysis (Horton et al., 1993) found that studying expert-made and student-generated concept maps seemed to have an equally positive effect on improving students' achievement. On the other hand, Cliburn (1990) noted that teacher-generated concept maps could support integrative understanding. O'Donnell et al. (2002) found that students could recall more central ideas when they learned from expert-made knowledge maps than when they learned from texts. Students with low verbal ability or low prior knowledge often benefited the most. Chang et al. (Chang, Sung, & Chen, 2001) compared generating concept maps [See table 5 in chapter 2: Types of Concept Mapping Tasks: Task type #2] to critiquing them [task type #11] using a computer-based tool that provided students feedback by comparing student-generated maps to an expert-generated benchmark map. Generating and critiquing concept maps led to similar results, both better than a control group that did not use concept maps. However, Novak (1980b) observed that studying pre-made expert maps in genetics instruction could be confusing to some students as expert-generated concept maps could be seen by students as the one correct solution [See study 2].

II. Concept Mapping and Learning Evolution

A. History of Mapping Ideas

Maps are simplified symbolic representations of information that highlight aspects important to the mapmaker. Harley and Woodward define maps as "graphic representations that facilitate a spatial understanding of things, concepts, conditions, processes, or events in the human world" (Harley & Woodward, 1987) (p. xvi).

Maps are always subjective representations as they only show selective information (Tversky, Franklin, Taylor, & Bryant, 1994). “To map is to construct a bounded graphic representation that corresponds to a perceived reality” (Wandersee, 1990) (p. 923). Maps are the products of compromises, omissions, and interpretations (Wilford, 1998).

The earliest maps were topological maps, showing hunting grounds, water holes, and shelter. However, as early as the 3rd century AD, people began making maps of abstract ideas (Sowa, 1992; Sowa, 2006). Maps of ideas adopted principles from topographic maps to show associated ideas, represented as words or images, in spatial arrangement. Similar to topological maps, maps of ideas are not comprehensive “windows into the mind” (Shavelson, Ruiz-Primo, & Wiley, 2005) but subjective selections of what is important to that person to include in the map. One of the oldest known maps of ideas is the “Tree of Porphyry” that is named after the 3rd century AD Greek philosopher Porphyry who visualized Aristotle’s ontology of the beings (Sowa, 1992; Sowa, 2006) [See figure 3: Tree of Porphyry]. The “Tree of Porphyry” was translated into Latin by Boethius and used in philosophical textbooks throughout the Middle Ages (Medieval Theories of Categories, 2010).

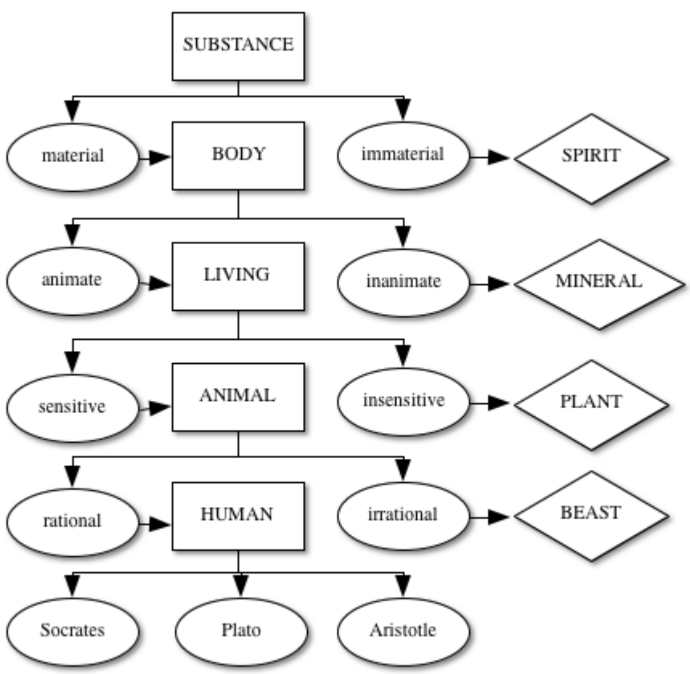


Figure 3: Tree of Porphyry. One of the oldest known maps of ideas was created by the 3rd century philosopher Porphyry based on Aristotle’s ontology of types of beings. [Re-created by Beat A. Schwendimann]

B. Node-Link Diagrams to Elicit Ideas

The term graphic organizer commonly describes two-dimensional visual knowledge representations, including for example node-link diagrams, timelines, and tables, that show relationships among ideas by means of spatial position, connecting lines, and intersecting figures (Alvermann, 1981; Ives & Hoy, 2003; Winn, 1991) (for a review of the range of graphic organizers specific to science education see (Hamer, Allmark, Chapman, & Jackson, 1998)). Node-link diagrams are of particular interest to biology education as biology is a traditionally fragmented field that lacks a shared form of representing ideas across topics [See chapter 2: Fragmentation of Biology](compared to physics that uses mathematics, or chemistry that uses structural formulae and reaction equations). Node-link diagrams are frequently found in biology textbooks and professional biology publications. A famous node-link diagram in evolution is the phylogenetic tree diagram Darwin drew in his notebook to illustrate the shared ancestry of species in the tree of life. Darwin noted that "…plants and animals, most remote in the scale of nature, are bound together by a web of complex relations" (Darwin, 1859) (Chapter 3, p. 109).

Besides phylogenetic tree diagrams, other frequently used node-link diagrams in biology include flow charts in ecology, (for example carbon cycle or food webs) and biochemistry pathways (for example cellular metabolic pathways). Node-link diagrams are also used in other fields, for example entity-relationship diagrams (Chen, 1976) are a form of node-link diagrams used in computer science to show the flow of information in relational database systems. Social network theory uses node-link diagrams to represent the interactions and adjacency between people. [See chapter 2: Concept maps as Learning tools].

Making connections visible can help students and scientists understand relationships between ideas in complex systems that would otherwise often be hidden. Node-link diagrams are important tools in scientific practice. Being able to understand node-link diagrams can be considered part of being scientifically literate. One way to learn how to interpret and use node-link diagrams can be generating and critiquing biology-specific node-link diagrams [See chapter 2: Generation and Critique].

C. Types of Node-Link Diagrams

A variety of node-link diagrams have been developed, for example mindmaps (bubble maps, spider maps) (Buzan & Buzan, 1996; Goodnough & Long, 2002), concept maps (Novak & Gowin, 1984), knowledge maps (O'Donnell et al., 2002), argument maps (van Amelsvoort et al., 2005), flow charts (Gilbreth & Gilbreth, 1921), fishbone diagrams (Ishikawa & Loftus, 1990), double-bubble diagrams (Hyerle, 2000), causal maps (Cheng, 2001), and semantic network diagrams (Chi & Koeske, 1983; Fisher, 1990).

Frequently found forms of node-link diagrams are, for example [see figure 4: Common types of node-link diagrams]:

[A] Mindmaps are arranged around a central concept. Connections represent non-specified associations.

[B] Concept maps consist of semantic propositions. The relationships between ideas are represented by labels (usually a verb) and arrows. The label describes the character of the relationship between two ideas (usually nouns). The connected propositions form a semantic network. Different than mindmaps or flow charts, the labels in a concept map can represent different forms of relationships, for example temporal, procedural, subset, superset, or causal. The spatial arrangement of ideas in a concept map is not constrained by a central hub (mindmap) or input/output flow (flowchart)[See chapter 2: Concept Map Definition].

[C] Flow charts show the intermediate steps between input and output of a system. Flow chart connections are usually ontologically of one kind and represent the quantified flow of information, energy, time, or material.

[D] Fishbone diagrams represent multiple causes that can affect a certain outcome.

[E] Double-bubble diagrams show similarities and differences between two ideas.

[D] Semantic network diagrams include multiple semantic relationships connecting to specific ideas.

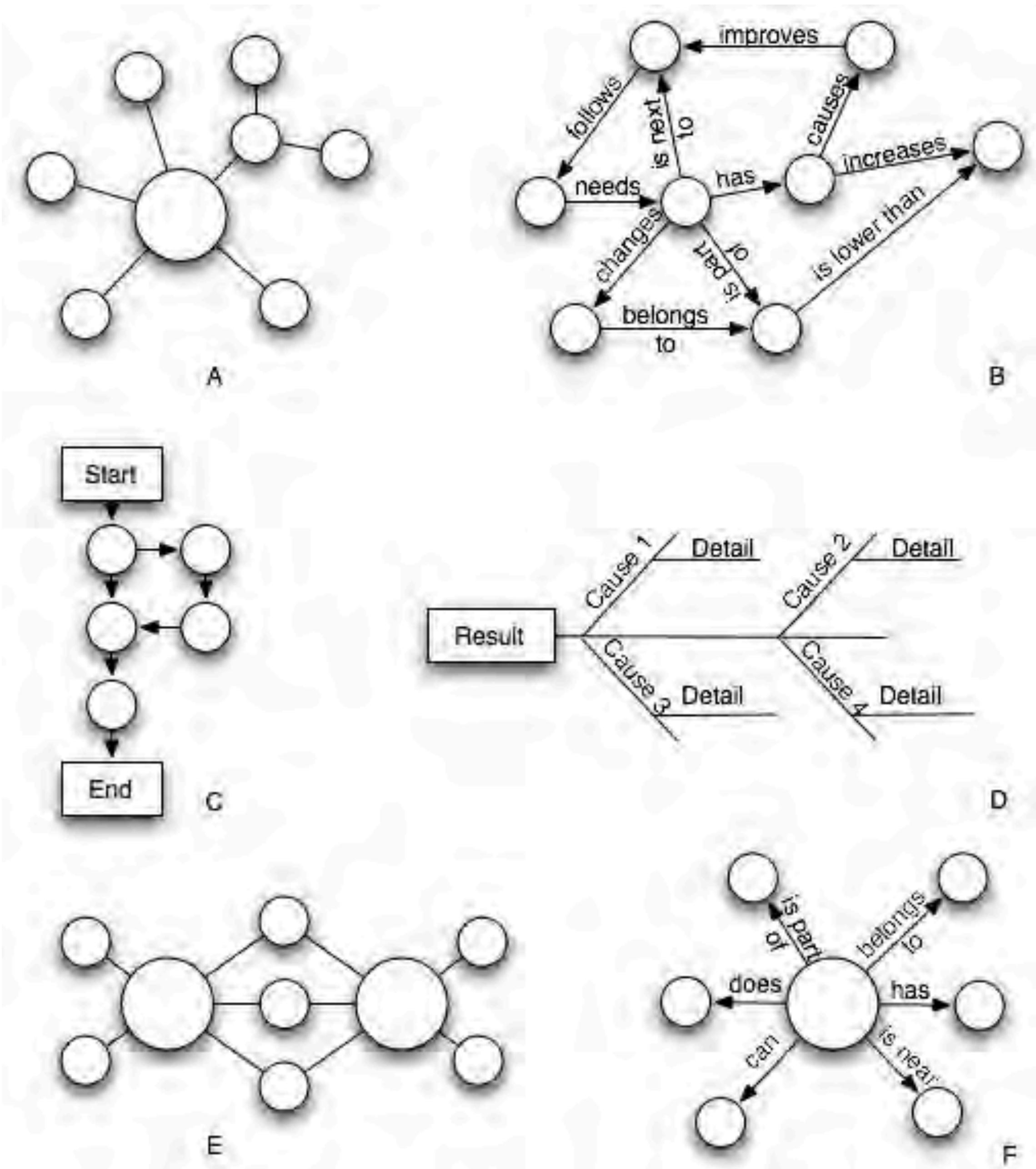


Figure 4: Common types of node-link diagrams: [A] Mindmap, [B] Concept map, [C] Flow chart, [D] Fishbone diagram, [E] Double-bubble diagram, [F] Semantic network diagram [© Beat A. Schwendimann]

Node-link diagrams can be described and distinguished by four different properties [see figure 4]:

1) Nodes.

-What does the node represent? Nodes can represent a single idea (for example in concept maps or mindmaps), a whole argument (for example in argument maps), or a process (for example in flowcharts). Nodes can have different shapes or colors to represent different types of nodes (as in flowcharts).

2) Link.

-Are there constraints regarding the types of relationships the links can represent? Links can be unspecified associations (for example in mindmaps); constrained to one type of relationship (for example temporal order in flowcharts); or allow any kind of relationship (for example concept maps).

-If links can represent different types of relationships, what kind of relationship can be used? Node-link diagrams relationships can include a wide variety of relationships, for example causal, flow (such as time, information, mass, energy), associations, structural (such as hierarchies), etc.

3) Topology.

-How is the topology of the node-link diagram constrained? There are different levels of topology constraints, from unconstrained (free form) to constrained (given network structure). Constrained topology can include a central hub (for example mindmap), chain (for example flow chart), circle, hierarchical tree, or decentralized network (Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005). Concept maps can take on any network structure.

-Are the nodes arranged in groups (clusters) according to field-specific properties (for example Knowledge Integration maps)? The map can have node-clusters in theory-driven levels, for example micro/macro or genotype/phenotype.

4) Construction.

-Node-link diagrams can be generated individually or collaboratively (in pairs or larger groups).

-Node-link diagrams can be created by teachers, experts, or students.

-Does the node-link diagram construction include a subsequent critique and revision step?

-Do node-link diagram authors receive feedback? Authors might receive no feedback, peer-feedback, teacher/expert feedback, or automated feedback (based on a benchmark map).

-Does the node-link diagram include deliberate errors for the purpose of a critique exercise?

-How do nodes get chosen? Nodes can be given; a given list of nodes to choose from (forced choice); a given list of nodes to choose from with the option to add own nodes (semi-forced choice); or entirely free choice of nodes.

Node-link diagrams are to varying degrees constrained along one or more of these four properties. Looking at typical forms of node-link diagrams can illustrate different variations of constraints. For example, flow charts use looped chain topologies with only one form of relationship (for example flow of information, energy, or material). Knowledge maps constrain the number of link labels and are often created by teachers/experts as advanced graphical organizers (O'Donnell et al., 2002). Entity-relationship diagrams represent the flow of information in computer databases (Chen, 1976). Mindmaps use hub topologies with connections that represent unspecified associations (Buzan & Buzan, 1996). Fishbone diagrams use a chain topology with cause-effect relationships (Ishikawa & Loftus, 1990).

D. Concept Map Definition

Based on the four properties nodes, links, topology, and construction, this dissertation research identified concept maps as one of the most versatile node-link diagrams. Concept maps are multi-purpose tools to visualize connections in complex systems in a wide variety of fields.

Concept maps can include any form of relationship (for example, temporal, procedural, functional, subset, superset, causal, etc.) and topological arrangement (for example, hierarchical, hub, decentralized network, circular, etc.) (Yin et al., 2005).

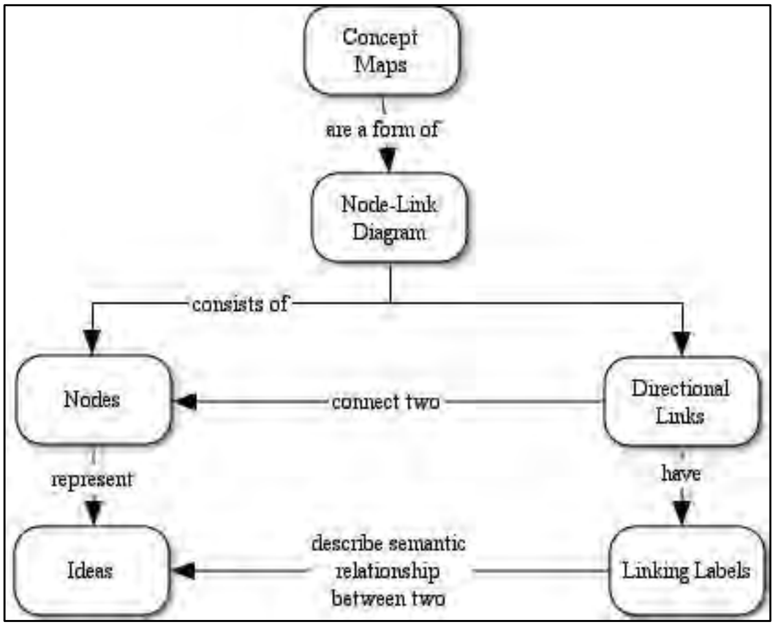


Figure 5: Concept map of a concept map. [© Beat A. Schwendimann]

Concept maps can be defined as a form of node-link diagram for organizing and representing semantic relations among ideas. Like other node-link diagrams, concept maps consist of visuo-spatially arranged nodes and links, but additionally they also present semantic information in the link relationships. A concept map consists of nodes (ideas), directional linking lines, and linking labels that describe the relationship between nodes [See figure 5: Concept map of a concept map]. Two nodes connected with a labeled line are called a proposition (Canas, 2003). The relational cognitive model assumes semantic propositions, consisting of nouns (nodes) and verbs (linking labels), can represent ideas and relationships between ideas. These properties define concept maps as versatile graphic organizers that can represent many different forms of relationships between ideas [See figure 6: Concept map example]. Graphic organizers, such as concept maps, can change students' understanding beyond remembering isolated ideas to constructing meaningful connections of organized knowledge (Bransford, 2000b). Mason (1992) observed that students exposed to 'mapping' during instruction demonstrated "insight into the interrelatedness of concepts" (p. 60), instead of seeing scientific knowledge as a collection of isolated facts. In 1972, Josef Novak and colleagues developed a concept mapping method to visually represent changes in children's knowledge assessed through clinical interviews (Novak & Gowin, 1984; Novak & Canas, 2006). With its emphasis on actively engaging learners in eliciting and connecting existing and new ideas, concept mapping is considered to be consistent with constructivist epistemology (Edmondson, 2000).

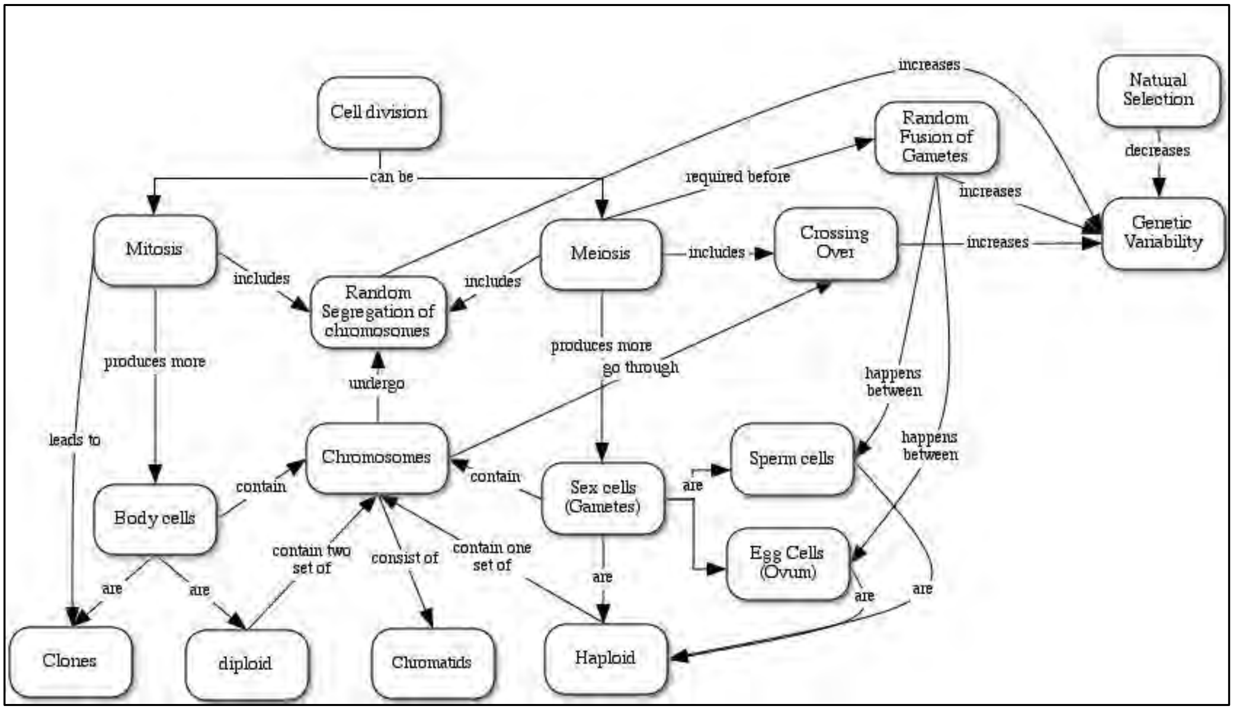


Figure 6: Concept map example. [© Beat A. Schwendimann]

E. Concept Maps and Knowledge Integration

Concept map activities can support eliciting existing ideas and connections (stored in long-term memory) through the process of visualizing them as node-link diagrams. The explicitness and compactness of concept maps can help keeping a big picture overview (Kommers & Lanzing, 1997). The 'gestalt effect' of concept maps allows viewing many ideas at once, increasing the probability of identifying gaps and making new connections. Generating concept maps requires learners to represent ideas in a new form which can pose desirable difficulties (Bjork & Linn, 2006; Linn, Chang, Chiu, Zhang, & McElhaney, 2010) - a condition that introduces difficulties for the learner which slow down the rate of the learning and can enhance long-term learning outcomes, retention and transfer. The process of translating ideas from texts and images to a node-link format may foster deeper reflection about ideas and their connections (Weinstein & Mayer, 1983) and prevent rote memorization (Scaife & Rogers, 1996). Throughout a curriculum, learners can add new ideas to their existing concept map. Unlike textbooks, concept maps have no fixed order and may thereby encourage knowledge integration strategies. For example, a student may decide to add the most important or most central idea first. Developing criteria to select ideas requires deeper processing than the student might normally exercise when reading text.

Students need to develop meta-cognitive strategies to distinguish alternative ideas, for example through predicting outcomes and explanation generation (Bransford et al., 2000). The scaffolded process of adding and revising concept maps requires students to decide which ideas and connections to include. The decision-making process may foster the generation of criteria to distinguish pivotal ideas. Clustering related ideas in spatial proximity can support learners' reflections on shared properties of and relationships between ideas. Cross-links between related ideas can be seen is indication for knowledge integration across different contexts. Concept maps may support making sense of ideas by eliciting semantic relationships between ideas [See table 2: Concept mapping for Knowledge Integration].

Knowledge integration suggests that a successful curriculum starts by eliciting ideas about scientific phenomena. Learners need tools to elicit their ideas and distinguish alternative ideas. Ideas (or concepts) are the way in which we organize our experience, but they cannot be understood in isolation. Ideas need to be connected to existing ideas, and their meaning can only be understood within such an integrated framework (Bruner, 1960). Learning an idea means seeing it in relation to other ideas, distinguishing it from other ideas, and being able to apply it in specific contexts. To learn a subject is to have actively integrated key ideas and the relationships between them [See chapter 2: Knowledge Integration].

Knowledge integration activities are designed to help learners construct more coherent understanding by developing criteria for the ideas that they encounter. Research suggests that concept mapping is especially efficient, in comparison to other interventions such as outlining or defining ideas, for the learning of relationships among ideas (Canas, 2003). Concept maps as a knowledge integration tool allow eliciting and critiquing ideas and relationships between ideas. The visual format of concept maps can foster critical distinctions between alternative ideas and relationships, either individually or through collaboration in communities of learners.

Cognitive science research (for example see (Bransford et al., 2000)) found that new ideas need to be connected to existing ideas to be stored in long-term memory. Eliciting existing ideas brings them from long-term memory to working memory. Learners make sense of new ideas by integrating them into their existing repertoire of ideas.

Knowledge integration suggests that ideas should be presented in multiple contexts and support generation of connecting ideas across contexts [See chapter 2: Knowledge Integration]. Multiple representations of ideas (for example dynamic visualizations, animations, pictures, diagrams) can facilitate learning and performance supporting different accounts of scientific phenomena (Ainsworth, 2006; Pallant & Tinker, 2004), for example by complementing each other or constraining interpretations (Ainsworth, 1999). However, having learners make connections between different representations can be challenging as they are connected through multiple relationships that are often not intuitively obvious to the learner (Duncan & Reiser, 2005).

Table 2: Concept mapping for Knowledge Integration

Knowledge Integration Process	**Concept Mapping Activity**
Eliciting existing Ideas	Concept maps can be used as a pretest activity to elicit' existing ideas.
Adding new ideas and connecting to existing ideas in repertoire	New ideas can be added to existing propositions in the concept map. If several alternative relationships between two ideas are possible, students have to decide which one to use in the map. If applicable, students decide which ideas to add to the map.
Distinguishing/ Critiquing Ideas	After adding new ideas, Ideas can be rearranged into new

	groups, and the concept map network structure might need revision to reflect the new ideas.
Sorting out Ideas/ Refining	Different sources of evidence can as reference to sort out ideas and further refine the concept map.
Applying ideas	Concept maps can be used as resources to generate explanations of scientific phenomena.

This dissertation research explores how providing biology-specific epistemic scaffolding for clustering related ideas KIMs can support knowledge integration [See chapter 5: Novel Concept Map Type].

F. Concept Maps as Tools

Concept maps can be used for a variety of different purposes [See figure 7] [See Canas et al. for a literature review of different usages of concept maps (Canas, 2003)]. Initially, concept maps were used by researchers to elicit core ideas and relationships from student interviews [See chapter 2: Concept Map Definition].

As illustrated in figure 7, concept maps can be generated by teachers or researchers to identify core ideas and knowledge structures when designing or revising curricula (for example see (Edmondson, 1995; Martin, 1994; Starr & Krajcik, 1990). Concept maps are frequently used as assessment tools: Concept maps as pretests or formative assessment can identify students' prior ideas which can be used to design curricula that connect to existing alternative ideas and provide feedback. Concept maps can be used as summative assessments, either alone or in comparison to pretest concept maps, to evaluate learning outcomes [See chapter 2: Concept Maps as Assessment Tools]. Concept maps can be used as advance organizers to provide an overview of core ideas prior to instruction (for example see (Mistades, 2009)). In technology-enhanced learning environments, concept maps can serve as dynamic user interfaces to navigate through activities (for example see (Puntambekar, Stylianou, & Huebscher, 2003)).

As learning tools, students can generate concept maps to elicit, summarize, and revisit core ideas and relationships (Kinchin, 2000a). The visual knowledge representation of concept maps can support collaborative learning (Canas, Suri, Sanchez, Gallo, & Brenes, 2003; Cicagnani, 2000; Gaines & Shaw, 1995) [See chapter 2: Concept Maps and Knowledge Integration], for example in decision making, or giving and receiving feedback from teachers and peers [See chapter 2: Concept Maps as Collaborative Tools]. Generating concept maps can promote students' self-monitoring of their understanding and scaffold building criteria to distinguish and sort out alternative ideas [See chapter 2: Concept Maps as Metacognitive Tools].

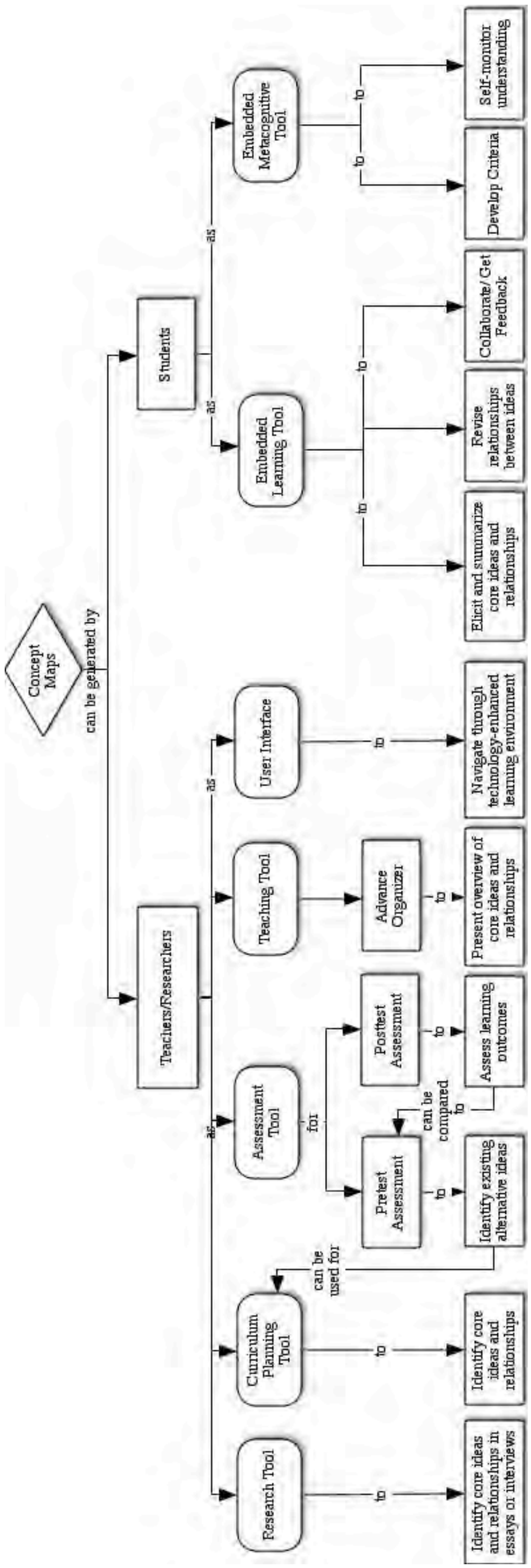


Figure 7: Different uses of concept maps. [© Beat Schwendimann]

This dissertation research explores using concept maps as embedded collaborative learning tools, assessment tools, and metacognitive tools to foster knowledge integration of evolution ideas.

1) Concept Maps as Learning Tools

Schmid and Telaro commented that: “Biology is so difficult to learn because it consists of a myriad of unfamiliar concepts involving complex relations. The schools' favored approach to teaching unfamiliar material is rote learning. Rote learning predictably fails in the face of multilevel, complex interactions involved in biology. Concept mapping ... stresses meaningful learning, and appears to be ideally suited to address biological content” (Schmid & Telaro, 1990) (p. 78-79). Concept maps are of particular interest to evolution education, a concept-rich field that connects ideas from many different areas. Several studies have investigated concept maps as learning tools to foster a system-dynamic view of evolution.

Biology in general, and evolution in particular, is a complex field that consists of a large number of ideas that are connected in different ways. Connections between genetic and evolution ideas are often not made explicit by teachers and textbooks. To learn about the connections between these ideas, students need to identify core ideas and elicit connections between them. As a learning tool, concept maps can support eliciting core ideas and connections, and can make possible clusters or hierarchies visible. Watson (2005) found that graphic organizers such as concept maps could scaffold integration of students’ isolated biology ideas to an organized interconnected network of ideas. Research indicates that the implementation of concepts maps can shift the epistemological authority from the teacher to the student, reduce emphasis on right and wrong answers, and create visual entry points for learners of varying abilities (Mapping Biology Knowledge, 2000; O'Donnell et al., 2002; Roth, 1993). Novak pointed out that “some students who are whizzes at rote memorization object to concept maps, for rote learning has little value in concept mapping” (Novak, 1981). Kinchin (2000b) suggested that concept mapping as learning tools should be introduced early in students’ educational career, before preferred study habits have been firmly established. When concept mapping is introduced at a later stage, the teacher should make the possible benefits for the learner explicit, for example to reflect, to communicate what would otherwise be incommunicable, or to keep trace of what otherwise would disappear (Lehrer, Schauble, Carpenter, & Penner, 2000).

Several meta-analyses reviewed the effects of concept maps as learning tools. Horton et al. (1993) compared the effects of concept mapping reported in 19 classroom-implemented quantitative studies. The meta-analysis found that concept maps as learning tools produced generally medium-sized positive effects on student achievement and large positive effects on student attitudes. Improved achievement was stronger in biology classrooms than chemistry or physics classrooms. The mean effect size for studies using pre-made maps was 0.59. Concept maps generated by students in groups produced a mean effect size of 0.88. Nesbit and Adesope (2006) conducted a meta-analysis of fifty-five experimental and quasi-experimental studies in which students learned using concept maps. The study included 5,818 students ranging from fourth grade to postsecondary in fields such as science, psychology, statistics, and nursing. Across different conditions and settings, the study found that the use of concept maps was associated with increased knowledge retention, with mean effect sizes varying from small to large depending on how concept maps were used. Canas et al. (2003) found concept maps to be effective learning tools with generally positive effects on knowledge acquisition. Concept mapping is especially good, in comparison to other interventions, for the learning of relationships among ideas. Concept maps can foster students' active generation of relationships between ideas presented in different contexts.

Concept maps have been investigated as learning tools in different science fields [See table 3]:

Table 3: List of studies of concept maps as science learning tools by subject.

Science (Number of studies)	**References**
Chemistry (10 studies)	Aydin, Aydemir, Boz, Cetin-Dindar, & Bektas, 2009; BouJaoude & Attieh, 2008; Brandt, 2001; DeMeo, 2007; Kaya, 2008; Liu, 2004; Markow & Lonning, 1998; Nicoll, Francisco, & Nakhleh, 2001b; Oezmen, Demircioglu, & Coll, 2007; Stensvold & Wilson, 1990; Uzuntiryaki & Geban, 2005
Physics (12 studies)	Adamczyk & Willson, 1996; Anderson, Lucas, & Ginns, 2000; Bascones & Novak, 1985; Carey & Spelke, 1994; Mistades, 2009; Moreira, 1987; Pankratius, 1990; Pushkin, 1999; Reiska, 1999; Roth, 1994; Roth, 1994; Van Zele, Lenaerts, & Wieme, 2004
Earth Science (7 studies)	Ault, 1985; Englebrecht, Mintzes, Brown, & Kelso, 2005; Hoz, Tomer, Bowman, & Chayoth, 1987; Hsu, Wu, & Hwang, 2008; Hsu, 2008; Rebich & Gautier, 2005; Snead & Snead, 2004
Biology (42 studies)	Briscoe & LaMaster, 1991; Brown, 2003; Buntting, Coll, & Campell, 2006; Burggraf, 1998; Byrne & Grace, 2010; Cakir & Crawford, 2001; Cathcart, Laura, Stieff, Mike, Marbach-Ad, Gili, Smith, Ann, & Frauwirth, Kenneth, 2010; Chang et al., 2001; Chang, 2007; Coleman, 1998; Donovan, 1983; Farrokh & Krause, 1996; Fisher, 1985; Fisher, 2001; de Groot, 1993; Heinze-Fry & Novak, 1990; Hmelo-Silver et al., 2007; Huai, 1997; Jegede, Alaiyemola, & Okebukola, 1990; Keraro, Wachanga, & Orora, 2007; Kern & Crippen, 2008; Kinchin, 2000a; Kinchin, 2001; Kinchin, De-Leij, & Hay, 2005; Markham, Mintzes, & Jones, 1993; Mintzes & Quinn, 2007; Mintzes, Wanderersee, & Novak, 2001; Novak, 1980a; Odom & Kelly, 2001a; Odom & Kelly, 2001b; Okebukola, 1992a; Okebukola, 1993; Pearsall, Skipper, & Mintzes, 1997; Preszler, 2004; Schmid & Telaro, 1990; Songer & Mintzes, 1993; Stewart, 1979; Thompson & Mintzes, 2002; Trowbridge & Wandersee, 1996; Tsai & Huang, 2002; Wallace & Mintzes, 1990; Wandersee, 1996
Ecology (2 studies)	Brody, 1993; Heinze-Fry, 1998
Astronomy (1 study)	Zeilik et al., 1997
Medicine (4 studies)	Edmondson, 1993; Edmondson, 1995; Irvine, 1995; Mahler, Hoz, Fischl, Tov-Ly, & Lernau, 1991

Concept mapping research has mainly focused on science classrooms but has been extended to include a wide variety of disciplines and contexts, for example language, mathematics, and history education (Kinchin & Hay, 2007). Study participants have ranged from elementary to college students and pre-service teachers, including middle school students (Coleman, 1998; Sizmur & Osborne, 1997), high school students (Stensvold & Wilson, 1990), college students (Heinze-Fry & Novak, 1990; Pearsall et al., 1997), and teacher credential students (Mason, 1992). Concept maps can represent very simple partial ideas to complex connected networks of ideas, which makes them usable with a wide range of learners.

For example, Kern and Crippen (2008) used embedded concept maps in a one month high school evolution unit. Using the electronic concept mapping tool Cmap (Canas, 2004), students individually generated concept maps from a given list of ideas and revised them three more times throughout the curriculum. Students received feedback from peers and the teacher. Findings indicate that embedded concept maps can support students' integration of evolution ideas and reveal conceptual change in students' understanding. This dissertation research uses a similar approach to implement concept maps but with these differences: 1) The duration of the WISE evolution unit is only five days which requires efficient concept map activities. 2) Students generate embedded concept maps collaboratively in dyads [See study 2 and 3] instead of larger groups. 3) Continuously revising concept maps throughout a unit, students might not revise their initial superstructures (Cheng, 2001; Kinchin et al., 2005). Instead, student dyads create several smaller concept maps from scratch. 4) Study 3 explores critiquing concept maps as an alternative to generating concept maps.

To track conceptual change of evolution ideas, Trowbridge and Wandersee (1994) asked college students to individually generate concept maps to summarize specific lectures. Students generated ten different concept maps from a given list and self-chosen ideas. The instructor graded all concept maps and provided feedback. Results suggest that changes in superordinate core ideas indicate conceptual changes in students' understanding of evolution ideas.

To support high school students' writing about evolution ideas, Wise (2007) used concept maps as a pre-writing activity. Concept maps were generated in dyads, while essays were generated individually. Results indicate that students' confidence in their ability to write about evolution and the quality of writing improved after using concept maps, especially for low-achieving students.

Research indicates that concept mapping as learning tools may be particularly beneficial for lower performing students (O'Donnell et al., 2002; Snead & Snead, 2004; Spaulding, 1989; Stice & Alvarez, 1987; Wise, 2007) and students with learning disabilities (Crank & Bulgren, 1993). Concept mapping activities can help low performing students to a greater degree because they model the active inquiring approach often found in higher performing students (Canas, 2003), and it can provide scaffolds for a more organized and deliberative approach to learning. The minimal number of words and propositional forms used to represent ideas in a concept map might be beneficial especially for English language learners (ELL) and students of low academic abilities (Schmid & Telaro, 1990).

2) Concept Maps as Metacognitive Tools

Concept maps can also be used as metacognitive tools that support learners by eliciting existing connections and reveal missing connections between ideas, especially cross-connections

(Shavelson et al., 2005). This can help students to reflect and contrast their existing ideas with new ideas in the learning material. It can encourage students to build on their own ideas, rather than isolate new ideas from existing knowledge. Several WISE studies found that monitoring your own learning progress through reflection encourages students to revisit and reorganize their ideas (Chiu, 2008; Chiu, 2009).

Eliciting one's understanding can promote student self-monitoring of their learning progress and support generation of self-explanations. Self-explanations as an attempt to make sense of new ideas have been found beneficial for the integration of ideas (Chi, 2000b). Ritchard et al. (2009) found that concept maps as a metacognitive tool can support student self-reflection about their conceptions of thinking and thinking processes.

Especially in less constrained concept mapping tasks [See chapter 2: Types of Concept Mapping Tasks], learners need to make decisions about which ideas and/or links to include in their map. Concept maps do not aim to include every possible idea and connection, but a careful selection [See chapter 2: History of Mapping Ideas]. Students need to generate criteria to identify and distinguish core ideas and their connections from other ideas and connections. Concept map generation and revision activities can encourage learners to revisit, reflect, and revise their existing ideas.

3) Concept Maps as Collaborative Tools

Concept maps can not only be seen as a cognitive tool that helps to elicit ideas and a meta-cognitive tool that help to support the generation of self-explanations, but also as social artifacts through which students communicate (Roth & Roychoudhury, 1993). The spatial arrangement of concept maps allows for fast information retrieval (Hook & Boerner, 2005), which can support social interaction. The high degree of explicitness makes concept maps an ideal vehicle for exchanging ideas for collaborative constructing knowledge. Several studies have reported that students who collaboratively generated concept maps achieved higher scores than those who constructed their concept maps individually (Okebukola, 1992b; Okebukola, 1989).

A social approach to concept maps emphasizes the communicative function of this inscription. Inscriptions are different forms of external representations, and are central to the construction of knowledge in scientific practice (Lehrer et al., 2000; Roth & McGinn, 1998). From a cognitive apprenticeship perspective (Collins, Brown, & Holum, 1991), it is therefore valuable for students to gain expertise constructing and interpreting inscriptions used in scientific practice [See chapter 2: Node-Link Diagrams to Elicit Ideas].

When concept maps are generated collaboratively in dyads or groups, they become shared social artifacts that elicit existing and missing connections and spur discussion among students and teachers. Both concept maps and collaborative learning have been found to have educational benefits (Canas, 2003). Combining the two could produce synergistic beneficial effects. As each proposition can consist of only one link, students are required to negotiate which connection to revise or newly generate. Berland and Reiser (2009) found that trying to persuade a peer of your ideas encourages students to support their ideas with scientific evidence.

Having to make a decision about which connection to revise or add creates an authentic need for effective criteria and supporting evidence to distinguish among ideas in students' repertoires [See chapter 2: Concept Maps as Metacognitive Tools]. Students need to determine which ideas are more effective, valuable, or more scientifically normative than others. This negotiation process is expected to encourage students to use evidence found in the curriculum to support their decision-making. This activity asks students to learn from each other and reach a shared consensus rather than just being responsible for obtaining the "right" answer from the teacher. This activity requires students to revisit their existing ideas and compare and contrast them to the new ideas introduced in the curriculum. The concept map becomes a social support for prompting students to articulate their understanding and integrate their knowledge through reflection.

4) Concept Maps as Assessment Tools

Many conventional assessment forms, like multiple-choice, true/false, and fill-the-blanks, focus on recall of isolated ideas (Ruiz-Primo, 2009). Hyerle (1996) has called for a shift in the focus of future teaching, learning, and assessment away from rote recall of "isolated things" towards recognition of "how students interactively construct the pattern that connects". Concept maps can be used as assessment tools to elicit students' connections between ideas (Edmondson, 2000; Ruiz-Primo, 2000; Stoddart, Abrams, Gasper, & Canaday, 2000; Mintzes et al., 2001). See Ruiz-Primo and Shavelson (1996) for a review of concept maps as assessment tools in science education.

Concept map assessments have been found to show varying correlation with conventional tests, depending on the type of conventional test, the concept map activity design, and the concept map scoring system (Stoddart et al., 2000) [See chapter 2: Forms of Concept Map Analysis]. More constrained forms of concept map assessment have been found to be highly correlated with multiple choice tests (Liu & Hinchey, 1993; Liu & Hinchey, 1996; Schau, Mattern, Weber, Minnick, & Witt, 1997; Rice, Ryan, & Samson, 1998). Course grades in a college biology course showed moderate correlation to concept mapping scores (Farrokh & Krause, 1996). Osmundson reported a moderate correlation between middle school essays and concept maps (Osmundson, Chung, Herl, & Klein, 1999). Since 2009, concept maps have been used in standardized large-scale assessments in the U.S. National Assessment of Educational Progress (NAEP) (Ruiz-Primo et al., 2009) to measure changes in conceptual understanding of science ideas.

Concept mapping can offer several advantages over conventional assessment forms:

1) Unlike recall oriented assessment forms, concept maps are generative forms of assessment [See chapter 2: Generation] that can also reveal partial understanding.

2) To understand and use ideas, ideas need to be connected to existing ideas.

Interconnection between ideas is an essential property of knowledge. One aspect of competence in a field is well-integrated and structured knowledge (for example see (Bransford et al., 2000; Glaser, Chi, & Farr, 1985; Novak & Gowin, 1984). Cognitive psychologists postulate that "the essence of knowledge is structure" (Anderson, 1984)(p. 5).

3). Experts and successful students develop well-differentiated and highly integrated frameworks of related ideas (Chi, Feltovich, & Glaser, 1981; Mintzes, Wandersee, & Novak, 1997; Pearsall et al., 1997). Concept maps can reveal students' knowledge organization by showing connections, clusters of ideas, hierarchical levels, and cross-links between ideas from different levels (Shavelson et al., 2005). Cross-links are of special interest as they can indicate creative leaps on the part of the knowledge producer (Novak & Canas, 2006).

4) The form of assessment directs students learning. Concept mapping can foster students' learning for conceptual understanding instead for memorization of isolated ideas. [See chapter 2: Concept Maps as Learning Tools]

5) Research indicates that concept maps can assess different kinds of knowledge than conventional assessment forms (Ruiz-Primo, 2000; Shavelson et al., 2005; Yin et al., 2005).

Concept maps as assessment tools have been used to assess prior ideas and/or changes in conceptual understanding in a wide variety of contexts (Edmondson, 2000; Mintzes et al., 2001; Ruiz-Primo, 2000; Ruiz-Primo & Shavelson, 1996). For example [See table 4]:

Table 4: Overview of research on concept maps as science assessment tools.

School Level	Science	References
Elementary School	General Science	González, 1997
Middle School	General Science	Gerstner & Bogner, 2009; Osmundson et al., 1999; Rice et al., 1998; Snead & Snead, 2004
High School	General Biology	Chang, 2007; Kinchin, 2000a; Novak, Gowin, & Johansen, 1983; Royer & Royer, 2004
	Evolution	Banet & Ayuso, 2003; Demastes et al., 1995; Wise, 2007
	Physics	Rye & Rubba, 2002; Yin et al., 2005
	Earth Science	Hsu et al., 2008
	Chemistry	Liu, 2004; Ruiz-Primo, Schultz, Li, & Shavelson, 2001; Uzuntiryaki & Geban, 2005
Undergraduate	Biology	Buntting et al., 2006; Cathcart, Laura et al., 2010; Pearsall et al., 1997
	Chemistry	Nicoll, Francisco, & Nakhleh, 2001a
	Computer Science	Acton, Johnson, & Goldsmith, 1994
	Earth Science	Rebich & Gautier, 2005
	Physics	Mistades, 2009
	Mathematics/ Statistics	Schau & Mattern, 1997
Graduate/ Post-Graduate	Medical	Bruechner & Schanze, 2004; West, Pomeroy, Park, Gerstenberger, & Sandoval, 2000
	Biomedical Engineering	Walker & King, 2002
	Research Methods	Hay, 2007
Science Teachers	Evolution	Nehm & Schonfeld, 2007; Rutledge & Mitchell, 2002

G. Concept Map Activity Design

A complete concept map activity consists of A) a concept map training phase, B) a concept map task, C) and a concept map analysis method.

1) Concept Map Training

A) Beginners often lack the skills to productively use concept-mapping tools and thus cannot exploit their full potential. O'Donnell et al. (2002) state that training is a key factor in making concept maps effective learning tools. An initial concept map training phase is important to familiarize learners with a) the concept mapping generation principles, and b) criteria for concept map evaluation (Novak & Gowin, 1984; Reader & Hammond, 1994; Shavelson, Lang, & Lewin, 1994). Ruiz-Primo (Ruiz-Primo, 2000) suggested that efficient concept map training activities could be designed.

Concept map training activities can, for example, consist of studying a worked-out concept map, generating a small map on a familiar topic, or critiquing a flawed map. Kalyuga et al. (Kalyuga, Ayres, Chandler, & Sweller, 2003) suggest that worked-out concept maps have been found effective with inexperienced learners, while more experienced learners should learn to construct their own concept maps.

2) Types of Concept Map Tasks

B) Concept mapping tasks are found in many different forms and provide different degrees of constraints. A concept map task consists of 1) a description of the task, 2) a concept map design, and 3) a concept map scoring system (Ruiz-Primo & Shavelson, 1996; Stoddart et al., 2000). The design of the concept mapping task is of importance as the task itself influences the outcome (Ruiz-Primo et al., 2001; Yin et al., 2005). The task and concept map constraints can range from less-constrained maps where students can choose their own ideas and labels to highly-constrained tasks where students select ideas from a given list to fill them into blanks in a provided skeletal network structure (Canas, 2006). Both extreme forms of concept mapping activities have advantages and disadvantages.

Table 5 suggests an overview of typical examples illustrating the broad diversity of different concept mapping tasks found in research and practice (also see (Anohina, Pozdnakovs, & Grundspenkis, 2007; Ruiz-Primo & Shavelson, 1996; Ruiz-Primo, Schultz, & Shavelson, 1997)). Concept mapping tasks can be distinguished by the degree of constraints, from few constraints (allowing students to create their own connections), to medium constraints (where student complete an existing map), to full constraints (where students study expert-made concept maps). The table distinguishes three different concept map task properties: Ideas (or concepts), labels, and links.

Table 5: Overview of typical concept map task types: X=Given on the worksheet (0 DoF), L=Given List (Word bank) (0.5 DoF), F = Free choice (1 DoF), C-F=Free Choice of Correction (1 DoF), C-L=Given List of correction options (0.5 (DoF). ***Degrees of freedom (DoF): 0=Highly constrained; 4=few constraints***

			Ideas (Concepts)	Labels	Lines	Degr. of Freedom	No.
Construct-a-map	Few Constraints	Free	F	F	F	3	1
		Lists only	L	L	F	2	2
			L	F	F	2.5	3
			F	L	F	2.5	4
Correct-a-map	Medium Constraints	Free Correction	C-F	C-F	C-F	3	5
			X	C-F	C-F	2	6
			C-F	X	X	1	7
			X	C-F	X	1	8
			X	X	C-F	1	9
		Forced Choice Correction	C-L	C-L	C-L	1.5	10
			X	C-L	C-L	2	11
			C-L	X	X	0.5	12
			X	C-L	X	0.5	13
Fill-in-maps	More Constraints	Lines Given	F	F	X	2	14
			L	L	X	1	15
			L	F	X	1.5	16
			F	L	X	1.5	17
		Ideas & Lines given	X	F	X	1	18
			X	L	X	0.5	19
		Labels & Lines given	L	X	X	0.5	20
			F	X	X	1	21
		Ideas & Labels given	X	L	F	1.5	22
			X	F	F	2	23
Study-a-map	Full constraints	Pre-made Map	X	X	X	0	24

Concept mapping tasks with few constraints provide students with a focus question while giving them free choice to select their own ideas and links. Focus questions are how- or why-questions that describe the purpose of a concept map and guide concept map generation (Derbentseva, Safayeni, & Canas, 2007). Concept maps can be seen as explanations of the focus question. Few-constraint tasks can be entirely free (see task type #1), or provide lists of link labels and/or ideas (see task types #2-4). More degrees of freedom can provide more insight into students' understanding, but make standardized comparison between students more difficult. Concept mapping tasks can start from an empty workspace, a workspace divided into horizontal hierarchy levels, or a workspace divided into specific vertical levels. In addition, a starter map can be provided to which students add additional ideas and connections.

Medium constraint forms provide students with pre-made concept maps that include errors that need correction. Students can be given free choice to make any (task type #5) or specific types of corrections (task types #6-9). Alternatively, students can be provided with lists of ideas or labels (tasks #10-13). This form of concept mapping task is explored in this dissertation research as it promises a balanced set of scaffolding constraints while allowing students to elicit their ideas [See study 2: Novel Type of Concept Map].

More constraint task forms provide students with a skeletal network structure with either blank nodes and/or unlabeled lines [Lines given: #14-17]. In addition to the network structure, nodes can contain given ideas [Ideas & Lines given: #18-19]. Students are asked to add matching link labels, either by generating their own or selecting from a given list. The opposite form provides students with a given network structure and labeled links but blank nodes [Labels & Lines given: #20-21]. Students are asked to add matching ideas to each node, either by generating their own ideas, or selecting ideas from a given list. An alternative close-ended form is to have ideas already in place, and asking students to add links and labels, either free choice or from forced choice lists [Ideas & Labels given: #22-23]. For example, "knowledge maps" (O'Donnell et al., 2002) are concept maps with a limited number of given different labels and a given network structure.

The most constrained form of concept mapping tasks is providing learners with expert-made concept maps to study as advance organizers or summaries (task type #24).

Fewer degrees of freedom allows for more standardized or even automated comparison across students. Providing more constraints can be beneficial for lower performing and younger students (O'Donnell et al., 2002). Ruiz-Primo et al. (2001) compared generating concept maps from a given list of ideas (task type #3; 2.5 DoF) to fill-the-lines (skeleton map with given ideas and list of link labels) (task type #19; 0.5 DoF) and fill-the-nodes maps (skeleton map with given lines and list of ideas) (task type #20; 0.5 DoF) [See table 5]. Results indicate that the less constrained form reflected students' knowledge structure better than the two more constrained forms. Highly constrained concept mapping forms can lead to ceiling effects that do not reveal changes in learners' understanding.

Yin et al. (2005) compared generating a map from a given list of ideas (task type #3; 2.5 DoF) to generating a more constrained map with lists of labels and ideas (task type #2; 2 DoF). The more constrained maps had lower scores, were simpler, and students needed more time to complete the activity, presumably because they had to search through label lists and idea lists. Results indicate that less constrained concept mapping forms can capture differences in students' understanding better, but are more difficult to score and compare. Too many constraints can hinder students' expression of their ideas, as they must discipline themselves to use only given ideas rather than freely follow their thought patterns (Fisher, 2000).

Concept maps activities can be implemented at the beginning, embedded, or as summative assessment at the end. Pankratius (1990) found that both treatment groups (concept map only at beginning and end vs. embedded concept mapping) performed better than the control that did not use concept maps. Results indicate that periodic embedded concept mapping can be more effective for science learning than summative concept mapping. Cheng (2001) and Kinchin (2005) noted that continuously revising embedded maps might cause students to revise propositions around the edges, but avoid revising the superstructure. Redrawing maps for revision might scaffold students to revisit and restructure their ideas. Using computer-supported concept mapping tools can facilitate revising concept maps [See chapter 3: Concept Mapping Software].

Nesbit (2006) concludes that more research on the use of concept maps is needed, especially in small group and classroom settings and as scaffolds for low performing students.

This dissertation research aims to develop and explore concept mapping forms that represent trade-offs between capturing students' rich repertoire of ideas while allowing for efficient scoring and comparison across students. Students received initial training [See chapter 2: Concept Map Training], step-by-step scaffolding, and a balanced amount of constraints for the concept map activities.

3) Forms of Concept Map Analysis

C) A concept map scoring system is a method with which students' concept maps can be analyzed accurately and consistently. Several studies established the validity and reliability of concept maps as assessment tools for science education (Wallace, 1990; Markham, Mintzes, & Jones, 1994; Michael, 1995; Ruiz-Primo et al., 1997; McClure, Sonak, & Suen, 1999a; Stoddart et al., 2000; Ruiz-Primo et al., 2001; Rye & Rubba, 2002; Shavelson et al., 2005; Yin et al., 2005). Research suggests that concept maps can assess different forms of knowledge than conventional assessment forms (Ruiz-Primo, 2000; Shavelson et al., 2005; Yin et al., 2005), for example knowledge structure and cross-connections. For overviews of concept map scoring systems, see (Stoddart et al., 2000; Nicoll et al., 2001a; Vanides, Yin, Tomita, & Ruiz-Primo, 2005; Yin et al., 2005) [See chapter 2: Concept Maps as Assessment Tools]

(i) Concept Map Analysis Overview

Literature indicates that concept map analysis is no trivial task and can use a wide variety of scoring methods. Concept maps can be analyzed either qualitatively or quantitatively. Figure 8 [See figure 8] provides an overview of different concept map analysis method.

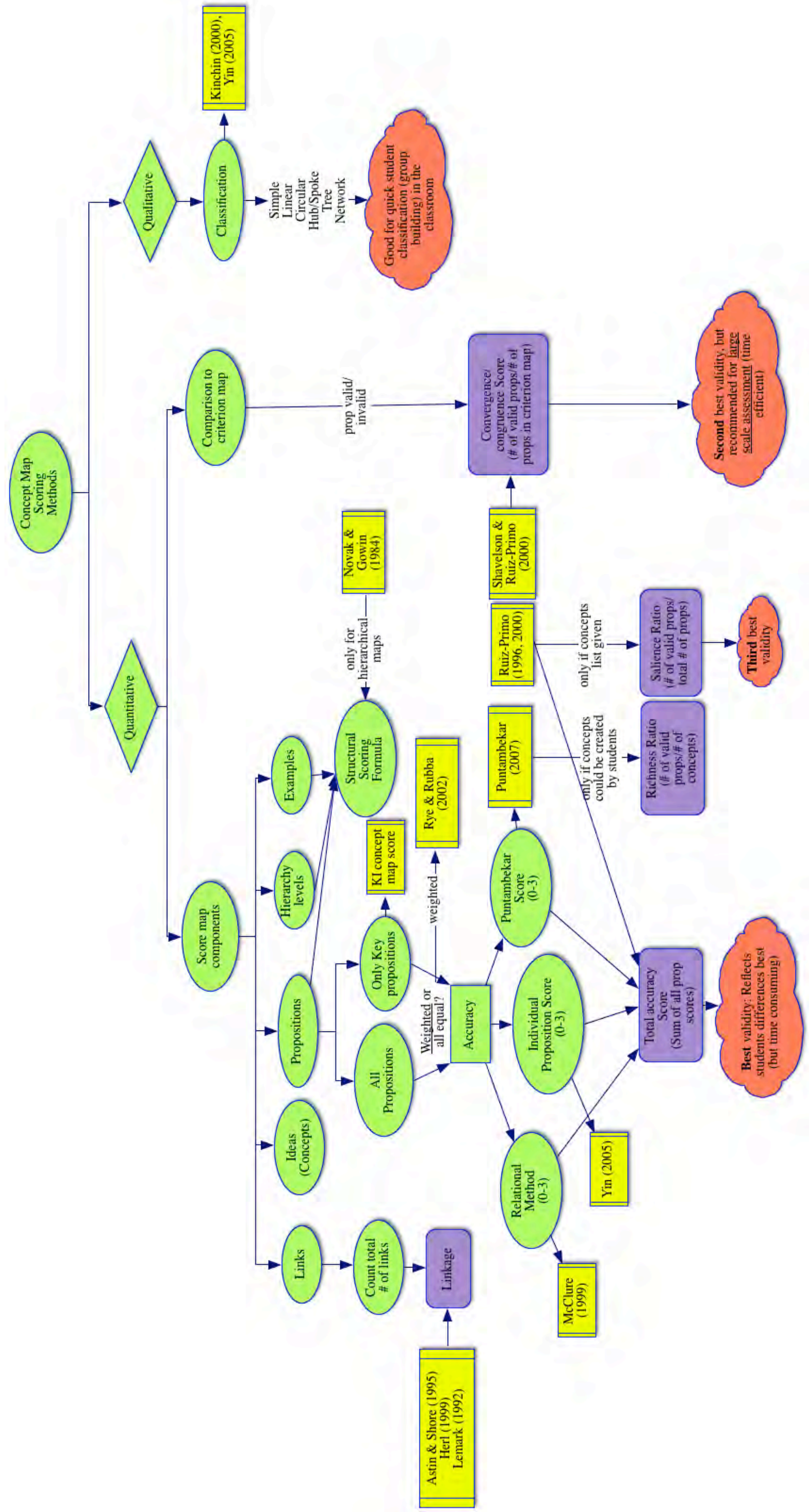


Figure 8: Overview of concept map analysis methods. [© Beat Schwendimann]

(ii) Quantitative Concept Map Analysis

The inclusion of concept maps as large-scale assessment tools, for example those used in the 2009 NAEP exam in science (Ruiz-Primo et al., 2009), requires economical as well as reliable and valid scoring methods. Several studies reported the validity and reliability of quantitatively evaluating concept maps as assessment tools (for example (Markham, Mintzes, & Jones, 1994; Ruiz-Primo, 2000; Ruiz-Primo & Shavelson, 1996; Ruiz-Primo et al., 2009; Ruiz-Primo et al., 1997; Ruiz-Primo et al., 2001; Stoddart et al., 2000; Yin et al., 2005)).

Concept maps contain several elements that can be quantitatively evaluated: Links, ideas (or concepts), hierarchy levels, and propositions. Links and ideas can be easily counted but their amount provides little insight into a student's understanding. A higher number of links does not mean that the student understands the topic better as many links might be invalid or trivial (Austin & Shore, 1995a; Herl, 1999).

Novak (1984) suggested evaluating the number of hierarchy levels. The existence of hierarchies is linked to a higher level of expertise, but hierarchy levels are difficult to differentiate and many students create non-hierarchical, but still valid maps.

Propositions, the composite of two ideas, a link label, and an arrow, are the most promising elements of a concept map to be evaluated in order to learn about students' understanding. It can be decided to evaluate all ideas equally, to weight certain propositions more than others (Rye & Rubba, 2002), or to analyze only certain core ideas (Ruiz-Primo et al., 2009). Yin (2005) showed that scoring each individual proposition on a four-point individual proposition scale, summed up to a 'total accuracy score', provided the best validity: 0 for scientifically wrong or irrelevant propositions, 1 for partially incorrect propositions, 2 for correct but scientifically 'thin' propositions, and 3 for scientifically correct and strong propositions. The 'total accuracy score' allows comparing the overall quality of students' concept maps. The disadvantage of this method is its time consumption, and equal evaluation of links that show deeper understanding and trivial links. Yin compared the total accuracy score to a second concept map scoring method, the convergence score (Yin et al., 2005). Propositions of the students' concept map are compared to an expert-generated benchmark map. The convergence score is the proportion of accurate propositions out of all possible propositions in the benchmark map. Study 1A will explore the generation of student and expert concept maps [See study 1A].

Concept maps can contain large numbers of rather trivial connections. An alternative to scoring all links is to focus only on a small number of selected links (Ruiz-Primo et al., 2009; Yin et al., 2005). Ruiz-Primo et al. (2009) suggest that scoring only essential links is more sensitive to measuring change because it focuses only on the key ideas of the concept map.

(iii) Qualitative Concept Map Analysis

In addition to quantitative propositional analysis methods, the geometrical structure of concept maps can be analyzed. For example, 1) Network analysis focuses on the connectedness of selected ideas, or 2) Topological analysis describes the overall geometrical structure of the concept map.

1) Network analysis: The network analysis strategy uses the frequency of usage of selected ideas as indicators for a more integrated understanding. As students develop a more complex understanding, they might also identify certain ideas as more important and connect them more often [See study 3]. The network analysis method is based on social network analysis

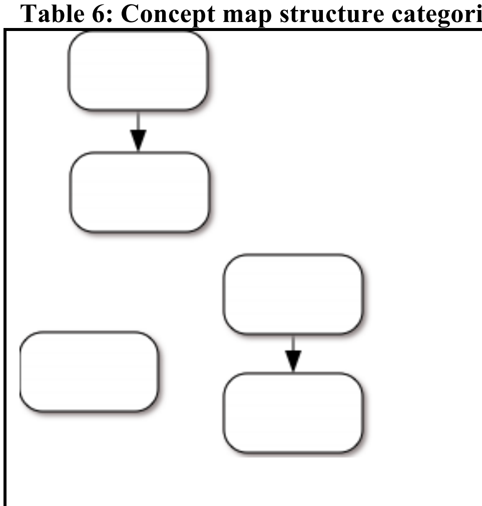
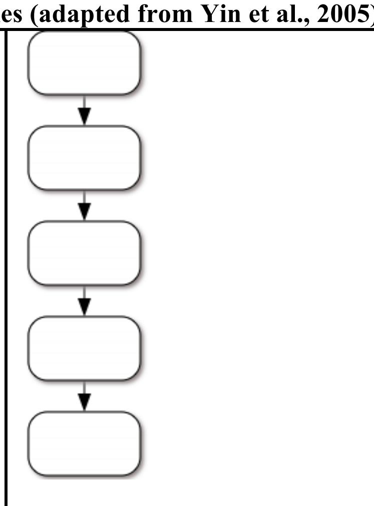
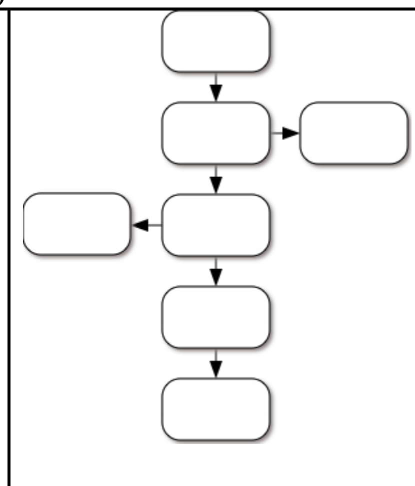
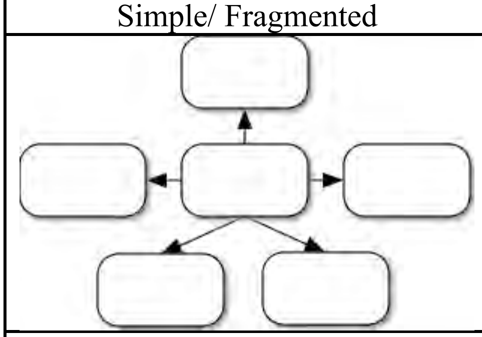
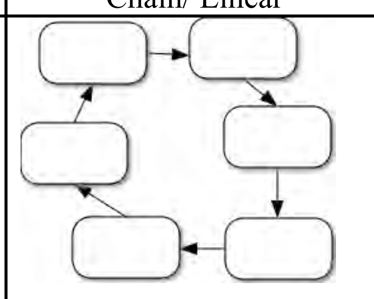
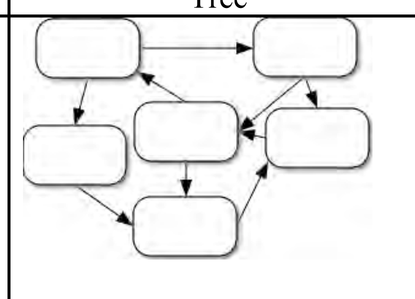
(Wasserman & Faust, 1994) (Chapter 5). Network analysis method can be used to identify changes in "centrality" (outgoing connections) and "prestige" (incoming connections) of selected indicator ideas (for example "mutation" for genotype level; and "natural selection" for phenotype level).

2) Topological analysis: Kinchin (2000b; 2001) suggested a framework of four classes (simple, chain/linear, spoke/hub, net) that refer to the major structure of a concept map. This quick way to categorize concept maps can be used at the beginning of a lesson to pair students accordingly. According to Vygotsky's 'zone of proximal development', it is beneficial to pair students of different ability levels (Vygotsky, 1978). Students who create a 'network' show a more coherent prior understanding than students who create a simple map or a chain. Yin (2005) suggested two additional classes (tree, circle) [See table 6]:

(0) Simple: Mostly isolated propositions
(1) Linear/chain propositions, which are chained together;
(2) Tree propositions, a linear chain that has branches attached;
(3) Hub or spoke propositions, which emanate from a center idea;
(4) Circular propositions, which are daisy-chained with the ends joined;
(5) Network or net propositions, a complex set of interconnected propositions.

A ranking of these categories is only possible at the extreme ends, with simple and chain at one end and networks at the other. All others classes fall in between.

Table 6: Concept map structure categories (adapted from Yin et al., 2005)

		
Simple/ Fragmented	Chain/ Linear	Tree
		
Hub/ Spoke	Circular	Network

H. Limitations of Concept Maps

Like every tool, concept maps have their strengths and limitations.

- Similar to geographical maps, concept maps do not aim to include all but only a selection of ideas [See chapter 2: History of Mapping Ideas]. This dissertation research sees concepts maps not as exact representations of a person's cognitive structure, but as a constraint and partial model thereof (Baumgartner, 2004; Trochim, 1989).
- Concept maps constrain connections between two ideas to a single relationship, which require distinguishing and selecting between multiple possible relationships.
- Students need to learn the procedure for how to generate, interpret and revise concept maps. Shavelson et al. (1994) pointed out that concept mapping can only be effective after an adequate training phase [See chapter 2: Concept Map Training].
- Generating and revising concept maps, especially less constrained forms or very large maps, can be time-intensive (McClure et al., 1999a).
- Especially less constrained concept maps can include many different kinds of ideas and connections. The amorphousness and arbitrariness of structure, mixture of different kinds of ideas (for example: physical object, process, abstract construct, property, etc.) and different types of links (for example causal, correlational, temporal, part-whole, functional, teleological, mechanical, probabilistic, spatial, etc.) can make interpretation and evaluation challenging. [See Study 3: KIM Qualitative Link Analysis].
- More constrained concept mapping forms that provide links, link labels, or ideas [See chapter 2: Types of Concept Map Tasks] can result in ceiling effects (Ruiz-Primo, 2000; Ruiz-Primo et al., 2001; Yin et al., 2005). Concept maps do not directly reveal if students understand ideas themselves, but only indirect evidence through the connections they make to other ideas or by triangulation with other artifacts. The value of concept maps might not be as assessment tools but in the process of generating and critiquing concept maps as learning tools.
- Due to space constraints, concept map link labels often describe the relationship between two ideas using a minimal number of words, for example "has", "leads to", or "lowers". In addition, generic link labels (such as "has" or "leads to") are less informative than a more elaborate explanation.
- Interpreting concept map propositions can be difficult as expert and novices might use the same expressions but with different meaning. Ariew (2003) points out that experts can use seemingly non-normative expressions as a "shorthand" for normative ideas, for example teleological expressions in biology "Beavers developed large teeth because they need to cut trees" [See study 1B].
- Concept maps often do not link to or contain supporting evidence. To better distinguish ideas, Tergan (2006) suggests using electronic concept mapping tools that allow the inclusion of supporting information in the map [See chapter 3: Concept Mapping Software].
- Concept mapping activities can be beneficial to improve conceptual understanding, but may have limited effects on basic recall (Karpicke & Blunt, 2011).
- Concept maps focus on declarative understanding, while other node-link diagram forms, for example flow charts and circle diagrams, focus more on procedural knowledge.
- Concept map analysis, especially of more constrained forms, has been found reliable and valid [See chapter 2: Concept Maps as Assessment Tools]. However, concept map analysis can be time consuming (McClure et al., 1999a).

III. Evolution Instruction

A. Instruction Design and Evolution

Science educators and researchers have developed a wide variety of instructional approaches to address learners' challenges with understanding evolution ideas (for overviews see (Demastes, Trowbridge, & Cummins, 1992; Nehm & Reilly, 2007).

A wide variety of different instructional approaches for evolution education have been developed [See overview table 7].

Table 7: Overview of evolution instruction methods.

Instructional Method	References	See also
Address students' existing alternative ideas	Banet & Ayuso, 2003; Bishop & Anderson, 1985; Bishop & Anderson, 1990; Demastes, Settlage, & Good, 1995; Jensen & Finley, 1995; Jensen & Finley, 1996a; Nelson, 2008; Settlage, 1994	[See chapter 2: Students' Ideas of Evolution]
Inquiry-based learning activities	Alters & Nelson, 2002; Crawford, Zembal-Saul, Munford, & Friedrichsen, 2005; Demastes et al., 1995; Maret & Rissing, 1998; Nadelson et al., 2009; Sandoval & Reiser, 2004; Thomson & Chapman Beall, 2008	
Technology-enhanced learning activities	Buckley et al., 2004; Crawford et al., 2005; Heitz, Cheetham, Capes, & Jeanne, 2010; Nadelson et al., 2009; Rosca, O'Dwyer, Lord, & Horwitz, 2010; Sandoval & Reiser, 2004; Tsui & Treagust, 2004; Tsui & Treagust, 2007	
Elicit differences between vernacular and scientific use of terminology (e.g. Fitness, adaptation, theory)	Bishop & Anderson, 1990; Dagher & Boujaoude, 1997	[See chapter 2: Difficult Use of Terminology]
Use concept maps as learning tools	Alters & Nelson, 2002; Demastes et al., 1995; Kern & Crippen, 2008; Kinchin, 2000a; Mackinnon, 2006; Rutledge & Mitchell, 2002; Trowbridge, 1994; Wise, 2007	[See chapter 2: Concept Mapping]

Use human evolution to teach the theory of evolution	Besterman & Baggott la Velle, 2007; Nelson, 2008; Nelson & Nickels, 2001; Thomson & Chapman Beall, 2008	[See chapter 2: Human Evolution as a Pivotal Case]
Focus on the nature of science	Alles, 2001; Alters & Nelson, 2002; Anderson, 2007; Andersson & Wallin, 2006; Dagher & Boujaoude, 1997; Passmore & Stewart, 2002; Scharmann & Harris Jr, 1992	
Modeling approaches	Lehrer & Schauble, 2004; Passmore & Stewart, 2002	
Paired-problem solving	Jensen & Finley, 1997	
Critical- thinking skills	Lawson & Worsnop, 1992; Lawson, 1990	
Ontology change	Ferrari & Chi, 1998	
Dynamic-systemic thinking	d'Apollonia, Charles, & Boyd, 2004	
Connection to everyday life experiences	Dole & Sinatra, 1998; Hillis, 2007; Bradley, 2001	
Discuss the historical development of evolutionary theory	Alters & Nelson, 2002; Jensen & Finley, 1995; Passmore & Stewart, 2002	
Evolution as a unifying theme throughout a science course	Alles, 2001; Demastes et al., 1995; Demastes et al., 1996	
Peer discussions	Nelson, 2008; Passmore & Stewart, 2002	
Discuss issues between evolution and religion	Alters & Nelson, 2002; Anderson, 2007; Jackson, 2007; Nelson, 2008; Padian, 2010; Scharmann, 1990; Wilson, 2005	

Education research found that even carefully designed curricula often had a limited impact on understanding evolution ideas. For example, Bishop and Anderson (1985; 1990) and Settlage (1994) found that instruction focused on eliciting students' alternative evolution ideas [See chapter 2: Students' Alternative Ideas of Evolution] improved understanding in some of the students. While it is encouraging that carefully designed instruction can improve some students' understanding of evolution ideas, many students' continued to choose non-normative ideas for their evolution explanations.

Despite the large number of new ideas to be learned, time for instruction in biology is short: Between 5th to 10th grade, students receive about 300 hours of biological education (Graf, 2000). Berkman (2008) found that U.S. biology teachers devote only an average of 13.7 hours to general evolutionary processes (including human evolution), with 59% allocating between three and fifteen hours of class time. Of teachers surveyed, 17% did not cover human evolution at all in their biology class, while a majority of teachers (60%) spent between one and five hours of class time on it.

Scaffolded Knowledge Integration (Linn et al., 2004) offers four pragmatic design principles for effective inquiry-based curricula by fostering adding new ideas, eliciting ideas, develop criteria, and sort out alternative evolution ideas [See chapter 2: Knowledge Integration] and [See chapter 3: Scaffolded Knowledge Integration].

B. Human Evolution as a Pivotal Case

This study proposes using human evolution as a pivotal case (Linn, 2005) to teach evolution. Pivotal cases refer to scientific examples that promote knowledge integration when added to the existing repertoire of ideas used by the students by promoting linking, connecting, and organizing of ideas to make sense of complex scientific situations. Pivotal cases promote knowledge integration by taking advantage of the interpretive, cultural, and deliberate nature of the learner (Linn, 2002).

Scientific knowledge of human evolution has special significance to us as a species because it tells us where we came from and how that affects who we are now (Alles & Stevenson, 2003). Rather than teaching human evolution at the end of evolution education, human evolution should be the starting point. Wilson (2005) states "One of the biggest tactical errors in teaching evolution is to avoid discussing humans" (p. 2060). Human evolution should be front and center in every biology curriculum, rather than being relegated to a section of its own at the back of the textbook. Typically, most curricula use examples such as Darwin's finches on the Galapagos Islands, or the peppered moth. Conceptual change research suggests that students see evolution ideas as personally relevant when they are connected to everyday experiences (Dole & Sinatra, 1998; Hillis, 2007). Understanding human evolution is often a 'sticking point' (Blackwell et al., 2003). Nelson and Nickels found that focusing on human evolution by comparing human phylogenetic trees created according to morphological or genetic criteria helped students understand humans being animals that share common ancestors with other organisms (Nelson, 2008; Nelson & Nickels, 2001).

Focusing on human evolution can address several non-normative alternative ideas: First, human evolution, and evolution in general, is not over but ongoing. Second, humans are animals and subject to evolutionary change like all other organisms. This addresses the often-found contextualization that humans are a special case in nature (Evans, 2008). Third, Besterman (2007) suggested using human examples to teach evolution as students relate better to humans than other animals. Many students have difficulties recognizing individual differences in animals that in turn support an essentialist view. On the other hand, humans are good at identifying differences among other humans. Bradley (2001) suggested the efficacy of connecting the topic of evolution to everyday observations. Using a human study could make the idea of individual genetic variation more accessible. Human evolution makes learning evolution personal as students are learning about themselves and how evolutionary history to the current state.

However, even biology teachers who address evolution in their classroom often spend little time on human evolution. Nickels identified three reasons why biology teachers often omit human evolution: 1) They run out of time as human evolution is usually at the end of the chapter.

2) Many biology teachers are less knowledgeable and confident about the topic of human evolution. 3) Many teachers try to avoid the almost certain controversy. However, omitting human evolution from the curriculum only perpetuates the idea that humans are a species "apart from" rather than "a part of" the natural world (Nickels, 1987)(p. 144). Nickels suggests to study human evolution because students posses an innate interest in learning about themselves and can relate more easily to humans than other animals or plants. If students believe that there is sound evidence that humans evolved, they will be more likely to believe in evolutionary explanations for other life forms. As human evolution has been identified as a major obstacle in understanding evolution (Nelson, 2008; Sinatra et al., 2003; Wilson, 2005), focusing on human evolution could be a promising approach.

There is little research on using human evolution as a pivotal case to teach evolution. Nickels (1987) found that learning about ourselves makes evolution more accessible as it connects to existing ideas. Alles and Stevenson (2003) argue that "what modern science can tell us about who and what we are is the most valuable knowledge we can teach our students" (p. 334). Wilson (2005) reported that a college-level course that included human evolution greatly increased students' interest in evolution. Thomson and Beall (2008) developed an inquiry-based curriculum in which students investigated hominid evolution using replica skulls of living and extinct vertebrates. They reported significant learning gains and increased interest in evolution. Evolution curricula focusing on human evolution are promising and need further research.

This dissertation research uses human evolution as a pivotal case to help students integrate their ideas to build a deep understanding of the modern theory of evolution. Using a case study of human evolution is expected to connect to students' prior ideas of human variability and to build on students' ability to observe individual differences in humans. Additionally, it may help students to reflect critically on the alternative idea that individual organisms can change their traits because they are needed to meet environmental pressures (for example, giraffes grew long necks because they had to reach leaves high up in trees) (Bishop & Anderson, 1985; Brumby, 1984; Settlage, 1994) [See chapter 7: Developing Human Evolution as a Pivotal Case].

IV. Students' Ideas of Evolution

A. Students' Alternative Ideas of Evolution

Research indicates that students can hold a rich repertoire of alternative ideas about evolution [See table 8], and human evolution [See table 9]. Additionally, students' cultural beliefs and understanding of the nature of science can also influence understanding of evolution ideas [See table 10]. Alternative non-normative evolution ideas have been observed in students of different grade levels, for example high school students (for example, (Clough & Wood-Robinson, 1985b; Deadman & Kelly, 1978; Demastes et al., 1995), undergraduate college students (for example, (Alters & Nelson, 2002; Bishop & Anderson, 1990; Dagher & BouJaoude, 1997b; Ranney & Thanukos, 2009), undergraduate biology students (for example, (Dagher & Boujaoude, 1997; Grose & Simpson, 1982), and post-graduate science students (Gregory & Ellis, 2009). Bishop (1990) observed that a majority of students held ideas that differed from accepted biological theory. Even after instruction, many students continued to use alternative non-normative ideas such as changes in traits because of need-driven adaptive processes, and gradual change of traits in all members of a population [See chapter 2: Individual Variation vs. Essentialism]. Even many first-year medical students, characterized as among the most successful science students in Australia, embraced Lamarckian and teleological ideas (Brumby, 1984) [See a more detailed discussion about students' different alternative evolution ideas in chapter 2: Understanding Evolution]. Knowledge integration explains that new more powerful ideas, like evolution, are more difficult to integrate if alternative ideas have already been used for long periods of time in a variety of contexts (Linn, 2008). Evolution instruction needs to help students distinguish between normative and alternative ideas and apply the new idea in different contexts. According to the knowledge integration view, learners need support to elicit their alternative ideas and distinguish them based on evidence. Crawford et al (2005) found that the technology-enhanced inquiry-based learning curriculum (Sandoval & Reiser, 2004). The Galapagos Finches (BGuILE) helped pre-service teachers improve their understanding of evolution ideas. There seems to be a strong need for well-designed curricula on evolution.

Table 8: Students' alternative ideas about the theory of evolution.

Alternative Idea	References	See also
Organisms change because of need.	Alters & Nelson, 2002; Anderson, Fisher, & Norman, 2002; Anderson, Randle, & Covotsos, 2001; Bishop & Anderson, 1985; Bishop & Anderson, 1990; Brumby, 1979; Brumby, 1984; Catley, K. M., 2001; Clough, 1994; Cummins et al., 1994; Demastes et al., 1996; Greene, 1990; Halldén, 1988; Jensen & Finley, 1996b; Kargbo et al., 1980; Lawson	[See chapter 2: Need]

	& Thomson, 1988; Lucas, 1971; Passmore & Stewart, 2002; Rudolph & Stewart, 1998; Shtulman, 2006; Sinatra et al., 2008; Sinatra et al., 2003; Southerland, Abrams, Cummins, & Anzelmo, 2001; Stewart, 2001; Tamir & Zohar, 1991	
Organisms change because of use/disuse of traits.	Alters & Nelson, 2002; Bishop & Anderson, 1990; Brumby, 1979; Brumby, 1984; Deadman & Kelly, 1978; Demastes et al., 1995; Hallden, 1988; Jensen, Settlage, & Odem, 1996; Kargbo et al., 1980; Samarapungavan & Wiers, 1997	[See chapter 2: Use or Disuse]
Organisms change because of intentions (intentionality).	Alters & Nelson, 2002; Evans, 2000; Evans, 2001; Evans, 2008; Inagaki & Hatano, 2008; Kelemen, 1999; Kelemen, 2003; Sinatra et al., 2008	[See chapter 2: Intentionality]
Evolution happens to individuals or Evolution happens to all individuals of a species (essentialism)	Alters & Nelson, 2002; Bishop & Anderson, 1985; Bishop & Anderson, 1990; Boster & Johnson, 1989; Brumby, 1979; Brumby, 1984; Catley et al., 2005; Crawford et al., 2005; Evans, 2008; Greene, 1990; Inagaki & Hatano, 2008; Jensen & Finley, 1995; Moore et al., 2002; Samarapungavan & Wiers, 1997; Sandoval & Reiser, 2004; Settlage, 1994; Shtulman, 2006; Shtulman & Schulz, 2008; Srinivasan Shipman & Boster, 2008	[See chapter 2: Individual Variation vs. Essentialism]
Confusion of scientific and vernacular use of evolution terminology (e.g. Fitness, adaptation, theory)	Bishop & Anderson, 1990; Dagher & Boujaoude, 1997	[See chapter 2: Difficult Use of Terminology]
Environment causes evolution.	Alters & Nelson, 2002;	

	Bishop & Anderson, 1990; Jensen & Finley, 1995	
All mutations are harmful.	Bixler, 2007; Cho, Kahle, & Nordland, 1985; Nehm & Reilly, 2007	
Other sources besides mutations and recombinations cause genetic diversity.	Brumby, 1979; Clough & Wood-Robinson, 1985a; Hallden, 1988	[See chapter 2: Alternative Ideas for Sources of Variation]

Table 9: Students' alternative ideas about human evolution.

Alternative idea	References	See also
Humans are a special case (human exceptionalism), e.g. Evolution for humans is over; humans are not subject to evolution.	Brem et al., 2003; Evans, Stewart, & Poling, 1997; Jensen et al., 1996; Nelson, 1986; Poling & Evans, 2004; Ranney & Thanukos, 2009; Sinatra et al., 2003	[See chapter 2: Contextualization and Human Exceptionalism] [See chapter 2: Human Evolution as a Pivotal Case]
Humans are descendants of monkeys or apes.	Dagher & Boujaoude, 1997; Dagher & Boujaoude, 2005	
Humans are the end result of evolution.	Dagher & Boujaoude, 1997; Jensen et al., 1996	

Table 10: Students' alternative ideas about the nature of science.

Alternative idea	References	
Evolution is “only” a theory	Alters & Nelson, 2002; Dagher & Boujaoude, 1997; Dagher & Boujaoude, 2005; Evans, 2008; Ferrari & Chi, 1998; Graf & Soran, 2010; Halloun & Hestenes, 1998; Johnson & Peeples, 1987; Lawson & Thomson, 1988; Lawson & Worsnop, 1992; Lombrozo, Thanukos, & Weisberg, 2008; Nehm & Reilly, 2007; Nelson, Nickels, & Beard, 1998; Rudolph & Stewart, 1998; Scharmann, 1990; Scharmann & Harris Jr, 1992; Songer & Linn, 1992	
Evolution explains the origins of life	Rice, Warner, Kelly, Clough, & Colbert, 2010	[See chapter 2: Levels of Understanding Evolution]
The theory of evolution is a question of belief.	Anderson, 2007	

B. Nature of Evolution Ideas

1) Evolution Ideas on Different Levels

Integrating evolution ideas is challenging because the modern theory of evolution consists of a complex network of ideas from different science fields and different levels (for example (Boggs et al., 2003; Catley et al., 2005). [See chapter 2: History of Modern Theory of Evolution] This suggests that a well-designed evolution curriculum should focus on eliciting the connections between ideas from different disciplines that contribute to the theory of evolution.

One main reason why evolution is difficult to learn is because it requires connecting ideas across multiple interacting levels (Wilensky & Resnick, 1999; Duncan & Reiser, 2007; Hmelo-Silver et al., 2007). An integrated understanding of evolution requires simultaneous thinking in and connecting ideas across different levels, for example non-observable underlying genetic processes and observable selection processes. Rather than understanding isolated ideas, learning about evolution requires integrating related ideas (Catley et al., 2005). Research suggests that students have difficulty connecting ideas across different levels (Hmelo et al., 2000; Marbach-Ad, 2000b; Penner, 2000).

Different levels, for example phenotype or genotype, use different vocabulary, and focus on different (but related) ideas. The distinction between phenotype and genotype levels is fundamental to the understanding of heredity and development of organisms (Mayr, 1988b). Bishop (1990) found that a majority of college students failed to recognize the distinction between the two distinct processes: The origin of new traits through mutation and recombination (genotype ideas) and selection by environmental factors (phenotype ideas). Connections are often not explicit in curriculum material. Additionally, the current curriculum structure in many schools teaches genetics and evolution in an isolated way that does not facilitate students to constructing links between these levels.

In order to form coherent understanding in biology, students need to integrate their various ideas about biology. Research on learning suggests that students hold a repertoire of loosely connected ideas, rather than internally consistent scientific theories, and that students often fail to connect ideas from one context to another (diSessa, 1988). Students can hold many alternative explanations for evolution, even after instruction (Bishop & Anderson, 1990; Alters & Nelson, 2002; Anderson et al., 2002). For example, many students construct teleological explanations for changes in the phenotype and fail to connect them to the underlying genotype events (mutations). The goal of instruction is to support students to make their existing alternative ideas and the connection between them explicit, critically sort them out by comparing them against scientific evidence, and apply scientific ideas more frequently in multiple contexts.

In addition to separating ideas by level, students often contextualize ideas by organism, for example students' explanation for evolution varies by organism [See chapter 2: TO WHOM does evolution happen?]

The different ideas that students need to integrate to build a coherent understanding of the modern theory of evolution are discussed in more detail in the following sections.

2) Nature of Evolution Phenomena

Evolution ideas are difficult to understand because they are emergent (d'Apollonia et al., 2004; Chi, 2005) and require statistical thinking that is not commonly used in everyday life. The two kinds of explanations that people are most familiar with are intentional ones and simple mechanical ones (Thagard & Findlay, 2010) (also see (Grotzer, 2003)). Humans frequently use intentions in social situations to predict actions of living organisms (Hatano, 1994; Inagaki & Hatano, 2002; Inagaki & Hatano, 2008) [See chapter 2: Intentions; Need]. Many everyday physical phenomena follow simple cause-effect rules. In contrast, the theory of evolution describes biological processes that are inherently statistical and emergent which can contradict existing (intuitive) ideas. Understanding evolution requires what Ernst Mayr called "population thinking" which refers to thinking about statistical chances in a population instead of typological thinking about changes in the essence of a species (Mayr, 1982) [See chapter 2: Individual Variation]. Evolutionary changes cannot be directly observed, as they are often slow and occur over many generations.

In addition to statistical thinking, students need to understand emergent properties of a system (Chi, 2005; Slotta & Chi, 2006). Properties of emergent systems are found in the behavior of the overall system but not in any of the system's parts (Bunge, 2003). For example, the occurrence of a new phenotypic trait in a gene pool is an emergent property arising from the combination of small genetic changes in a few individuals and more successful survival and reproduction of those individuals. To understand emergent phenomena such as evolution, students need to understand the underlying processes and their interactions, for example the connection between selection processes and sources of diversity. This dissertation research investigates the use of concept maps to elicit alternative evolution ideas and their connections [See chapter 2: Concept Mapping].

C. Understanding Evolution

1) TO WHOM does evolution happen?

(i) Contextualization and Human Exceptionalism

Many people seem to accept and understand evolution in a piecemeal fashion and only in limited contexts. There appear to be two walls of resistance, one denying the theory altogether and the other denying its relevance to human affairs (Wilson, 2005). Human evolution is often considered a special case different from other animals or plants (human exceptionalism) (DYG, 2000; Gallup, 2008). Contextualizing the process to human evolution does not allow people to understand the universality of evolution and the common ancestry of all life on earth. Many people, from young students to college students and parents, see human evolution as an exception and special case (Nelson, 1986). To integrate evolution ideas, students need to understand to whom evolution happens. For scientists, evolutionary change happens continuously to all organisms, from bacteria to plants and animals (which include humans). Many students contextualize evolution ideas according to different organisms (species-specific reasoning). Contextualization of ideas is a central property of the knowledge in pieces perspective of learning (diSessa, 2008). The contextualization of evolution ideas by organism might be influenced by different factors. Students might identify more with organisms that are familiar to us and be reluctant to invoke the ravages of natural selection upon species they feel empathy for (Jensen et al., 1996). Students might see intelligent organisms as being able to outwit natural selection with their behavior.

Wilson noted that “There appear to be two walls of resistance, one denying the theory [of evolution] altogether and the other denying its relevance to human affairs” (Wilson, 2005)(p 2058). Students might accept evolution happening to non-human organisms, but often reject evolution for humans. On the other hand, students might attribute human evolution to human conscious efforts (Bizzo, 1994) and a desire for human self-determination over natural selection forces outside of our control (Ranney & Thanukos, 2009).

Several studies investigated how students contextualize evolution of different organisms. Jensen (1996) found that U.S. college students did not consistently apply the idea of natural selection. Students contextualized alternative ideas about natural selection for different non-human organisms. Brem (2003) found that many US college students who favor creationist ideas believe that humans were created while non-human organisms evolved. Ranney (2009) studied college students’ belief in evolution of plants, animals, and humans. Participants were more accepting of evolutionary explanations for plants than for humans. Besides organism-depended contextualization, students’ overall attitude towards evolution, biological knowledge, and item characteristics influenced students’ use of alternative ideas of natural selection. Evans (1997) found that US parents are less likely to explain human origins to their children in terms of evolution than they are to explain dinosaur origins. Sinatra and Southerland (2003) also observed that belief in evolution is often contextualized depending on the organism. They found a significant relation between understanding and reported belief in photosynthesis, but not for animal or human evolution. Sinatra suggests that understanding is linked to belief when the topic is perceived to be less controversial or less ambiguous (as is the case of photosynthesis) than human evolution. Poling and Evans (2004) found that school children and lay adults were reluctant to accept that extinction may be inevitable for all species, especially in the case of human extinction. On the other hand, evolutionary biologists interviewed for the study endorsed the possibility of human extinction.

Understanding and accepting to whom evolution happens requires connecting several ideas [See chapter 2: Integrating Evolution Ideas].

The first idea in the TO WHOM-column is the understanding that evolution happened and continues to happen. The (false) idea that humans do not (or no longer) evolve is an important barrier to accepting evolution (Nelson, 2008). Before the introduction of Darwin’s theory of evolution, most people believed organisms to be unchanging as originally created by God. Darwin and many other scientists showed that organisms change from one generation to the next. This links the idea to the basic idea of the HOW-column, understanding individual variation.

The second idea in the TO WHOM-column is that humans are a part of the animal kingdom. For millennia, humans have regarded themselves as categorically different from other creatures in their mental, moral, and aesthetic abilities (Wilson, 2005). When speaking about organisms, many people refer to "humans, animals, and plants", giving humans a special status. This contextualization of evolution places humans in a separate category. Humans are either seen as being God's special creation, the pinnacle of creation (or the evolutionary "ladder"), or being rational beings that can control their evolution intentionally. Science found that humans belong to the animal kingdom and share common ancestors with other primates, mammalia, vertebrata, chordata, animalia, and eukaryota. As all cellular life on earth, humans share the same genetic code. Evans (2008) found that accepting humans as an animal is an important cognitive barrier to accepting evolution.

The third idea in the TO WHOM-column is that evolution happens to all organisms, including humans. This idea connects to the previous three ideas and can only be understood if all ideas are integrated with each other.

2) HOW does evolution work?

(i) Alternative Ideas of Evolution

To understand evolution ideas learners need to understand TO WHOM evolution happens and HOW evolution happens. Students can have a rich repertoire of ideas about how evolution happens that can consist of a complex mixture of, for example Lamarckian, Darwinian, and teleological ideas (Brumby, 1979; Brumby, 1984; Deadman & Kelly, 1978; Hallden, 1988; Jensen et al., 1996). Ideas learners hold can differ from scientific ideas (for example (Mayr, 1982)) in many different ways (for a review of alternative evolution ideas, see for example (Catley et al., 2005).

Alters (2002) identified three major differences between students' understanding of HOW evolution happens:

- The environment changes traits: Teleological/Lamarckian ideas (change because of need; change because of use or disuse) [See chapter 2: Use or disuse; Need; Intentionality].
- No connection between genetic variation and evolution. Bishop (Bishop & Anderson, 1990) observed that many students do not recognize the connection between random changes in genetic material (mutations, sexual recombination) and selection by environmental factors (natural selection) [See chapter 2: Evolution Ideas on Different Levels].
- Essentialism: Students understand evolution as change in a whole species, instead of variation among individuals. Evolution is seen as gradual change in traits instead of changing proportions of individuals with certain traits (population genetic view). Many students do not distinguish individual variations, but understand evolution as a process that shapes the species as a whole. E.g. "The cheetahs had to run fast and gradually their muscles adapted to this." [See chapter 2: Individual Variation vs. Essentialism]

Education research identified numerous other alternative ideas students might hold about the nature of science, to whom evolution happens to, and how evolution works [See chapter 2: Integrating Evolution Ideas]. Commonly found alternative ideas in each of these three issues will be discussed in the following paragraphs.

(ii) Individual Variation vs. Essentialism

The first idea in the HOW-column is that organisms of the same species have individually varying traits. Many students tend to think "typologically," they see individuals as representative of an entire population (Greene, 1990). Such a view can make it difficult to see the importance of individual variation, which is crucial to understanding the explanatory power of the theory. A typological view is often connected with an essentialist view of evolution. Students who hold the idea of "essentialism" understand evolutionary change not as individual variation but as changes to the "essence" of a species (to all members of this species). If students consider change in a population that they define as a stable type, then individuals are seen as essentially alike and variations will have little importance. Change will be seen as being generated when it is needed, since variations in the population are only imperfections from the type and are not part of the change process itself. Students have difficulties understanding that evolutionary change results from the survival and reproduction of a few individuals, not from the gradual change of all individuals (their "essence") in a population. Students holding this alternative idea give explanations like "Insects become more resistant" instead of "More insects become resistant" (Brumby, 1979). Evans (2008) and Inagaki (2008) reported that young children hold essentialist ideas that continue to exist even as they learn to distinguish individual differences. Samarapungavan noted that "It is likely that the lack of attention to within species variability will make it hard for many novices to restructure to Neo-Darwinian theory" (Samarapungavan & Wiers, 1997).

Perhaps one of the sources of essentialism is students' tenuous grasp of the mechanisms of natural selection and random variation, especially mutation (Catley et al., 2005). Settlage (1994) found that part of students' difficulty can be attributed to their poor understanding of variation and of mutation acting in populations. Also, students fail to recognize that variations must already exist to be selected (Bishop & Anderson, 1985; Brumby, 1984; Settlage, 1994). Instead, many students hold the idea that individual organisms change their (inheritable) traits during their lifetime in response to environmental pressures (for example, giraffes grew long necks because they had to reach leaves high up in trees).

Shtulman (2008) found that essentialism leads students to devalue within-species variation and, consequently, to fail to understand natural selection. Studies found evidence that conceptualizing species in terms of essences (inner natures) is an impediment to understanding evolution by natural selection (Shtulman, 2006; Shtulman & Schulz, 2008). Green found that students who adopted the idea of populations being a repository of many variations showed a better understanding of natural selection (Greene, 1990).

A major intellectual advance, first used by Darwin, was the use of population rather than typological thinking (Mayr, 1984). For Mayr, Darwin's theory of evolution by natural selection was not simply a new theory, but a new kind of theory - one which discredited essentialist modes of thought within biology and replaced them with what Mayr has called "population thinking" (Sober, 1980). To critically evaluate and sort out typological and essentialist ideas, learners need to recognize individual differences between members of a species and understand evolution not as a gradual change in essence but as a statistical phenomenon that describes changes in allele frequencies in a population over time. Sandoval and Reiser (2004) found that middle school students need to learn to think about individual variation as a precursor to understanding natural selection. Also, students need to learn to discern inheritable and non-inheritable phenotypic traits, which requires learning about inheritance and the relationship between genotype and phenotype [See chapter 2: Use or Disuse]

Recognizing individual differences in animals (for example (Boster & Johnson, 1989)) or plants (for example (Srinivasan Shipman & Boster, 2008)) can be difficult for novices and need to be learned. To the untrained eye, many animals or plants of the same species look alike. This study proposes that using humans as a case study could facilitate recognizing individual differences, as humans are well versed in detecting differences among ourselves [See chapter 2: Human Evolution as a Pivotal Case].

(iii) Inheritance and Genes

The second idea in the HOW-column is the understanding of which individual traits can be passed on to the next generation. Genetics has become an integral part of the modern theory of evolution.

Over the past decade, researchers have found that genetics is a conceptually difficult topic to teach and learn (Bahar et al., 1999). A number of studies documented students' alternative ideas about genetics (Demastes et al., 1992; Hallden, 1988; Jensen & Finley, 1995; Kargbo et al., 1980). Many students do not understand the mechanism of inheritance through which traits can be passed on, often believing that acquired characteristics can be inherited (Sandoval, 2003). Deadman and Kelly (1978) found that students come to the study of evolution with many alternative ideas, such as adaptation being an individual's inherited response to environmental change.

To understand inheritance ideas, students need to learn about the differences between inheritable phenotypic traits caused by genes and non-inheritable phenotypic traits caused by the environment. Many students understand genes as "trait-bearing particles" (Lewis & Kattmann, 2004) that directly control or contain phenotypic traits. Students who hold such a view do not see a necessity to distinguish between phenotype and genotype. Genes are difficult to understand because of their dual ontology, being both a physical particle and genetic information (Duncan & Reiser, 2007). Shea suggested that students need to learn about the role of proteins as the connecting element between genes and phenotypic traits (Shea & Golan Duncan, 2010).

(iv) Variation and Selection

The third element of the HOW-column consists of two intricately connected ideas that form the core of understanding evolution: First, where do individual variations come from (genotype level ideas), and second, how do individual variations get selected (phenotype level ideas). A major hindrance to understanding evolution seems to be students' inability to integrate two distinct processes in evolution: The occurrence of new traits in a population, and their effect on long-term survival (Bishop & Anderson, 1990).

(a) Alternative Ideas for Sources of Variation

To understand the source of variations, students need to focus on the genotype level: Random mutations in gametes and sexual recombination lead to individually different new variations of traits in organisms in the next generation. Young children to adults have trouble reasoning about random phenomena, such as random mutations (Metz, 1998).

Research has found that learners can hold a rich repertoire of alternative ideas of why traits of organisms change over time, such as “need”, “intentions”, “use or disuse”, or divine control (Bishop & Anderson, 1990). Several decades of research suggest that students’ often continue using ideas of goal-oriented and need-directed evolution even after extensive instruction (Lucas, 1971; Brumby, 1979; Kargbo et al., 1980; Brumby, 1984; Bishop & Anderson, 1985; Halldén, 1988; Lawson & Thomson, 1988; Bishop & Anderson, 1990; Greene, 1990; Clough, 1994; Cummins et al., 1994; Demastes et al., 1996; Jensen & Finley, 1996b; Rudolph & Stewart, 1998; Anderson et al., 2001; Catley, 2001; Southerland et al., 2001; Stewart, 2001; Anderson et al., 2002; Passmore & Stewart, 2002; Sinatra et al., 2003). Settlage (1994) found that more than half of fifty randomly selected high school students expressed teleological (need) or Lamarckian (use or disuse) ideas. Even after instruction, only ten percent of students used the normative idea of genetic mutations. Bishop and Anderson found similar results in university students (Bishop & Anderson, 1985).

Students have limited understanding that random mutations and recombinations alone are the cause for new heritable characteristics (Brumby, 1979; Hallden, 1988; Clough & Wood-Robinson, 1985a). Mutations can be challenging to understand as the idea of mutation can be used in different ways: First, mutation is the process of errors occurring in the genetic material. Second, mutations are the location on the DNA where a change happened. Third, mutation can also describe the state of DNA, for example a mutated DNA sequence. Many students hold the non-normative idea that mutations can fundamentally alter a current organisms’ phenotype and are inherently negative, which might have been influenced by the portrayal of evil mutants in movies (for example (Bixler, 2007)).

Also, students fail to recognize that variations must already exist to be selected (Bishop & Anderson, 1985; Brumby, 1984; Settlage, 1994). Instead, many students believe that individual organisms change their traits during their lifetime in response to environmental pressures (for example, giraffes grew long necks because they had to reach leaves high up in trees).

This study proposes that in order to understand where change in population comes from, students need to integrate the genotype ideas of sources of genetic diversity by connecting them to phenotype level ideas.

(b) Evolution and Development

Evolutionary theory is difficult to understand because it is, to some degree, counterintuitive (Wolpert, 1994). Ernest Mayr pointed out that “Evolution, in a way, contradicts common sense” (Mayr, 1982) (p. 309). Evans (2008) noted “Evolutionary theory is probably one of the most counterintuitive ideas the human mind has encountered, so far” (p. 270).

Our intuitive ideas are formed throughout our childhood. Piaget’s genetic epistemology (Piaget, Gruber, & Vonèche, 1977) describes how children’s ideas develop over the years: In an early realism stage, a child is egocentric and does not draw a distinction between him and the external world. A young child’s world is filled with tendencies and intentions. The ideas “need”

[See chapter 2: Need] and “intentionality” [See chapter 2: Intentionality] as the driving forces for change are established in early childhood as a way to distinguish living from non-living objects (Hatano, 1994; Hatano et al., 1993; Inagaki & Hatano, 2002; Inagaki & Hatano, 2008). Children develop early an understanding of biology, for example they develop their own criteria to distinguish living from non-living things (Keil, 1994) by attributing to them a vital force (Inagaki & Hatano, 2002) or goal-directed behavior (Carey, 1985). However, research into naive psychology (Inagaki, 1997) has found that humans start early on to project human properties to non-human entities. Human brains are set to understand goal-oriented behavior. This trait is shared with other primates who live in communities (Evans, 2008).

Over time, learners can add scientifically normative ideas to their repertoire, but even adults will never completely extinguish their intuitive ideas (diSessa, 2007; Mintzes & Quinn, 2007; Linn, 2008). At every stage of the conception of nature there remain fragments of intuitive ideas (Piaget et al., 1977). Fragments of these early views can often influence explanations of biological phenomena. Evolutionary explanations of children and adults often show aspects of animism or finalism: Things happen because they are needed (for the good of men (anthropocentric) or other purposes) or because they were intended to happen (Inagaki & Hatano, 2008). Adults differ from children mostly by having added additional ideas to their repertoire and by having developed criteria to sort out ideas to apply in a certain context (Evans, 2008).

Inagaki (2008) found that the powerful new ideas of modern evolution theory do not develop spontaneously, but need to be taught. Children’s’ intuitive ideas often resemble Lamarckian or Creationist ideas. In this sense, scientific evolution ideas may seem counter-intuitive as they contradict existing intuitive ideas of changes because of need, intention, use or disuse, or a divine plan. From a conceptual change perspective, learning is seen as a shift in preference for certain alternative ideas. Knowledge Integration aims to help learners to add, connect and distinguish, and select scientifically normative ideas over intuitive non-normative ideas (Linn & Hsi, 2000) [See chapter 2: Knowledge Integration].

(c) Use or Disuse

The single most frequently used alternative ideas to Darwinian evolution are Lamarckian ideas (Demastes et al., 1995; Jensen & Finley, 1996b). The French zoologist Jean Baptiste de Lamarck proposed a theory for evolutionary change based on three ideas: First, internal intentional forces drive an organism’s adaptation, second, phenotypic traits change because of frequent use or disuse, and third, such acquired traits are inheritable and can be passed on to the next generation (Bowler, 1992).

Many students, from young children to college level, hold the idea that that evolution is the result of trait use or disuse and that acquired traits are passed down from one generation to the next (Bishop & Anderson, 1990; Samarapungavan & Wiers, 1997). Lamarck’s first idea resonates with the intuitive anthropomorphic ideas of changes due to need or intention [See chapter 2: Evolution and Development]. Knowledge Integration predicts that such old intuitive ideas that have been frequently used in different contexts become more integrated and are more resistant to change.

Lamarck's second idea builds on the intuitive idea of changes of phenotypic traits because of use or disuse. For example, cave salamanders became blind because they did not use their eyes in the dark cave. Another reason for the frequent use of Lamarckian' ideas could be students' focus on teleological instead of ultimate reasons: Many students see the explanation of the function of a certain trait as a sufficient explanation in and of itself of how the trait evolved (Bishop & Anderson, 1990).

Lamarck's third idea builds on a lack of understanding of inheritance [See chapter 2: Inheritance and Genes]. Students tend to confuse non-inherited adaptations acquired during an organisms' lifetime (phenotypic changes) with adaptive changes that are inherited in a population (genotype changes) (Kargbo et al., 1980). Bishop (1990) found that a majority of college students held Lamarckian ideas that acquired traits can be inherited. Bishop explains students' preference for this non-normative alternative idea partly because students do not understand the connections between genotype (sources of genetic diversity) and phenotype (selection) ideas.

(d) Need

Teleological ideas are central ideas in people's reasoning about evolutionary change (Shtulman, 2006; Southerland et al., 2001; Tamir & Zohar, 1991). Aristotle coined the term "teleology" (Aristotle & Lawson-Tancred, 1998) to refer to the purpose of nature (Sinatra et al., 2008). Seeing biological phenomena, for example a certain behavior or physiological trait, through a teleological lens means reasoning about what "need" led to this phenomenon. Merriam-Webster defines needs as "a physiological or psychological requirement for the well-being of an organism; a condition requiring supply or relief. Behavior towards fulfilling a need leads to purposeful directed action." This dissertation research distinguishes between two related ideas of "need" and "intention." Need-based reasoning sees the organism in a passive role to which things happen because they are needed by the organism. Intentionality-based reasoning sees organisms in an active role in which they make things happen according to their will [See chapter 2: Intentionality].

It can be seen as one of Darwin's greatest achievements to show that Aristotle's idea of teleology, the so-called fourth cause, does not exist. Darwin's theory of evolution by natural selection replaced theological, or supernatural, science with secular science (Mayr, 2002). However, the scientific view of evolution is often opposed to existing ideas. Need-based ideas are established in early childhood and become intuitive ideas in our repertoire. Things change because they are *needed* relates to Piaget's finalistic idea (Piaget et al., 1977): The end-goal or the function of an object explains its existence. For example, "Humans have opposable thumbs so that they can hold objects better" or ' "Cheetahs need to run fast to capture their prey, so they developed faster running skills." This functional explanation states that opposable thumbs and the ability to run faster appeared because their function was required.

It is difficult to distinguish different uses of teleological ideas. Explanations can for example use anthropomorphic (bacteria have ''shown considerable ingenuity in developing resistance to antibiotics''), teleological (''cacti developed tough skin because it was needed to minimize water loss''), or progressive alternative ideas (''humans are higher on the evolutionary scale than chimps'') (Anderson et al., 2002). Jungwirth (1975) and Ariew (2003) argued that experts as well as novices frequently use alternative ideas. However, experts are more likely to use them metaphorically as short-hand for scientific processes rather than literally, which might additionally confuse novices. Teleological ideas can be used as an anthropomorphic lens to see deliberate patterns in non-directed phenomena (Ochs, Gonzales, & Jacoby, 1996). Humans tend to project human motivation to non-human organisms and inanimate objects when reasoning about their form and function. Humans intuitively search for a pattern or an organizing will behind phenomena, for example human need or a divine plan.

However, many learners do not distinguish acquired behavior (phenotype) from genetically determined traits (genotype) when using teleological ideas. The misconception lies in that acquired behavior is not inheritable. While learned behaviors are indeed need-based, many phenotypic traits are genetically determined. While need-based behavior is a contributing factor to the survival of an organism, and therefore part of natural selection, it does not alter the genetic material accordingly. Mutations in sex cells do not occur directed to meet a certain need of the current or next generation. The different usages of teleological ideas in different contexts can add to the difficulty for learners to distinguish ideas.

Teleological ideas are opposed to the normative view that evolutionary changes are not goal-directed and happen because of the interplay between random mutations and non-random natural selection. Biologists describe natural selection as being neither teleological (goal-directed) nor deterministic (Mayr, 2002) (p. 121). Teleological ideas, however, might be connected to the misconception that evolution is goal-directed and eventually leads to perfect adaptations. Scientific ideas of non-directed evolutionary change can appear counter-intuitive to the learner as they can contradict prior existing intuitive ideas of need. Introducing learners to counter-examples such as genetic drift, neutral mutations, and vestigial organs might support eliciting alternative ideas.

Southerland (2001) identified need as a “phenomenological primitive” (p-prim) in biology. “P-prims” (diSessa, 1993) or “core intuitions” (Brown, 1995) can be defined as atomistic intuitive knowledge structures that are unconsciously activated by the learner in certain situations. P-prims do not change and cannot be extinguished through contradicting evidence. However, learners can be supported to elicit their intuitive ideas, and critically distinguish them from scientifically normative ideas. The goal of education is to help students to integrate the normative idea of random mutation within and across multiple contexts by building and strengthening the connections through evidence. By experiencing the stronger explanatory power of evolutionary ideas in different contexts, the new ideas can reach a higher “cueing priority” when constructing explanations (Smith, 1994) [See chapter 2: Integrating Evolution Ideas: House Building Analogy: Figure 2].

This dissertation research poses the hypothesis that the continued use of the idea “need” to explain evolutionary change is caused by a disconnection between evolution (phenotype-level) and genetics (genotype level). Students who understand evolution only on a phenotypic level might use the idea of “need” instead of the genotype level “mutation.” This dissertation research uses concept maps as a learning tool [See chapter 2: Concept Maps as Learning Tools] to help students visually generate relationships between genotype and phenotype-level ideas. Students who build a strong integration of ideas of these two different levels might use the idea “mutation” more frequently in their explanations than students who have a disconnected understanding.

(e) Intentionality

Intentionality is closely related to need-based reasoning. Intentionality is the tendency humans have to perceive purposiveness caused by an intentional agent with a mind of its own, even when confronted with the random actions of inanimate objects (Bean, Sinatra, & Schrader, 2010). Things happen because they are *intended* relates to Piaget’s dynamistic and animistic view. Intentional explanations relate to the intentions of an agent. For example, “Humans developed opposable thumbs because they wanted to be able to make better tools.” This is a central difference between the Lamarckian and the Darwinian view of evolution. According to Lamarck, evolutionary changes happen because organisms intended a certain change. They can pass these changes on to the next generation. The Lamarckian view, which is based on inheritable changes due to need and intentions, relates to views people establish in early childhood.

Humans, and other primates, learn at a young age to identify their own intentions and predict other’s intentions. Human babies develop a theory of mind that allows them to realize themselves and to reflect on the intentions of others. Intentionality ideas are established early in a humans’ life and are frequently used in different situations. The intentionality idea is especially prevalent in young children who tend to apply an intentional model to phenomena (Kelemen, 1999; Kelemen, 2003). Young children tend to apply intentionality explanations to living and non-living things, for example “Rocks are pointy to protect themselves from being smashed by animals” (Kelemen, 1999). Intentionality ideas are used by all age groups, although adults tend to apply them more often to living things than children (Inagaki & Hatano, 2008). Identifying intentions behind behavior allows humans to predict future actions and can give them a feeling of being in control.

Intentional behavior often aims to fulfill a certain need. Organisms act in order to meet their needs, for example food, water, shelter, and mates. From personal experience, humans know that we act because we are in need of something. Maslow (1943) described a hierarchical model of human needs: Physiological needs, safety needs, love and belonging, esteem, and self-actualization. Other researchers suggested non-hierarchical need models (for example (Wahba & Bridwell, 1976)).

Piaget noted that the view that things happen due to intentions is the most primitive (intuitive), but also the one that survives the longest (Piaget et al., 1977). Even after years of instruction, the idea of ‘intentionality’ remains prominent in people’s repertoire of ideas to explain change and behavior in living things. Early intuitive intentionality ideas, along with teleological and essentialist ideas, easily connect to and reinforce creationist or intelligent design ideas (Evans, 2000; Evans, 2001; Evans, 2008; Sinatra et al., 2008) [See chapter 2: Need].

Darwin’s ideas deprived organisms of the control over their evolution and identified the interplay between selection and changes in the organism’s genetic material as the sources for evolution. Only changes in the genetic material (genotype) can be passed on to the next generation, but not acquired changes in the phenotype. For example, loosing a limb in an accident does not affect the number of limbs of the offspring of this organism. The current environment defines the criteria according to which natural selection leads to a better chance for survival and reproduction for well-adapted organisms.

Modern evolutionary theory tell us that evolutionary changes do not come about by intention or the need of the organism, but instead are the result of the combination of random mutations, recombinations, and non-random natural selection.

(v) Natural Selection

Besides the sources of variation, the center part of the HOW column consists of different selection processes [See chapter 2: Integrating Evolution Ideas: House Building Analogy: Figure 2]. Despite several years of instruction, high school students, undergraduates and even medical students have difficulties understanding the role of natural selection. (Anderson et al., 2002; Bishop & Anderson, 1985; Brumby, 1984; Greene, 1990; Lawson & Thomson, 1988; Lucas, 1971). Students can hold different alternative ideas of natural selection.

For example:

- Students can see selection processes as the source of evolutionary changes (Settlage, 1994).
- Students can understand evolution by natural selection as directed progressive development to help specific organisms to survive [directed evolution].
- Students can see evolutionary changes as pure chance [random evolution].
- Students can hold the alternative idea of natural selection as isolated events happening to individuals instead of seeing it as statistical process in a complex system (Slotta & Chi, 2006).

[See literature review on alternative ideas of natural selection (Gregory, 2009)].

Different than the sources of variation (random mutations and recombination) that happen on a genotype level, selection processes act upon phenotype level traits. The connection between non-random selection and random variation forms the basic mechanism of evolution (Dawkins, 1976). Students often struggle to understand the connections between genotype and phenotype ideas (Schwendimann, 2009). Natural selection (including sexual selection) and genetic drift act upon the phenotypes of organism and affect their reproductive success. Organisms with adaptations that fit the current environment or through good luck may survive long enough to pass their genes on to the next generation.

To understand natural selection, students need to understand geographical isolation. Not all members of a species live in the same environment. They encounter different selection factors and as a result, different individuals successfully reproduce (Demastes et al., 1995). Learning about selection and variation and eliciting the connections between genotype and phenotype ideas could help students build a more integrated understanding of the mechanism of evolution.

(vi) Gene Pool and Population Genetics

(a) Confusion of Individual and Population

The fourth idea in the HOW-column is that the interplay between variation and selection leads to non-directed changes in the allele frequencies in the gene pool. Evolution can be seen as a process that happens 1) to individuals, 2) to all members of a species (essentialism), or 3) as an emergent statistical effect at the population level [See chapter 2: Nature of Evolution Phenomena].

Many students hold the alternative idea that evolutionary changes happen to an individual organism during its lifetime. For example "Eagles developed larger wings because it needed to fly better." This statement holds several alternative ideas: Essentialism, need, and change during one's lifetime. Representing evolution as a statistical effect on a gene pool level could help students understand evolution as a non-directed change in a population. Ernest Mayr called this "population thinking" (Mayr, 1982) [See chapter 2: Individual Variation vs. Essentialism].

Evolutionary change needs to be understood on A) an individual and B) a population level.

A) The individual level contains ideas of sources of individual genetic diversity. Random mutations and recombination lead to genetically diverse individuals. However, evolution instruction needs to be carefully designed not to present evolution as an "individual's struggle for existence". Evolution does not happen to individuals but to populations [See chapter 2: Difficult Use of Terminology].

B) The population level focuses on changes in the gene pool of populations, which are based on the genetic differences of its members. As different populations have different gene pools, additional effects like migration, can add or remove genetic variety. Selective effects like natural selection and genetic drift filter the gene pool in favor of well-adapted or lucky individuals.

This dissertation research aims to address genetic variety on both the individual and population level. From an education perspective, this might help learners to avoid the misconception that evolution helps individuals survive better. Evolutionary change happens not to currently living individuals but as a statistical effect in the population gene pool over time (depending on the variety and frequency of their offspring). Evolutionary changes are non-directed.

It is important to distinguish between sources and effects of genetic variation. This makes it explicit that the effects (improved chances for adaptation and survival) cannot be the cause for specific genetic changes - addressing a possible functional reasoning. Teachers might use the "struggle for survival" of a single individual to illustrate the mechanism of evolution. This might reinforce the idea that evolutionary changes are because of goal-directed processes that happen to individuals during their lifetime.

The misinterpretation of evolution as individual progress is frequently found in popular media. Numerous illustrations and videos show evolution as an individual's linear march of progress from earlier life forms to the current ones. The iconic "March of Progress" illustration shows a sequence of individual hominids, from earlier forms to current forms [See figure 9]. This might lead to the misinterpretations of an individual evolving from earlier forms in one's lifetime and humans being the final pinnacle of evolution. Evolutionary biologist Stephen Jay Gould critiqued the iconology of this image (Gould, 1990): Gould asserted that "… the march of progress is *the* canonical representation of evolution – the one picture immediately grasped and viscerally understood by all…. The straitjacket of linear advance goes beyond iconography to the definition of evolution: the word itself becomes a synonym for *progress*…. [But] life is a copiously branching bush, continually pruned by the grim reaper of extinction, not a ladder of predictable progress" (pp. 30-36). The illustration also implies that a) humans are the end-of-the-line of the evolution process, and b) that evolution is a goal-oriented process that culminated in humans.

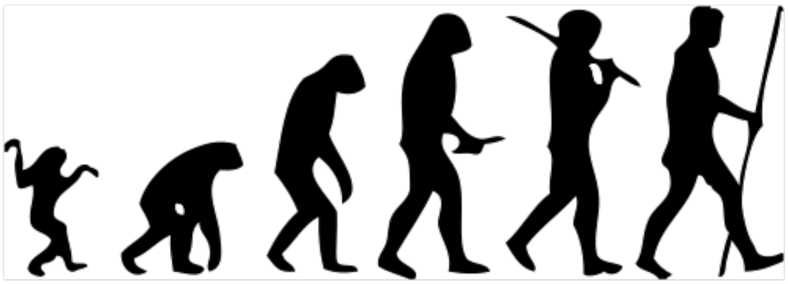


Figure 9: A commonly found misleading picture of evolution. ***An individual's march of progress (Original artwork by Rudolph Zallinger*** **(1965), edited by** ***Jose-Manuel Benitos (2007)***

Another source of misconception about individual evolution might be evolution-style computer games. One example is the video game 'Spore' that allows the player to 'create and guide a creature through five stages of evolution' (Electronic Arts, 2008). The player is in the role of a designer who needs to develop his creature to meet certain challenges. The gameplay allows direct manipulation of the outcome of reproduction and evolution directly relates to the cognitive bias of intentionality (Kelemen, 1999). This might reinforce the alternative idea of 'need' (e.g. "birds evolved wings because they needed to be able to fly to escape predators") and evolution of individuals rather than populations. Bean, Sinatra, and Schrader (2010) suggest that careful scaffolding is required to avoid a reinforcement of non-normative ideas through games like 'Spore'.

(vii) Difficult Use of Terminology

Learning biology can be compared to learning a new language. Students must learn the language of science in order to understand evolutionary theory (Moore et al., 2002; Sinatra et al., 2008). Different from learning a natural language where terms match one-on-one, for example "house" means "casa", scientific terms often refer to large constructs, for example "cell division" or "evolution" includes a whole set of connected ideas.

Biology curricula and textbooks introduce a large number of scientific ideas. Graf (1989) found between 1,995 to 3,818 different biological terms in high school biology textbooks. Evans (1976) found that UK biology textbooks (GCE-o-level) contain up to 1521 different biological terms. In addition, a number of biology textbooks have been found to describe scientific ideas and their connections inadequately (Swarts, Anderson, & Swetz, 1994; Linhart, 1997; Bybee, 2001; American Association for the Advancement of Science, 2005).

Many terms in biology are used differently in vernacular language, such as adaptation, fitness, theory (Bishop & Anderson, 1990; d'Apollonia et al., 2004; Zaim-Idrissi, Desautels, & Larochelle, 1993), or species (Inagaki & Hatano, 2008). For example, in vernacular language, adaptation refers to individuals adapting their behavior to a new situation, but in science, adaptation refers to inadvertent changes in populations over generations. Students also describe the cause of adaptations being an overall purpose or design (teleological reasoning), or adaptations as a conscious process to fulfill one's needs or wants (Brumby, 1979; Clough & Wood-Robinson, 1985a; Lucas, 1971).

Darwin chose the term "natural selection" as the counterpart to "artificial selection" conducted by animal breeders. However, students' experience with selection could imply a selector - some form of intelligence that determines the criteria for the selection. This might foster non-normative ideas of the nature of natural selection. Evolution by natural selection is often associated with the phrase "survival of the fittest." The phrase "survival of the fittest" was coined not by Darwin but by British economist Herbert Spencer. Darwin adopted the term starting with the fifth edition of the "On the Origin of Species" (published 1869). The phrase "survival of the fittest" is misleading in a number of ways (Gregory, 2009): First, many students use the term "fitness" in its vernacular meaning "most physically fit" (Bishop & Anderson, 1990). On the other hand, evolutionary biologists define "fitness" as "best suited to a particular environment." Fitness is measured as reproductive success, measured in the number of offspring an organism contributes to a breeding population. The distinction between the scientific and vernacular meaning of "fitness" is crucial, especially when the meaning gets further distorted to "only the strong survive." Second, "survival of the fittest" places the emphasis on survival not reproduction. Natural selection includes not only "survival of the fittest" but also "death of the least fit." From a biological point of view, survival is only important insofar as it means that an organism lives long enough to produce offspring.

Additionally, experts and novices might use the same terms to describe a relationship between ideas, but the terms might represent different meanings. Ariew (2003) noted that experts often use vernacular, design-based, or teleological expressions as a short-hand for complex scientific ideas. Experts might for example say that "The beak of this bird is designed to reach nectar in this flower" while referring to the underlying process of natural selection that led to this particular beak shape.

V. The Field of Biology & Evolution

A. Evolution Seems Simple

Prominent evolutionary biologists, like Gould (1997) and Mayr (1997; 2000), suggest that the basic idea of evolution by natural selection, unlike many other pivotal ideas in the history of science, appears to be quite simple: Evolution by natural selection essentially consists of a set of basic principles leading to an almost syllogistic conclusion (Ferrari & Chi, 1998): First, all organisms tend to produce more offspring than can possibly survive (due to limited resources). Second, offspring are individually different variants from each other and their parents. Third, some of these variations are inherited by the next generation. This leads to variation in a population. Fourth, some of these variants are better suited for the environmental conditions in which the individual finds itself and will have more offspring that survive (differential fitness). These basic principles form the main mechanism of evolution, which Darwin called "natural selection" (in contrast to artificial selection done by animal breeders). The combination of these three principles results in evolutionary change. As resources are limited, some individuals in a population will not survive and reproduce. On average, individuals whose variation happens to be best suited for the current environment will survive to reproduce and pass their genes on to the next generation. Over time this leads to change in allele frequencies in the gene pool of a population.

B. History of Modern Evolution Theory

Evolution is a process unique to biology and a unifying theory in the otherwise fragmented field of biology [See chapter 2: Fragmentation of Biology] [See chapter 2: Importance of Biology]. The idea that species change over time existed long before Darwin; what was lacking was knowledge of a plausible mechanism and evidence for it (Bishop & Anderson, 1990). Darwin contributed two major ideas: A mechanism for evolution (natural selection) and the idea of common ancestry. The process of natural selection applies essentially to every organism, from bacteria to plants and animals. Darwin amassed an overwhelming amount evidence for evolution. Mayr (1982) described Darwin's theory as a composite of five theories: (a) the theory of a non-constant and evolving world, (b) the theory of evolution by common descent, (c) the theory of gradual evolution, (d) the theory of population speciation, and (e) the theory of natural selection.

In the 150 years since Darwin's publication, scientists from many different fields scrutinized Darwin's theory and found further supporting evidence. A major extension was the rediscovery in the 1900's of Mendel's work on inheritance that explained how existing traits are inherited.

A second major extension was the discovery of genes in the 1920's, which made it possible to explain what Darwin could not: The mechanism of the origin of novel traits through mutations and sexual recombination (Ayala & Valentine, 1979; Mayr, 1982). The new field of genetics shifted the focus of evolution from phenotypes to genotypes. Richard Dawkins (1976) took the gene-centered view of evolution as far as describing genes as the central unit of natural selection. According to Dawkins, adaptations are the phenotypic effects through which genes achieve their (selfish) propagation. Other prominent biologists (Sober & Wilson, 1999) including evolutionary biologist Ernst Mayr and paleontologist Stephen Jay Gould challenged the gene-centric view of evolution. Mayr criticized Dawkins' view as being reductionist by not taking the connectedness of biological systems into account. Gould called attention to a hierarchical perspective on selection. He pointed out that natural selection does not act directly on genes but only on phenotypes, which are influenced by the environment as well as the genotype. Genes alone do not provide a causal explanation for the phenotype. A deep understanding of evolution requires an understanding of interactions between genotype and phenotype.

A third extension was the development of mathematical models to describe changes in allele frequencies in populations. G. H. Hardy and Wilhelm Weinberg developed a mathematical model for genetic equilibrium - a hypothetical state in which both allele and genotype frequencies in a population remain constant from generation to generation (i.e., there is no evolution). The Hardy-Weinberg equilibrium is impossible in nature. It serves as a baseline against which genetic change can be measured. Several factors disturb the equilibrium: Non-random mating, mutations (new alleles), migration (gene flow between populations), limited population size (leading to genetic drift), and natural selection against certain traits. In the

1930's, R.A. Fisher, Sewall Wright, and Jack Haldane developed the mathematical model for the genetic theory of natural selection, now known as population genetics.

Seminal figures like Ronald Fisher, Ernst Mayr, J.B.S. Haldane, Sewall Wright, Theodosius Dobzhansky, Julian Huxley, and Gaylord Simpson forged a synthesis between Darwin's theory of natural selection, Gregor Mendel's basic understanding of genetic inheritance, genetics, paleontology, population genetics, systematics, and advances in mathematical modeling toward a synthetic theory of evolution, referred to as the "modern synthesis" (Catley, 2006) [See figure 10] Scientists sometimes disagree *how* evolution happens, but not *if* it happens. The basic principles of the synthetic theory of evolution (also called neo-Darwinism), the interconnection between random mutations and non-random selection, are supported by multiple lines of evidence and firmly accepted by the community of professional biologists (Bishop & Anderson, 1990).

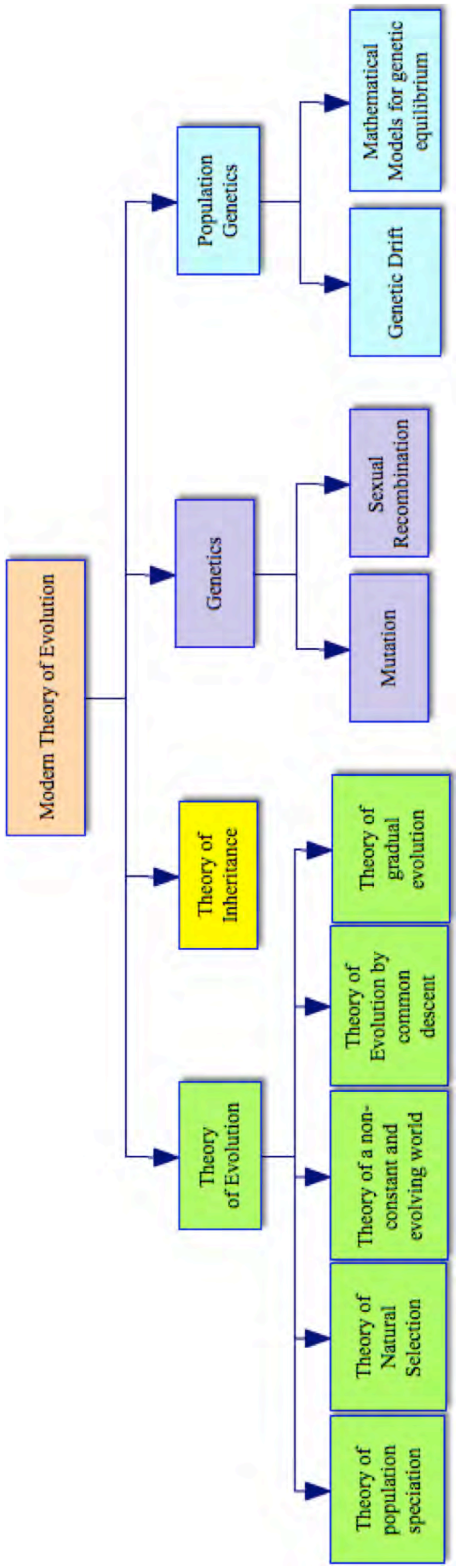


Figure 10: Some of the branches of the modern theory of evolution.

C. How Does Biology Differ from Other Sciences?

Biology differs from the physical sciences (such as physics and chemistry) in several ways - from multiple causalities to evolving entities embedded in a complex system.

1) Fragmentation of Biology

The term "biology originated in the 19th century (DeBoer, 1991). The precursors of this broad field were natural history, botany, and medicine (including anatomy and physiology). Darwin's theory of evolution, coupled with Mendel's work and later enhanced by molecular biology, connects all of biology. However, unlike chemistry or physics, which have a more recognized and coherent content, biology is still splintered into fragmented sub-divisions with different levels of focus and methods; accordingly, biology education is often presented in similarly fragmented way.

Ernest Mayr (1982) distinguished three general kinds of biology knowledge: [See chapter 2: Epistemology of Biology]

1) Descriptive biology (WHAT), for example botany.

2) Functional biology (HOW -> Proximate causes) -> Uses Experiments, for example molecular biology.

3) Evolutionary biology (WHY ('How come') -> Ultimate causes) -> Uses historical observations (a posteriori) and comparisons. It needs to be added that also some physical sciences cannot conduct experiments and are observational, e.g. astronomy, meteorology, geology, and oceanography.

2) Epistemology of Biology

Biology is focused on theories and "ideas." Biological theories differ from the natural laws in the physical sciences, as biological theories are not universal and often have specific exceptions (Mayr, 2002). Using Kant's framework (Kant, 1965), the theory of evolution through natural selection is strictly *a posteriori* as it does not allow predicting future developments. Evolutionary theory can only provide historical explanations but cannot generate precise predictions. The idea of natural selection is *synthetic* in nature as the outcome is not contained in the ideas itself and therefore requires observation. This absence of predictability is an important facet of biology, and different from, for example, physics (Mayr, 1988b).

Graf (2010) and Wiles (2010) point out an important distinction between evolution and the theory of evolution: The process of evolution needs to be distinguished from the theory of how evolution happens. According to Gould (2002), evolutionary theory involves explanations about the mechanisms of evolution, essentially how evolution occurred rather than whether it occurred. Rudolph and Steward (1998) noted that scientific theories, complex as they are with their multiple, interdependent elements, are constructed to fill the dual role of explanation and exploration—to make sense of what is known and to guide future inquiry. Evolution instruction needs to address both functions: Darwin's theory of evolution does not only explain the existing diversity of life, but is also a tool of inquiry that can be applied in a variety of disciplines. Darwin's theory of evolution cannot be fully understood as an abstract backwards-looking theory but needs to be applied to explain current biological phenomena. The scientific community has generally accepted the phenomenon of evolution as a fact. What biologists are still working on is how exactly evolution happens, therefore, the details of the theory of evolution. Mayr (1997) explained that evidence for the occurrence of evolution is so overwhelming that today's biologists "consider it a fact--as well-established as the fact that the Earth rotates around the sun and that the Earth is round and not flat" (p. 178). Some biologists even suggest not to refer to the "theory" of evolution or the "theory" of natural selection, and call it the "law" of natural selection instead (Linhart, 1997), as biologists probably know more about the details of natural selection than physicists know about the law of gravity.

Understanding the nature of science includes understanding the meaning of "theory." Many students refer to evolution as "just a theory", using "theory" in the vernacular sense of conjecture, supposition, guess, unproven assumption, or hunch with little evidential support (Alters & Nelson, 2002; Evans, 2008). On the other hand, scientists define theories as "concise, coherent, systematic, predictive, and broadly applicable explanations, often integrating and generalizing many hypotheses" ("Understanding Science - How Science Really Works," 2010). Using the vernacular meaning of "theory" instead of the scientific definition feeds a misconception about how established the theory of evolution is in the scientific community.

3) Entities: Genotype and Phenotype

One major difference between biology and physical sciences lies in the ontology of the objects biology studies. Chemistry and physics typically study inanimate objects that do not contain (genetic) information stored in them, and that do not have goals, ends, purposes, or functions. Living objects, on the other hand, have (and vary in) information content and have a history that matters. Each entity in nature is unique, down to the molecular level - whereas inanimate entities are built from identical components. The dynamic, synthesizing, organizing, energy-consuming nature of living objects sets them apart from inanimate objects. Organisms have a dual nature (genotype-phenotype duality):

- Organisms contain a genetic program (genotype) that is the source of "ultimate" (evolutionary) causes. Ultimate causes are based on changes in the genetic material.
- Organisms consist of a body (phenotype) that was produced according to the instructions of the genotype. The phenotype is responsible for "proximate" causes - all physiological and developmental processes and behavior of an organism and its organs.

Different than phenomena in the physical sciences that can often be reduced to a single law, such a reductionist approach cannot be applied to biological systems. Many ideas need to be understood in context of several different levels. For example, 'genes' have a dual ontology: Genes are both physical structures on the molecular level as well as information carriers. The information content can only be represented on a symbolic level (Duncan & Reiser, 2007).

The distinction of the "genotype" and "phenotype" is important in order to understand how genetic variation is inherited. The idea "genotype" refers to the entire genetic material of an organism. Only a small fraction of this genetic material is expressed in phenotypic traits. Mutations in non-coding areas do not affect the phenotype. Recessive alleles are only expressed in the phenotype if the organism is homozygous for this allele. The idea "phenotype" refers to the traits in an organism that are expressed (genes plus environment). The same phenotype can be caused be several different genotypes, for example an organism showing a dominant phenotypic trait could be homozygous or heterozygous for this allele. The phenotype is a result of the genotype and influences by environmental factors, for example a human's body height depends both on inheritance and health.

Only mutations in the genotype of sex cells can be inherited. Mutations in somatic cells, for example skin cancer, are not passed on to the next generation. Also, any physiological changes, for example more muscular arms due to weight training or the loss of an extremity due to an accident, do not affect the genotype and are therefore not passed on (this is the reason for Lamarck's misinterpretation of evolution).

4) Multiple Explanations: Proximate and Ultimate

Biological phenomena often require multiple levels of explanation and consist of interconnected concepts - which differs from the physical sciences that can often be reduced to single laws. Ernest Mayr suggested that for every biological phenomenon, there are two causal explanations: a proximate one (which answers "HOW" a change occurs), and an ultimate one (which answers "WHY" a change occurs) (Southerland et al., 2001). In the physical sciences, questions that begin with "WHAT?" and "HOW?" are often sufficient. In the biological sciences, no explanation is complete until a third question has been asked: "WHY?" In essence, this is the difference between the actual mechanisms of a physiological change undergone by an organism as opposed to the adaptive or evolutionary reasons for the change. Multiple levels of causality in biology and the dual nature of living objects often allows explaining a phenomenon in more than one way, for example a certain adaptation might have been caused by many different factors.

For example, when observing the migration behavior of birds, we can generate a proximate or ultimate explanation.

Mayr (1988a; 1993) described proximate explanations as the 'development is the execution of a genetic program'. Genetic reasoning reflects on the temporal sequence of how the subject evolved from an earlier form. Reasoning about the origin of forms and functions of organisms can strengthens people's genetic reasoning. Genetic reasoning requires multiple other forms of reasoning. First, causal reasoning, for example "How do genes code for amino acid chains?", and second, functional reasoning, for example "What is the function of an objects or process in a system?" (Nagel, 1961).

Ariew (2003) suggested revising Mayr's understanding of proximate by looking at individual level causal explanations: This view includes all factors that contributed to an individual's life history, including development and physiology). It is measured as individual fitness, the ability of an individual to survive and reproduce in a given environment.

Mayr's ultimate explanation (1988a; 1993) refers to explanations of an organism's evolutionary history by natural selection. Ariew (2003) suggested viewing evolution not only as an a-posteriori explanation of an individual's history of natural selection, but also as a statistical population-level explanation. Ultimate explanations include what events in their life history organisms in the same population have statistically in common. It is measured in trait fitness, the average fitness of a group possessing a particular trait and the expected survivability and reproductive rate of a group possessing a particular trait.

5) Systemic and Complex

Biological entities and phenomena have an evolutionary history that cannot be explained directly through a strictly causal-mechanistic explanation, as it is possible in the physical sciences. (Mayr, 1988b). The components of biological systems that self-regulate, self-repair, maintain a steady state balance (homeostasis), develop, and reproduce are seriously constrained by their requirement for survival and need to be seen in context among each other and the environment. Biological systems are complex and often show emergent new properties that cannot be reduced to single elements, such as genes (as argued by Dawkins (1976)). This dissertation research aims to bridge the genetic view and the systemic view by eliciting the connections between levels.

CHAPTER 3: WISE AND DESIGN-BASED EXPERIMENTS

I. WISE Environment

This dissertation research used technology-enhanced science learning environments developed in the Web-based Inquiry Science Environment (WISE) (Linn et al., 2003). The design of WISE modules is guided by the Knowledge Integration framework (Linn & Eylon, 2006)[See chapter 2: Knowledge Integration]. WISE is a powerful digital platform for multiple users and purposes that supports research innovation and teacher customization of inquiry activities in science classrooms.

Well-designed technology-enhanced learning environments, such as WISE, can provide many different types of scaffolding to integrate challenging science ideas (Goldstone & Wilensky, 2008; Kali, Linn, & Roseman, 2008) and foster critical reasoning (Linn, Davis, & Bell, 2004; Quintana, Zhang, & Krajcik, 2005; White, 1993). Technology can be used to deliver information and knowledge representations (for example dynamic visualizations (Kozma & Russell, 1997; Mayer, 2008) or concept maps (Canas et al., 2000)) that can help students learn abstract science ideas (Penner, 2001; Xie & Tinker, 2006). The system makes it possible to deliver content to students in several different experimental conditions, provide them electronically with feedback, and collect all embedded student data in real time. WISE projects enable cognitive and educational researchers to design and deliver inquiry science curricula over the Web (Linn et al., 2003; Linn et al., 2004). WISE modules implemented in the classroom include students who carry out the activity, the technology to deliver the activity, the teacher who facilitates the activity, and the community where the activity is situated (Shen, 2010).

WISE offers numerous scaffolded inquiry tools such as drawing, graphing, data tables, online discussions, and student journals. WISE modules have three main features. First, the WISE Inquiry Map shows the structure of a WISE module and guides learners through the different steps, for example evidence steps, dynamic population visualization steps, concept mapping steps, and reflection steps. A series of steps can be grouped together to promote the knowledge integration process. For example, the pattern "Predict-Observe-Explain" (White & Gunstone, 1992) can help elicit students' alternative ideas before observing a dynamic visualization and revisiting their ideas when generating an explanation. Second, dynamic visualizations can enhance student learning of otherwise unobservable phenomena by making them accessible and manipulable, for example genetic drift, mutations, or natural selection. Third, WISE modules incorporate embedded formative assessments to make students' thinking visible and to scaffold students' reflection, revision, and decision-making. WISE embedded assessments can for example include multiple choice, short-essay, concept maps, and drawing items. Students can receive automated or teacher feedback. In addition to embedded assessments, WISE modules can deliver pre- and posttests as summative assessments.

WISE modules for this dissertation research were created through the partnership model of the Technology-Enhanced Learning in Science (TELS) center, bringing together teachers, education researchers, science experts, and programmers to develop curricula that can be implemented in a classroom settings while allowing investigating key theoretical issues. Three WISE evolution modules were developed for this dissertation research: *Meiosis - the next generation* [See study 1], *Space colony - Genetic diversity and survival* [See study 2], and *Gene Pool Explorer* [See study 3].

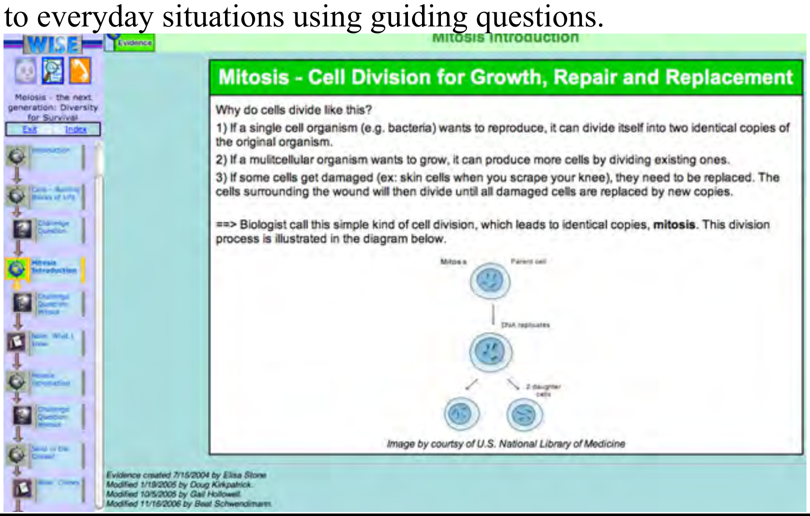
All three WISE projects developed for this dissertation research align with the grade 9-12 California State life science standards (California State Board of Education, 1998) for genetics and evolution.

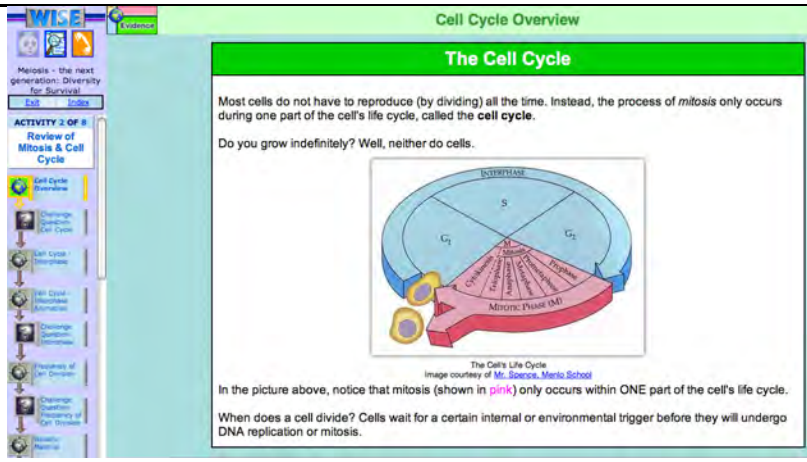
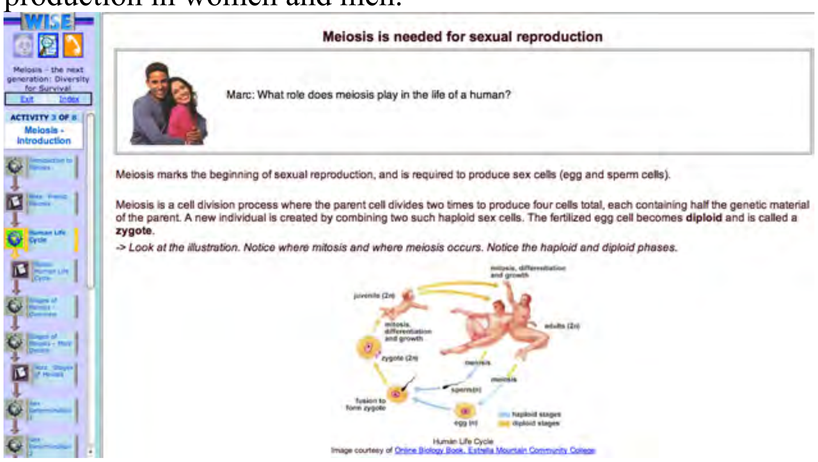
A. Study 1B WISE module structure

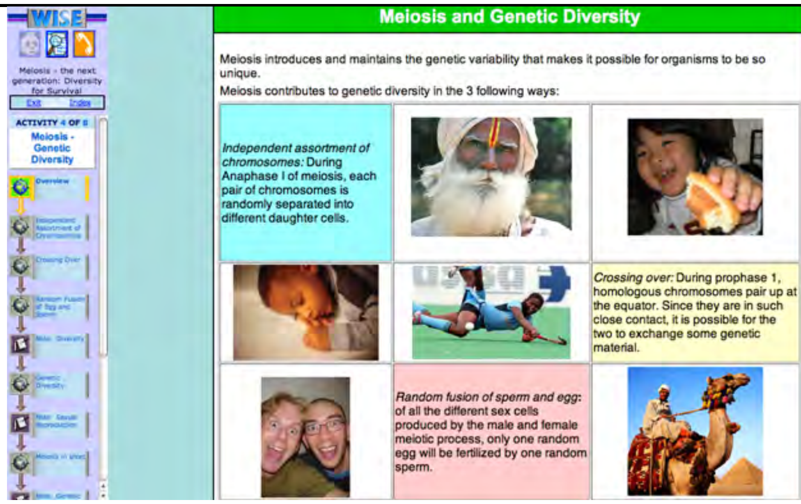
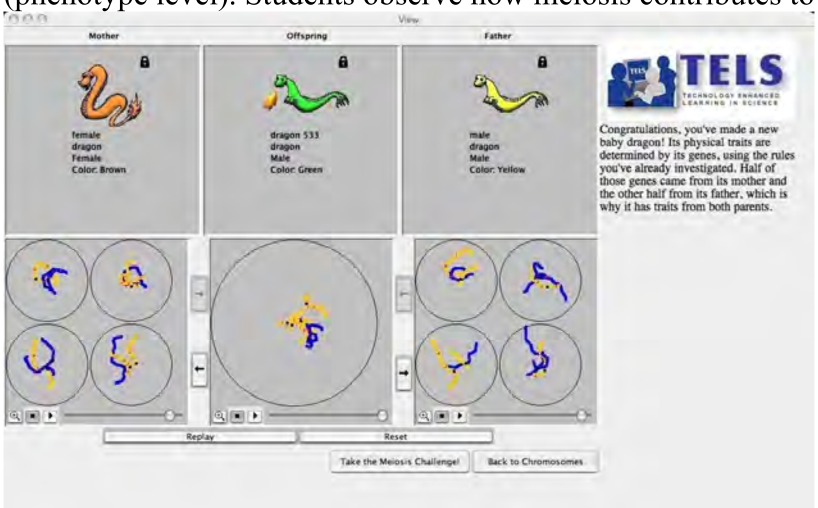
The WISE human evolution module was designed according to the principles of scaffolded knowledge integration [See chapter 2: Scaffolded Knowledge Integration] and iteratively refined in study 1B, 2, and 3 [See chapter 1: Table: Dissertation studies overview].

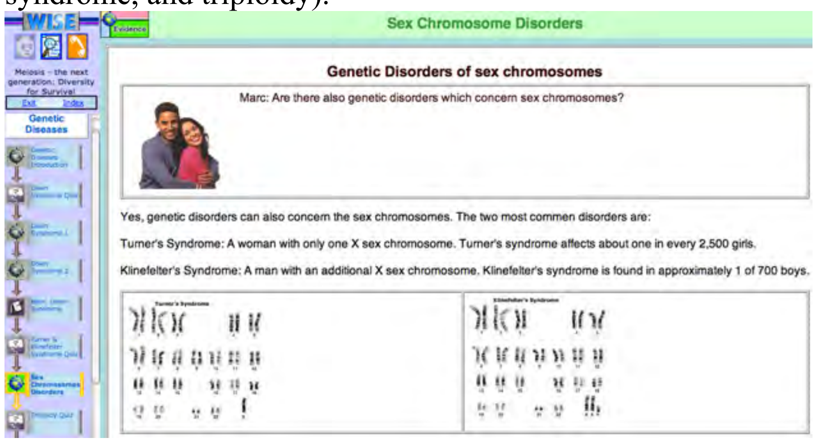
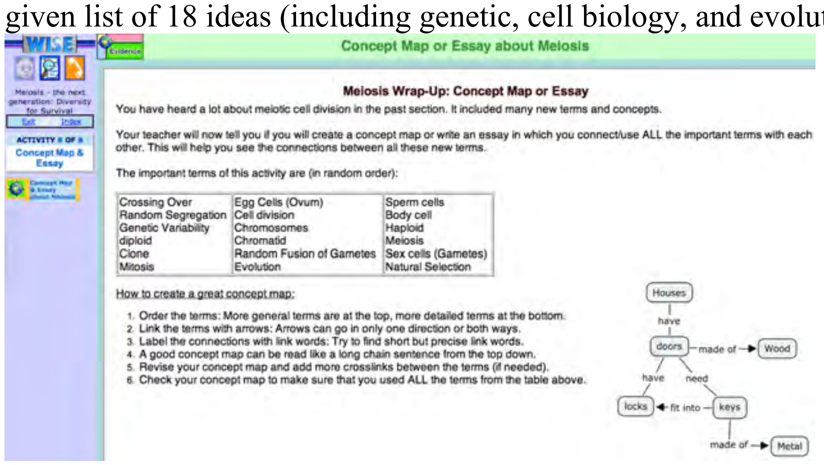
Developed for study 1B, the WISE module *Meiosis – the next generation* consists of seven online activities and one offline activity. The activities cover the topics: Cell cycle, mitosis, meiosis, genetic diversity, and genetic disorders [See table 11]. The module has a modular structure that allows teachers to adapt the length of the module to their needs and omit certain activities if they were already covered previously. The activities "Mitosis" and "Make a baby activity (offline)" are considered optional. Students work collaboratively in dyads sharing one computer and spent about 45 minutes to complete each activity.

Table 11: Activities of the WISE module "Meiosis – the next generation"

<table>
<tr><th>Activity</th><th>Description</th></tr>
<tr><td>Activity 1:
Introduction</td><td>Students reflect on common alternative ideas about the inheritance of parents' traits in human babies. Students connect ideas of inheritance and genetic diversity to everyday situations using guiding questions.

</td></tr>
<tr><td>Activity 2:
Mitosis &
Cell cycle</td><td>Students manipulate interactive visualizations to review the predictable nature of mitotic cell division.</td></tr>
</table>

	
Activity 3: Meiosis Introduction	Students review multiple representations to distinguish between meiotic and mitotic cell division. Students learn about the differences between sex cell production in women and men. 
Activity 4: Meiosis & Genetic diversity	Students study multiple visualizations to learn about processes that contribute to genetic diversity in humans (independent assortment of chromosomes, crossing over, and random fusion of egg and sperm cell). Students compare the differences between mitotic and meiotic cell division.

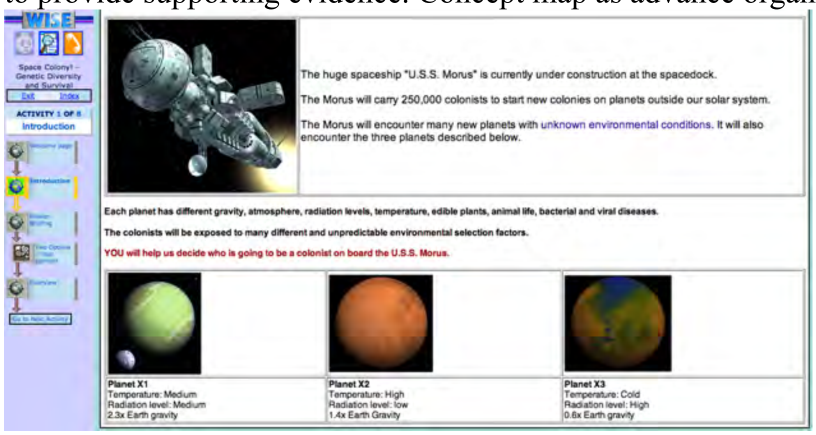
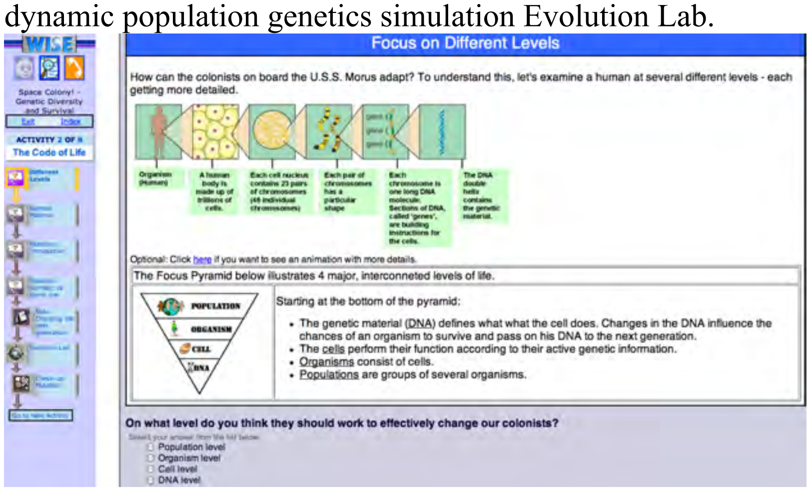
<table>
<tr><td></td><td>
</td></tr>
<tr><td>Activity 5:
BioLogica Dragon Genetics visualization</td><td>Students manipulate alleles (genotype level) and see changes in the phenotype (phenotype level). Students observe how meiosis contributes to genetic diversity.

</td></tr>
<tr><td>Activity 6:
Make a Baby</td><td>The offline activity ‘Make a baby’ consists of two parts. In the first part, students learn about different single-allele phenotypic traits. Students identify those traits and their likely genotypes for themselves and several family members. In the second part, student dyads receive a worksheet with instructions for the steps of meiotic cell division and how to randomly combine two gametes to create virtual offspring.</td></tr>
</table>

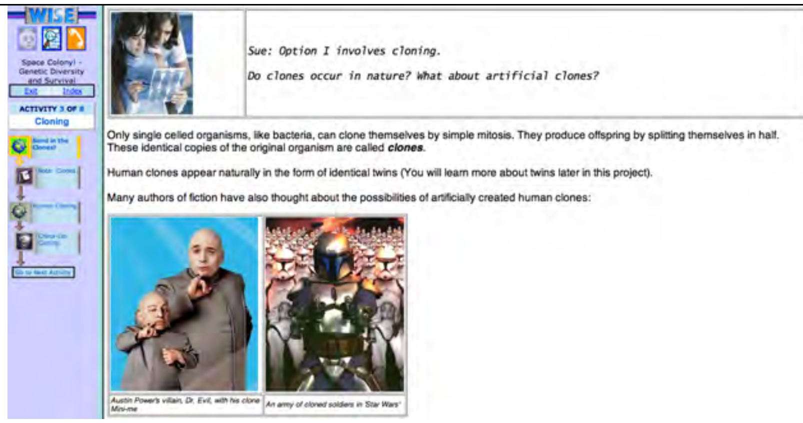
	
Activity 7: Genetic Disorders	Students analyze different karyograms to learn about common autosomal and gonosomal genetic disorders (Down syndrome, Turner syndrome, Klinefelter syndrome, and triploidy). 
Activity 8: Concept map or Essay	Students individually write either an essay or generate a concept map from a given list of 18 ideas (including genetic, cell biology, and evolution ideas). 

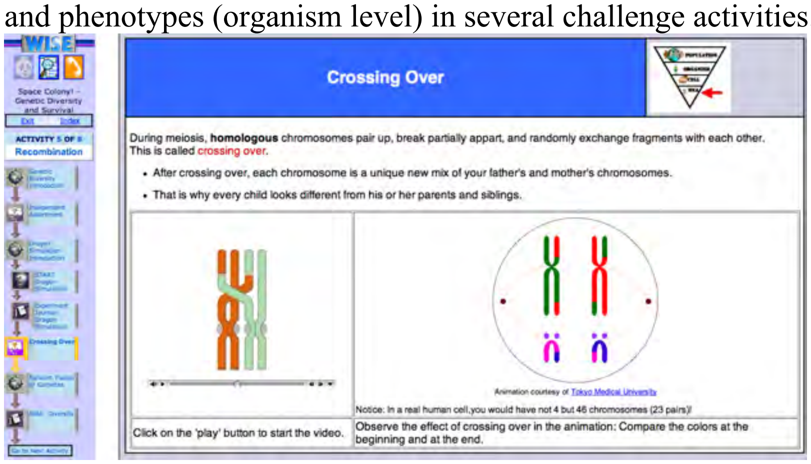
B. Study 2 WISE module structure

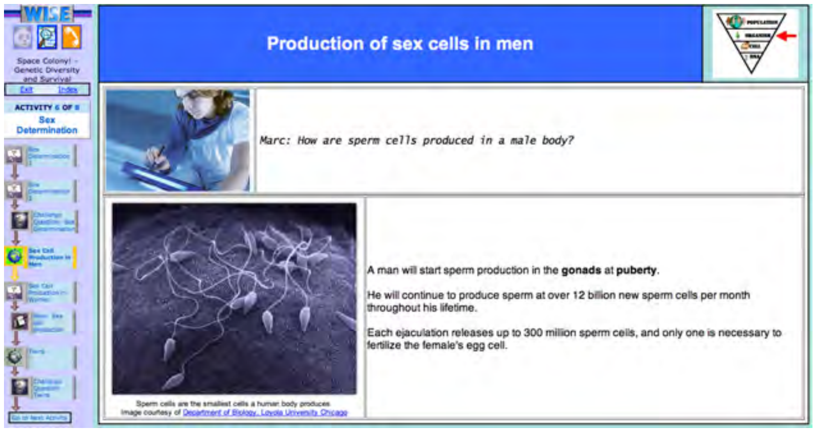
Developed for study 2, the WISE module *Space Colony* emphasizes connections between the underlying genetic processes and cell division, and the overarching evolution principles [See table 12 and appendix study 2]. The sequence of topics in the WISE module is asexual reproduction (cloning), sexual reproduction (meiosis), mechanisms of genetic diversity (mutation, recombination), and evolution. The content of this WISE module is based on the assumption that meiosis can only be fully understood in the context of genetic diversity and evolution. Evolutionary selection explains the need for genetically diverse populations. The WISE module distinguishes between asexual and sexual reproduction (in the light of evolution). To understand sexual reproduction, the mechanism for sex determination needs to be introduced.

Table 12: Activities of the WISE module "Space Colony"

<table>
<tr><td>Activity</td><td>Description</td></tr>
<tr><td>Activity 1:
Introduction</td><td>Introduction to the background story, main learning goals, and overview of the module. Students have to decide if genetic diversity or genetic homogeneity leads to better survival chances in changing environments. Students are asked to provide supporting evidence. Concept map as advance organizer tool.

</td></tr>
<tr><td>Activity 2:
The Code of Life</td><td>Introduction of genetic ideas (DNA, gene, mutation). Students learn about different forms of mutations (somatic and germ line). Students investigate the connection between mutations (DNA-level), genetic diversity, and natural selection (population level) through scaffolded inquiry activities using the dynamic population genetics simulation Evolution Lab.

</td></tr>
<tr><td>Activity 3:
Cloning</td><td>Introduction to cloning as an example of asexual reproduction.</td></tr>
</table>

<table>
<tr><td></td><td>
</td></tr>
<tr><td>Activity 4: Meiosis</td><td>The role of meiosis in the human cycle of life. Students study videos, animations, and drawings of the main stages of meiosis. Focus in the contribution of meiosis to genetic diversity.

</td></tr>
<tr><td>Activity 5: Recombination</td><td>Animations, pictures, and illustrations compare the three recombination mechanisms that contribute to genetic diversity: Crossing over, random assortment, and random fusion. Using the BioLogica Dragon Genetics visualization, students explore the connections between mutations (DNA level) and phenotypes (organism level) in several challenge activities.

</td></tr>
<tr><td>Activity 6: Sex</td><td>Introduction to mechanisms of sex determination in humans. Difference</td></tr>
</table>

<table>
<tr><td>Determination</td><td>between sex cell production in men and women. Twins are used as an example of human clones.

</td></tr>
<tr><td>Activity 7: The Big Picture: Evolution</td><td>Discussion of the connection between genetic diversity, natural selection, and evolution. Addresses alternative ideas of ‘humans are the pinnacle of evolution’ and ‘human evolution is over’.

</td></tr>
<tr><td>Activity 8: Decision making</td><td>Students revisit and maybe revise their initial decision (if genetic diversity or genetic homogeneity leads to better survival chances in changing environments) from activity1. Students are asked to support their decision with an explanation and supporting evidence.

</td></tr>
</table>

C. Study 3 WISE module structure

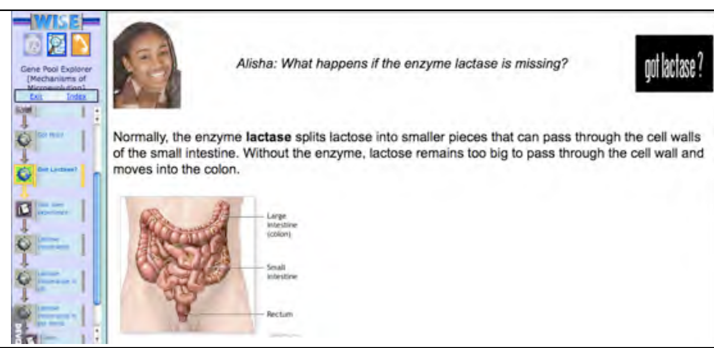
Developed for study 3, the WISE *Gene Pool Explorer* module consists of six activities [See table 13]. In the WISE *Gene Pool Explorer* module, students start with a phenotypic real-life observations (1) Introduction: Lactose intolerance and 2) Introduction: Gene Pool), exploring the underlying genetic mechanisms (3) Mutation), investigate changes in the gene pool over time (4) Natural Selection and 5) Genetic Drift), and explain the differences in phenotypic traits (6) Lactose intolerance treatment). The first three activities focus on changes in the genotype: The first activity introduces the human lactose intolerance case study. The second activity introduces the concept gene pool. The third activity consists of an overview of the connections between mutations and genetic variability in the gene pool. The fourth activity presents two guided inquiry activities using the population genetics visualization "Allele A1" to explore the connections between mutations, natural selection, and genetic diversity. The fifth activity introduces the idea of genetic drift as an additional selection process and explores the effects of small population sizes on genetic drift in "Allele A1". Students generate or critique a concept map on phenotype concepts. The last activity discusses treatment and dietary options for people who are lactose intolerant.

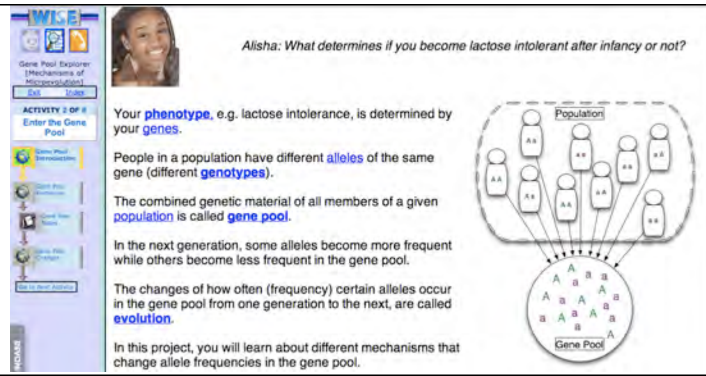
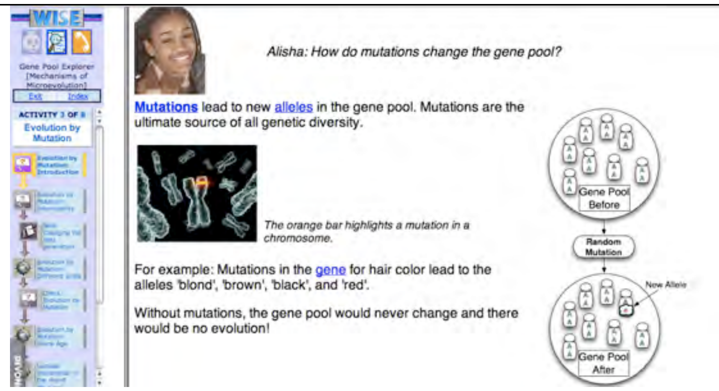
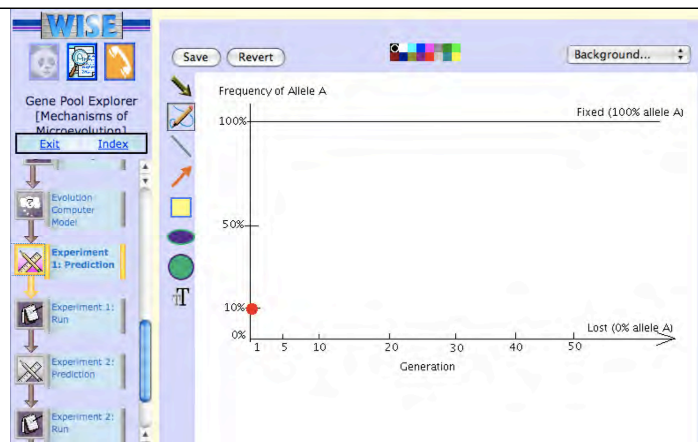
The WISE module aims to connect genotype and phenotype level ideas:

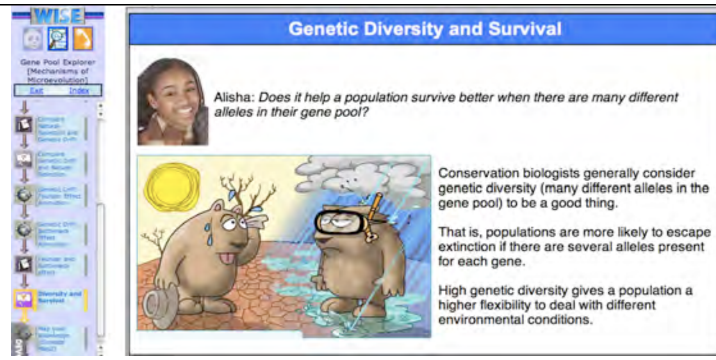
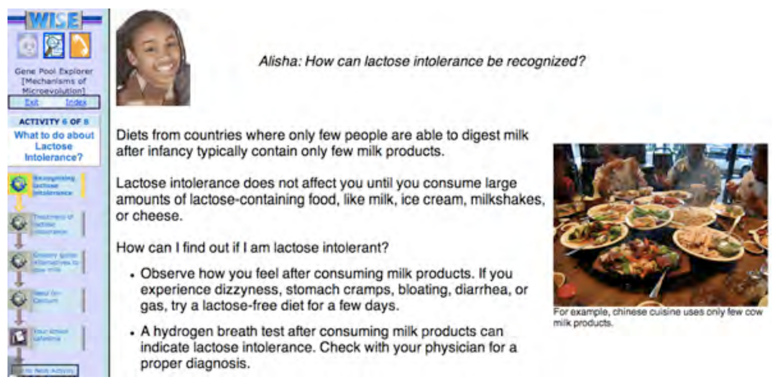
I) Sources of genetic diversity (genotype level): Gene pool, mutation, recombination (Hardy-Weinberg principle) [See chapter 2: Sources of Variation]

II) II) Effects of genetic diversity (phenotype level): Natural Selection, fitness, genetic drift, migration (gene flow) [See chapter 2: Selection of Variation]

Table 13: Activities of the WISE module "Gene Pool Explorer"

<table>
<tr><td colspan="2">Activity 1: Introduction</td></tr>
<tr><td>Students learn about lactose, enzyme lactase and the frequency of lactose intolerance in different ethnic groups in the US and worldwide. This activity connects to students' prior experiences with lactose intolerance.</td><td>
</td></tr>
<tr><td colspan="2">Activity 2: Enter the Gene Pool</td></tr>
</table>

Students get introduced to the idea of "gene pool" and three major processes that influence it (mutation, natural selection, genetic drift). This activity introduces the genetic view of evolutionary changes.	
Activity 3: Evolution by Mutation	
This activity focuses on different types of mutations. Students revisit the geographic distribution of lactose intolerance (activity 1) with a genetic viewpoint to illustrate the connections between genotype and phenotype. Students create or critique Knowledge Integration map #1 about genotype ideas.	
Activity 4: Evolution by Natural Selection	
This activity focuses on natural selection from a gene pool point of view. Students draw a line graph to predict allele frequencies in a population without (Experiment #1) or with (Experiment #2) cow farming. Students run the simulation 'Allele A1', compare to their predictions, and explain their observations. Embedded prompts encourage reflection.	
Activity 5: Evolution by Chance (Genetic Drift)	

Students run experiment #3 to explore the effects of population size (genetic drift) on the gene pool. Students compare and contrast observations from all three experiments with each other and write explanations about the difference between the two selection processes (natural selection and genetic drift). Students create or critique Knowledge Integration #2 about phenotype ideas.	
Activity 6: What to do about Lactose Intolerance?	
Students learn how to turn their knowledge about lactose intolerance into real-life actions (grocery shopping, cooking, diet).	

II. Scaffolded Knowledge Integration

The design of WISE modules uses the scaffolded knowledge integration (SKI) framework (Linn et al., 2004) that translates the KI framework into four pedagogical meta-principles: *Making science accessible*, *making thinking visible*, *helping students learn from others*, and *promote autonomy and lifelong learning* (Linn & Hsi, 2000). Together, the four SKI tenets serve to provide students with opportunities to form meaningful connections between ideas from multiple contexts. These four meta-principles serve as guidelines for instruction or curriculum design. SKI aims to combine views of learning through the two different lenses of science learning, for example development of expertise, and cognitive research, e.g. memory, skills, and reasoning development. Cognitive processes in the KI framework include 'recognizing and adding new ideas', 'generating connections', 'evaluate alternative ideas', and 'monitoring learning progress' [See chapter 2: Knowledge Integration].

Making science accessible connects to students' prior ideas by placing the curriculum in a context that is familiar and relevant. For example, students investigate why each of their siblings looks different. Using real-life examples provides students with an opportunity to revisit scientific ideas autonomously after formal instruction.

Making thinking visible serves the dual purpose of modeling scientific thinking and visualizing scientific principles through multiple representations, as well as providing insight into students' thinking through embedded assessments. For example, students are prompted to make a prediction, make an observation in a scaffolded inquiry activity, and then revisit their ideas by generating an explanation for the observed phenomenon.

Helping students to learn from each other is consistent with Vygotsky (1978). Working in pairs (Howe, Tolmie, Anderson, & Mackenzie, 1992) allows students to solve challenges above the level they could solve by themselves alone. This "zone of proximal development" (ZPD) was formulated by Vygotsky (1978). He distinguished the distance between a child's "actual developmental level as determined by independent problem solving" and the level revealed in "potential development as determined through problem solving under adult guidance or in collaboration with more able peers" (p. 86). Students are encouraged to consider the ideas of their peers, teachers, or additional expert sources as a way of adding and comparing ideas in their repertoire. Students formulate their own norms, standards and cultural values as a base for their comments and critique. Ideas presented by peers are often more accessible because they are presented in familiar terminology.

Promoting autonomy and lifelong learning allows students to monitor their own learning progress, reflect on ideas, and develop criteria for sorting and reconciling their ideas. Students learn to self-monitor their learning progress through scaffolded activities and feedback. Formal schooling cannot teach students about all science topics in detail within the limited time. A solid understanding of scientific core ideas and learning strategies empowers students to learn additional science topics when the need arises later in their lives, e.g. to make a personal health decision or to vote about a science related issue. Students should learn to self-monitor their own learning and devise their personal goals in order to develop their metacognition.

III. Concept Mapping Software

Traditionally, concept maps are generated using paper and pencil (Novak & Gowin, 1984), or moveable cards (Scheele & Groeben, 1988; Bonato, 1990). However, using computer software to create concept maps can facilitate learners in re-arranging, color-coding, adding, or deleting nodes and links with relative ease. Research suggests that concept mapping software can reduce many of the mechanical obstacles to editing complex maps (Novak, 1998; Novak, 2002; Canas, 2003). Sturm (2002) reported that learners usually prefer the higher flexibility of computer-generated concept mapping. Royer (2004) compared paper-pencil to computer-based (using "Inspiration") [See appendix chapter 3: Table 65 for detailed comparison] concept map generation. Findings indicate that the computer-group generated significantly more complex maps than the paper-pencil-group. Computer-based concept maps can contain additional information (pictures, sounds, videos, texts, weblinks) and meta-information (source of information) (Tergan et al., 2006). Computer-generated concept maps can be stored, are easier to read than hand-written maps, and can support online collaboration.

To identify computer-based concept mapping tools suitable for this dissertation research, an evaluation survey of available tools was conducted. The survey included computer programs that were specifically designed for concept map generation.

The evaluation used the following criteria: [See table 65 in appendix chapter 3]

1) Developer
- Who developed this tool?

2) Customizability
- License: General public license (GPL), Educational Community License (ECL).
- Custom setup: Does the program allow one to setup templates, for example a word bank with a given list of ideas, or a drawing area divided into levels (for example genotype and phenotype)?

3) Accessibility
- The concept mapping tool should be available for different operating systems (Win, OSX, Linux) and for different languages.
- Platforms: Available for multiple platforms (for example Windows, OS X, Linux).
- Online/Offline: Online and/or offline mode (in case of unreliable internet connections, offline mode is preferable).
- Languages: Available in multiple languages (for international usage).
- Storage: Are the concept maps stored locally or online? If online, is it possible to set up your own server? Does the program allow recording user's mapping progress?
- The concept mapping tool should allow individual user accounts that allow identification of each student.

4) Costs: Free or commercial
- The concept mapping tool should be freeware or open-source.

5) Graphical user interface (GUI) design
- Users should be able to create new ideas (nodes) and connections (arrows) with a single drag and drop function. This allows quickly creating a concept map and revising existing maps.
- Generating new links.
- Re-arranging ideas.
- Quick-connect available (create new link with one click).
- Does the program prompt students to generate link labels?
- Does the program prompt users to label each arrow and create arrowheads as a default?

6) Collaboration
- Does the program allow online collaboration, for example annotated reviews?

The evaluation identified "Inspiration" as the best commercial concept mapping tool, and "Cmap" as the best freeware concept mapping tool. Both tools have well-designed graphic interfaces that make adding ideas, generating links, and rearranging easy. Both tools prompt learners to add link labels. Inspiration saves files locally while Cmap allows saving concept maps either locally, on a Cmap server, or on one's own server. Cmap allows users to collaboratively work on concept maps, and receive comments from teachers and peers. Cmap allows automatic comparison with criterion maps. Both tools are available for multiple platforms. Cmap is available in multiple languages, while Inspiration is available only in English. Both tools allow setting up custom tasks, for example an idea bank, focus question, or specific drawing areas. Inspiration was used for the interviews in study 1A, and Cmap in the classroom studies 2 and 3.

IV. Design-Based Experiments

This dissertation research uses design-based experiments (Brown, 1992; Collins, 1992) in authentic classrooms to investigate, employ, and refine specific principles concerning the integration of evolution ideas through concept map activities. Design-based experiments are a means for building understanding of learning by designing the elements of a learning system and then studying the functions of these interrelated elements as the design is put into play. The purpose is to contribute to greater understanding of discipline-specific processes of learning. Developing learning environments involves iterative cycles of design, implementation, analysis, and refinement (Cobb, 2001).

For example, the BGuILE (Biology Guided Inquiry Learning Environments) (Reiser et al., 2001; Sandoval & Reiser, 2004) developed and studied the use of technological and curricular supports for the teaching and learning of evolution ideas. The natural selection curriculum underwent multiple iterative cycles of design, implementation, evaluation, and refinement. While designing a successful inquiry-based learning environment, the BGuILE researchers also contributed to the understanding of epistemic scaffolding to support students' generation of scientific explanations (Sandoval & Reiser, 2004).

Design-based research (Brown, 1992; Cobb et al., 2003) investigates learning in authentic contexts by systematic design and iterative refinement of generalizable principles for effective classroom instruction (The Design-Based Research Collective, 2003). Design-based research aims for a synergy between theory and practice, in which learning theories inform the design of learning environments, and the results of design research inform refinements of learning theories. Brown (1992) argued that classroom-based learning could not be understood by isolating factors, such as teachers, students, or activities, but only by carefully designing the entire environment. This dissertation research investigates the design, implementation, assessment and iterative refinement of a human evolution curriculum unit using the WISE platform (Bell, Hoadley, & Linn, 2004; Linn, 2000) in multiple authentic classrooms [See chapter 3: WISE Environment]. This experimental setting allows isolating specific factors within that learning environment that can influence the integration of evolution ideas. This dissertation research aims to identify specific design principles that can be used by other researchers and practitioners to build and refine authentic learning environments.

CHAPTER 4: STUDY 1: CONCEPT MAPS AS GENERATIVE ASSESSMENT TOOLS

I. Study 1 Rationale

Study 1 consists of two connected studies (study 1A and 1B) that investigate concept maps as generative summative assessment tools for the integration of evolution ideas.

Study 1A compares the reasoning of experts and novices while creating concept maps using ideas from cell biology, evolution, and genetics. Study 1A aims to study the process of concept map generation and the sensitivity of concept maps as assessment tools to distinguish novices' and experts' understanding of evolution ideas. The study investigates if domain-knowledge influences the reasoning type (constraint-based or model-based) when creating concept maps. The research questions of study 1A are: 1) How do biology novices and experts differ in their concept map generation and revision process? 2) How do novices of different academic performance levels differ in their concept map construction? 3) How does verbal reasoning (talk aloud) match with concept map construction?

While study 1A explores the process of generating concept maps as a summative form of assessment, study 1B investigates the implementation of concept maps as assessment tools after a WISE module on human evolution. Study 1B describes the design and implementation of the WISE evolution module *Meiosis - the next generation* in high school biology classrooms. This study investigates ways to help students connect different biology domains to form a coherent systemic view that allows understanding real life phenomena. The research questions of study 1B are: 1) How did students' integration of evolution ideas change after using the WISE module *Meiosis - the next generation*? 2) How do the generative summative assessments methods concept mapping and essays differ in describing students' understanding of the connections between evolution ideas after the WISE module *Meiosis - the next generation*? 3) How can quantitative and qualitative concept map analysis methods (concept map topology, concept map accuracy score, and concept map convergence score) be used to distinguish different levels of knowledge integration? 4) How does the dynamic visualization BioLogica support knowledge integration of evolution ideas?

The curriculum incorporates an interactive dynamic technology-enhanced visualization, BioLogica, intended to facilitate students to make connections across different biological levels (genetics, cell biology, and evolution). The visualization allows students to explore the connections between genetics and cell biology by manipulating the genotype of a virtual organism. The curriculum connects the visualization to the pivotal principles of evolution to promote a systemic view. Study 1B explores students' integration of evolution ideas from the WISE module *Meiosis - the next generation* through concept maps and essays as summative generative assessment tools.

II. Study 1A: Concept Map Generation by Experts or Novices

A. Study 1A Rationale

Experts and novices differ in how they structure and connect ideas (Chi et al., 1981; Mintzes et al., 1997; Pearsall et al., 1997). Concept maps can reveal students' knowledge organization by showing connections, clusters of ideas, hierarchical levels, and cross-links between ideas from different levels (Shavelson et al., 2005). Connections between ideas can be seen as an indicator for more integrated knowledge (for example, see (Bransford et al., 2000; Glaser et al., 1985; Novak & Gowin, 1984).

Concept mapping can be a helpful metacognitive tool to visualize the interaction between new and prior ideas of the learner. The ability to construct a concept map illustrates two important properties of understanding: Representation and organization of ideas (Halford, 1993). The term representation is used differently in many contexts and therefore quite ambiguous. As a working definition for this study, a representation is a model (representing world), reflecting certain, but not all, aspects of the represented world (Palmer, 1978). A representation can be either a mental model or a materially embodied external representation (inscription) (Roth & McGinn, 1998). Internal and external representations are two indispensable parts of the representational system of any distributed cognitive task and interact with each other through cognitive processes. An inscription (e.g. diagram, text, maps, charts, tables, graphs) influences the existing mental model by providing new information that can be evaluated against the prior existing knowledge. Inscriptions are a medium that allows people to communicate. Through negotiation over an inscription, teacher and students can identify common ground and discrepancies. Inscriptions are not just peripheral aids to cognition, but provide a different form of representation (Zhang & Norman, 1994). They can provide memory aids or anchor and structure cognitive behavior. An external representation contains embedded rules that provide constraints by strictly determining what kind of information can be perceived, what processes can be activated, and what structures can be discovered from it. Zhang called this 'representation determinism'.

A person's internal representation affects the person's perception of the world as well as the production, comparison, and critical evaluation of inscriptions. An inscription is perceived through our senses, but it does not interpret itself (Von Glasersfeld, 1987). Perceiving, from a constructivist viewpoint, is always an active process, rather than passive receiving. To give a perception meaning, it needs to be interpreted. Interpretations require both domain knowledge as well as knowledge about the socially constructed conventions that informed the creation of this inscription.

Novices' insufficiency in both regards makes interpreting inscriptions very difficult for many students (Leinhardt, Zaslavsky, & Stein, 1990). Experts' content knowledge allows them to distinguish salient surface features from structurally important features of a representation. They are (often) aware of the limitations of a representation as it shares only a limited number of features with the represented world. Experts can better decide if a certain inscription allows them to illustrate, communicate, and analyze a certain principle and create new inscriptions, if required. This ability has been named meta-representational competence (DiSessa, 2004; diSessa, Hammer, Sherin, & Kolpakowski, 1991). Experts, such as research scientists, show a high level of meta-representational competence when creating inscriptions to reflect and communicate with one another. Inscriptions are an important part of their work (Kozma, 2003).

Learning about the commonly used inscriptions of a certain profession, and shared ways to make meaning out of them, is an essential element of becoming of member of this community. Inscriptions do not hold meaning by themselves, but have to be interpreted according to the practice of that field (Roth & Bowen, 2001). By frequently using inscriptions in the classroom, such as diagrams, tables, and concept maps, students increasingly learn to use inscriptions (Lynch, 1990). Experts however, due to their greater domain knowledge, can detect important elements of inscriptions better and cluster information, which reduces their cognitive load. Experts often create specific inscriptions to communicate a certain point. An expert will often not make the same inferences from the same inscription as a novice (Kozma, 2003).

The cognitive processes that connect the represented and representing world (directly or through intermediate steps) are complex and not yet well understood. Larking and Simon (1987) offered a computational model that focused primarily on internal representations: Diagrams are beneficial because they allow for faster indexing than text – but only to those who know the appropriate computational processes for taking advantage of them (experts). Diagrams allow to group information together, which reduces search time; automatically support a large number of perceptual inferences; use location to group information about a single element, avoiding the need to match symbolic labels (p. 98). This also applies to the concept maps used in this study [See chapter 2: Concept maps and Knowledge Integration]. Larkin and Simon later broadened their view and acknowledged the importance of external representations and the internal/external relationship.

Scaife and Rogers (1996) proposed an alternative framework which suggest three, somewhat overlapping, characteristics of this relationship: 1) "Computational offloading" refers to the extent to which an external representation reduces cognitive lead required to solve a problem. 2) "Re-representation" describes how the structural properties of an external representation can make problem solving easier or more difficult, for example familiarity with certain conventions (Zhang & Norman, 1994). 3) "Graphical constraining" refers to how graphical elements in a graphical representation constrain the kinds of inferences that can be made about the underlying represented world. As an inscription maps onto only a limited number of features in the represented world, it provides a constraint for the user. Expert and novice users have different awareness of these constraints. Constraints in inscriptions influence the reasoning about this inscription (Parnafes & diSessa, 2004). Relating to their work, this current study will use two different modes of reasoning as the framework for analysis of the representations and creation process: 'Constraint-based reasoning' refers to the cognitive process of finding values for a set of variables that will satisfy a given set of constraints. When utilizing this kind of reasoning, learners focus primarily on the constraints, one at a time. They try to find a solution that satisfies all given constrains. The second mode is 'model-based reasoning', a holistic approach, were learners try to address all or most constraints at the same time. They create a global model of the whole scenario.

Concept maps as assessment tools are often analyzed as completed artifacts without considering the thought processes that lead to this stage. Study 1B investigates how biology experts and novices differ in their concept map construction using a talk-aloud protocol. This case study describes observations made from three biology researchers and three high school students completing a constrained concept mapping task using a given list of evolution ideas. Study 1B compares how domain experts and novices differ in their use of constraint-based and model-based reasoning. Findings from study 1B aim to improve understanding of knowledge represented in concept maps.

Study 1A anticipates that domain experts create concept maps faster than novices because of their more integrated content knowledge; Experts' concept maps are more hierarchical and grouped than novices' because of their greater content knowledge; Experts' concept maps contain more cross-links than novices' do; Concept maps contain either a structural (e.g. organisms, cells, chromosomes) or a procedural/temporal pattern.

B. Study 1A Research Questions

Study 1A aims to answer the research questions:

1) How do biology novices and experts differ in their concept map generation and revision process?

2) How do novices of different academic performance levels differ in their concept map construction?

3) How does verbal reasoning (talk aloud) match with concept map construction?

C. Study 1A Methods

1) Study 1A Participants

Study 1A included three adult domain experts (two postdoctoral biology researchers and one biology teacher) and three 9th and 10th grade students from a public high school. The students received extra credit from their teacher for their voluntary participation.

2) Study 1A Procedure

Prior to the concept mapping task, the participants were interviewed about their familiarity with concept mapping in general, their evolution biology knowledge, and their experience with the concept mapping software "Inspiration". If necessary, a short training in concept mapping and the software "Inspiration" was given. The training phase included a presentation of a sample concept map of familiar everyday field [See figure 11] and a step-by-step concept map protocol, based on the networking technique (McClure et al., 1999a). Using this technique, ideas (or concepts) are connected with labeled arrows to describe the relationship between them. The participants were instructed to 1) group related ideas, 2) link ideas with arrows, 3) label each link, 4) add cross-links, and 5) revise the whole map.

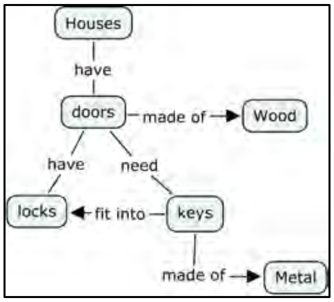


Figure 11: Concept map used to illustrate the concept mapping method.

All participants were instructed to talk aloud to describe their actions and reasoning while generating their concept map. The think-aloud technique has been found to reveal thought processes in a variety of tasks (Ericsson & Simon, 1985), for example concept map generation (Ruiz-Primo, Shavelson, Li, & Schultz, 2001), multiple-choice test taking (Levine, 1998), performance assessment (Ayala, Yin, Shavelson, & Vanides, 2002), and problem solving (Baxter & Glaser, 1998). Ericsson suggests that verbalization is a direct encoding of heeded thoughts that reflects their structure (Ericsson & Simon, 1985). Verbalizing one's inner dialogue does not need translation and does not cause additional processing; therefore talking aloud does not slow down task performance – as long as connections between ideas can be recalled from memory. When connections between ideas need to be newly generated, it leads to measurably slower verbalization. Because of their greater existing content knowledge, biology experts might need to generate fewer new connections between ideas when discussing evolution ideas than novices. Biology-experts might therefore show more fluent and faster verbalization of their knowledge and generation of concept maps in this study.

All participants were asked to verbalize their thinking while performing the concept mapping activities. Yin (2002) suggested that some information might get lost if only verbal data was recorded. Therefore, this study used screen capturing software and video recordings [See study 1B: Data Sources]

Participants received two tasks: The first task consisted of a concept map generation task [See chapter 2: Generation] from a given list of eighteen ideas [See table 14]. These ideas were identified by the researcher as core ideas in the US national educational standards for cell biology, genetics, and evolution. Ideas from all three different levels (cell, DNA, and evolution) were chosen and provided in a randomly arranged list (without the grouping shown in table 14). The forced choice design constrained the participants to use only provided ideas. The pivotal idea "mutation" was deliberately omitted from the list to investigate if participants would introduce the idea on their own. Participants received no time limit and were allowed to work on their concept map until satisfied with the final product.

Table 14: List of given ideas (organized by levels)

Evolution	Organism	Cell	DNA
Evolution Genetic variability Natural Selection	Random fusion of gametes Clones Diploid Haploid	Cell division Mitosis Meiosis Body cells Sex cells (gametes) Sperm cells Egg cells (ovum)	Chromosomes Chromatids Crossing over Random segregation of chromosomes

The second task consisted of a concept map critique task [See chapter 2: Critique], created by the researcher, which included five deliberate errors. Participants were instructed to identify possible errors and suggest corrections while talking aloud about their rationale. Each interview lasted between thirty to forty-five minutes.

3) Study 1A Data Sources

Four different kinds of data were collected:

- Concept maps: Concept maps can be drawn by hand or by using specialized computer software (e.g. Inspiration or Cmap). Royer's comparison between these two methods revealed significantly more complex concept maps when generated using concept mapping software (Royer & Royer, 2004). Study 1B used the concept mapping software "Inspiration" (Inspiration, 2007).
- Video: A video camera, placed behind the participants, recorded the computer screen, gestural and speech information.
- Screen recording: A screen recording software (Wisdom Soft, 2007) was used that allowed recording the concept map construction process.
- Detailed fieldnotes were taken by the researcher during the study.

4) Study 1A Analysis Methods

Concept maps were analyzed using the same methods as in study 1B. Each map was qualitatively classified according to the framework suggested by Yin (2005) [See study 1B]. Total accuracy score (of all propositions) and KI scores (of core propositions) were generated.

D. Study 1A Results

1) Biology Experts

The final concept maps of all six participants can be found in the attachment [See appendix chapter 4: study 1A].

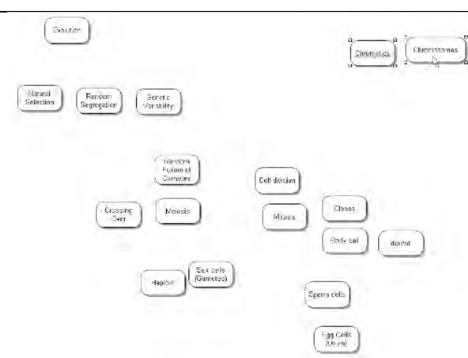
(i) Biology Expert A

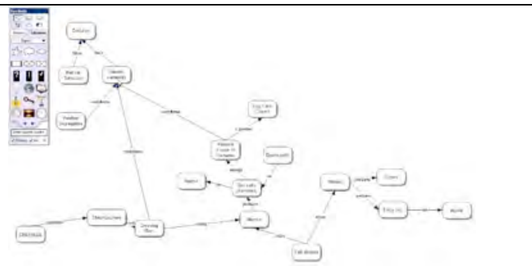
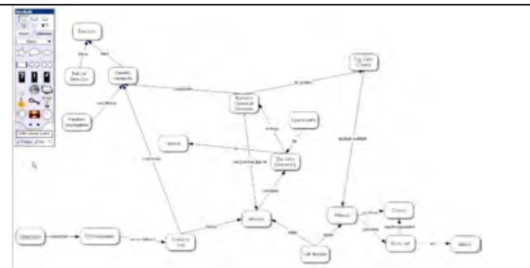
Expert A is a postdoctoral fellow in biophysical sciences at a major U.S. research university. He conducted his Ph.D. research in biomedical sciences in French at a Belgian university. He has no prior experience with concept mapping or the “Inspiration” software, but frequently uses flow charts in his professional presentations. He quickly understood the principles of concept mapping and the handling of the Inspiration software after the introduction.

Concept map generation task: Expert A began his concept map by dividing the ideas into two groups: cell division/meiosis/mitosis/clones and body cells/ sex cells/ sperm cells/ crossing over/ random fusion of gametes [See table 15]. He placed the most comprehensive idea “evolution” on top and grouped related terms, natural selection/ random segregation of chromosomes/ genetic variability, around it. In a second arrangement phase, he divided the terms into the groups meiosis and mitosis. Only after arranging all ideas, he began linking them. A said “I am thinking hierarchical, but the connectors are not going to be very hierarchical because sometimes an idea is the subject and sometimes an object”. And pointed at a horizontal chain which he just created. At the end of his systematic activity, which took only 15 minutes, he started, after prompting by the researcher, adding cross-links. This lead to the final concept map, which partially followed the ‘circle of life’-model: Random fusion of gametes -> fertilized ovum -> mitosis -> meiosis -> new gametes. A did not connect between egg cells and sex cells because he interpreted egg cells as being already fertilized. He also did not connect meiosis with genetic variability. He argued that the central idea “mutation” was missing in the list of given ideas and that without mutation meiosis will not enhance genetic variability. The comprehensive idea “cell division” was placed at the bottom of the map.

Concept map critique task: Expert A identified all five deliberate errors and offered alternatives.

Table 15: Concept map development of expert A.

	
Stage 1	**Stage 2**

	
Stage 3	**Stage 4**

(ii) Biology Expert B

Expert B is currently a postdoctoctoral fellow in neurogenetics at a major U.S. research university. P had no prior experience with concept mapping or Inspiration. He understood the principles of concept mapping quickly after the short introduction.

Concept map generation task: B began his concept map with the structural pairing of sex cells, sperm cells, and egg cells. From this starting point, he developed a temporal chain to illustrate meiotic and mitotic cell division. Like both other experts, he noticed the absence of the idea “mutation”. He explained that without mutation there would be no alleles and therefore no variability in meiosis. He stated that a reduction of evolution to the Darwinian view of natural selection and survival of the fittest leads to an inaccurate oversimplification. He suggested that ‘genetic drift’ should be added to the ideas. He created an interesting connection between body cells/ mitosis/ meiosis, by arguing that body cells can undergo either one of these two cell division processes. While working on his concept map, he tried to put himself in the position of high school students, as he perceived the given ideas as a restraint that forced him to make over-simplifications and large ‘logical stretches’. B made several connections, especially to evolutionary ideas, which implied several sub-steps. After finishing his first phase of connections, he began adding cross-links. He never connected the idea “cell division” with “meiosis” and “mitosis”. His final map did not show a hierarchical structure but mostly temporal chains. B invested 27 minutes on his concept map.

Concept map critique task: B identified all five errors without problems. He argued that meiosis does not take place in sex cells, but leads to their production. He did not express the same critique for the connection between mitosis and body cells.

(iii) Biology Expert C

Expert C has two years of experience teaching biology at a U.S. public high school. She received a bachelor degree in biology and a biology teacher credential degree. C teaches concept mapping to her students, but does not use it often herself.

Concept map generation task: C started by grouping the ideas into meiosis and mitosis under the top-level idea “cell division”. She placed chromosomes and chromatids between the two groups, as they belonged to both. The evolutionary ideas (evolution, natural selection) were singled out until the end of the activity. She then arranged and connected terms in each group either according to structure (e.g. cell type, haploid) or function (e.g. crossing over, genetic variability). In a second phase she rearranged the ideas to follow closely the life-cycle model from the biology textbook: Meiosis -> Fusion of gametes -> Body cells -> Mitosis. She recognized her approach herself as such from a meta-perspective. Chromosomes remained as the connecting element in the center. Finally, she added many cross-links and connected the evolution group with the cell division group, through the idea "genetic variability". Like the other two experts, C noticed the absence of the idea "mutation" and worked around this constraint by referring to mutation in the link label between chromosomes and genetic variability. Concluding, C stated that this activity has been 'really hard' and that she could now better appreciate what her students had to do. She spent 33 minutes until she expressed her satisfaction about her concept map. C created the most cross-linked concept map of all six participants.

Concept map critique task: C identified all five errors in the second task without problems. She critiqued two additional links: First, "meiosis does not take place in sex cells but produces them" – which is the same argument as expert C. Secondly, "evolution does not require genetic variability but natural selection does."

2) Biology Domain Novices

Novices

All three high school students were taught by the same teacher (biology expert C). The teacher identified these three students to represent the range of general academic performance level in her class (high, middle, and low). All students completed the weeklong WISE module *Meiosis - the next generation* [See study 1B] prior to participating in study 1A. All ideas used in the concept mapping activity were introduced in the WISE module. All three students were familiar with concept mapping and talk aloud activities from previous classroom activities. None of the students has used the software 'Inspiration' before but they experienced no difficulties using the software after the introduction.

The first concept mapping task was part of a regular homework assignment for all classes of the teacher. Both students D and F asked to revise their concept maps again at home, where they could use their textbooks, before handing them in. Student E decided not to revise the concept map at home.

(i) Biology Novice D

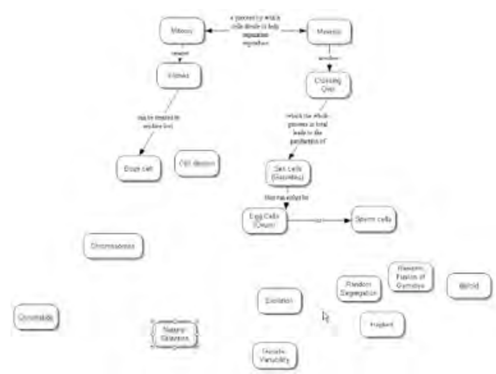
Student D is in 9^{th} grade and described as a high performing (A+ grade range) student by her teacher. D showed complex and coherent understanding of the topic, despite being in a lower grade than the other two novice participants. She was the most articulate of all three students and engaged in checking, revising, and investing the most amount of time in her concept map (45min) of all six participants.

Concept map generation task: She revised the validity of every proposition again each time after adding another idea. Her approach was very thorough and systematic. Like expert C, she first grouped all ideas into two groups, meiosis and mitosis, and placed the idea 'chromosomes' in-between them. She then arranged and linked the ideas in each groups according to procedural criteria. She correctly linked evolution to the meiosis group, but failed to make correct connections between genetic variability, random segregation, and random fusion of gametes. She created a proposition that genetic variability leads to natural selection, which would have to be considered incorrect at first, but after prompting, she gave a comprehensive oral description of the relationships between meiosis, genetic variability, natural selection, and evolution. Finally, she added several cross-links and checked each proposition again [See table 16].

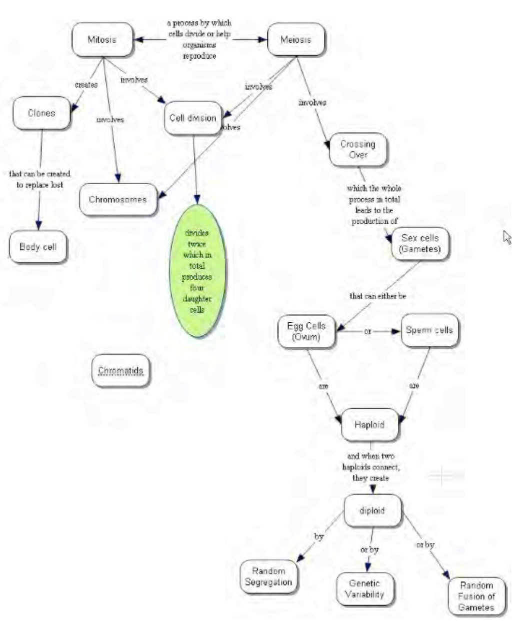
Concept map critique task: D identified 3 out 5 errors correctly: She missed 'mitosis leads to evolution' and 'genetic variability is like random segregation'. Like expert C, she disagreed with the proposition that meiosis takes place in sex cells, and also did not produce the same argument about mitosis.

Table 16: Concept map development of student D.

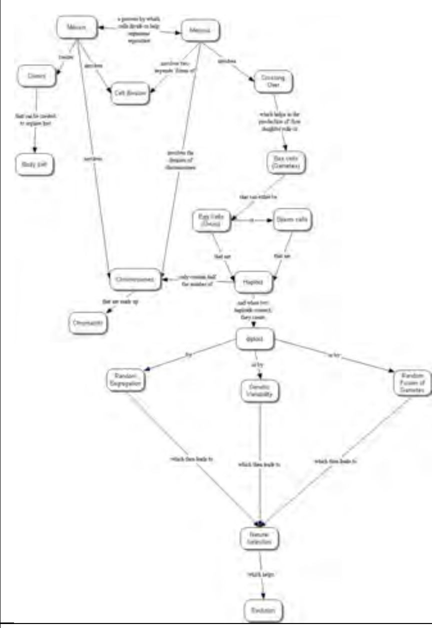
Stage 1



Stage 2



Stage 3



Stage 4

(ii) Biology Novice E

Student E is a 10th grade student whose teacher described her as a mostly middle level (B/C grade range) student.

Concept map generation task: E first divided all ideas into two groups, mitosis and meiosis. Like expert C, he placed chromosomes between the two cell division subgroups. He singled out evolution and natural selection and did not connect them until the end of the activity. After prompting by the researcher, he readily realized the connection between genetic variability and evolution. AA was not sure about the ideas haploid and diploid, but nevertheless placed them correctly. He did not use the ideas chromatids and crossing over, as he could not recall their meaning. Like all three experts, he noticed the absence of the idea mutation. E worked very systematic and fast; he finished his concept map in only 12 minutes. Except for the link between cell division and evolution, his mapping flowed fast and his comments were valid and precise. This supports the assumption that he had existing connections between the given ideas and did not have to newly generate them.

Concept map critique task: E identified all five deliberate errors without problems. Additionally, he wrongly marked two correct propositions: "Chromosomes consist of one or two chromatids", and "crossing over contributes to genetic variability". However, he supported his choices with the valid argument that genetic variability needs to exist *before* crossing over.

(iii) Biology Novice F

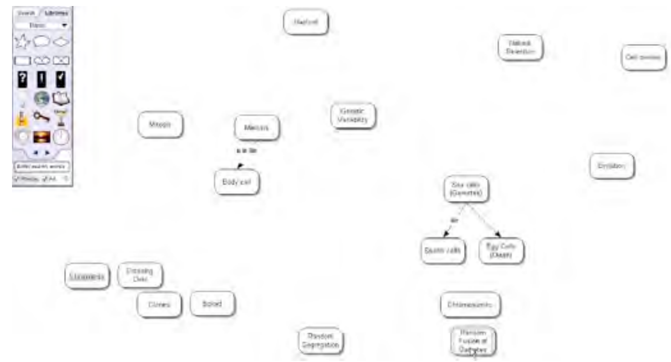
Student F is in 10th grade and described as a low level (D+/C grade range) student by the teacher. F was unfamiliar with a majority of the given ideas and needed more prompts by the experimenter than the other five participants of the study.

Concept map generation task: F started by creating three different groups: cell division/meiosis/mitosis, evolution/natural selection, and sex cells/sperm cells/ egg cells. She was confused about the ideas mitosis and meiosis and could not remember the meaning of haploid and diploid. F began to connect the ideas in rather hesitant and unsystematic way. Her three initial groups evolved first into pairs and which were then prolonged into three independent chains. The chains followed the temporal sequence of cell division. F's labels were mostly very short, e.g. *and*, *or*, or *then*. She did not create a hierarchal order in her map. Even after prompting by the researcher, she failed to identify any cross-links between her three chains. F spent 25 minutes on her map and expressed her satisfaction after all links were "somehow connected". Her map, as well as her knowledge, seemed to be very fragmented and incomplete [See table 17].

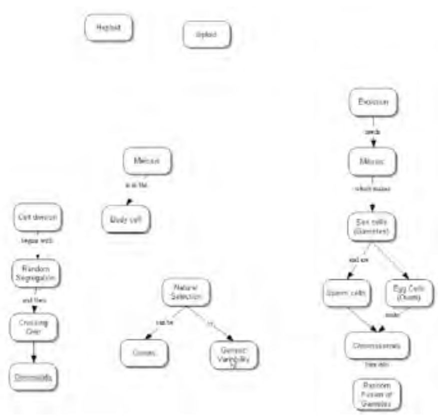
Concept map critique task: F could identify only one ("evolution leads to clones") out of five mistakes.

Table 17: Concept map development of student F.

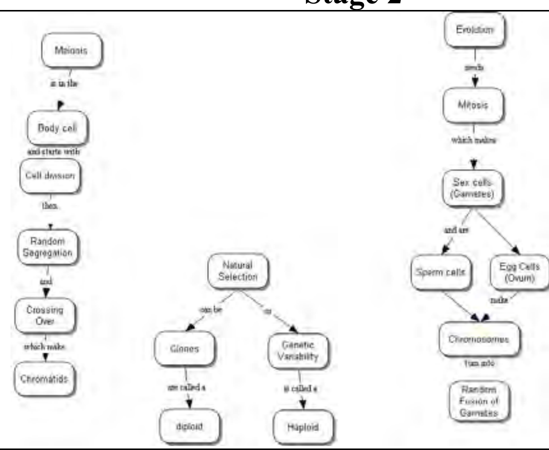
Stage 1



Stage 2



Stage 3



Stage 4

E. Study 1A Discussion and Conclusions

Analysis of the six case studies suggests that verbalization allows for more elaborate descriptions of one's reasoning than the condensed form of the concept map propositions alone. The reason might be that verbalization requires less translation of thoughts into another (graphical) form and poses fewer constraints than the concept mapping task. Several times, oral explanations clarified concept map propositions that would otherwise had to be considered invalid, for example see student D. Like all inscriptions (including language), concept mapping can represent knowledge only to a limited extend. During concept map generation, correct intermediate propositions were often changed to invalid propositions, and vice versa. Initial groupings and hierarchies disappeared during the further development of the concept map. These intermediate stages are not accessible to somebody who only receives the final concept map.

The initial assumptions about differences between experts and students were not verified: Their maps differed much less from each other than anticipated. Teacher-expert C created the most complex map, followed by students D and E. Experts and novices did not significantly differ by time requirements or by their ability to create groups and hierarchies. Maps of knowledgeable students showed as many cross-links and network complexities as maps created by experts.

An explanation could be that concept mapping task constraints favor short-hand descriptions of relationships between ideas that do not fully reflect more extensive expert knowledge. All three experts, but only one of the students, mentioned that the pivotal idea 'mutation' was missing. The given list of ideas can restrict the expression of learners' knowledge, but several times they found ways to work around this limitation, for example by using the omitted idea 'mutation' in a link label.

The three experts and the knowledgeable students D and E fluidly generated their concept maps, which suggests that they had previously existing connection between the given ideas. On the other hand, student F progressed slowly and struggled creating connections in the concept map, which suggests that her biology ideas were not well integrated.

"Constraint-based reasoning" refers to the cognitive process of finding values for a set of variables that will satisfy a given set of constraints. When utilizing this kind of reasoning, learners focus primarily on the constraints, one at a time. They try to find a solution that satisfies all given constrains. The second mode is "model-based reasoning", a holistic approach, were learners try to address all or most constraints at the same time. They create a global model of the whole scenario. Results of the six case studies indicate that concepts maps can allow for both constraint-based reasoning and model-based reasoning, depending on the content knowledge of the participant. Content experts and knowledgeable students demonstrated their awareness of the constraints by noting that the given ideas represent only a limited representation of their actual understanding. After working on the concept map for some time, they observed that they sometimes hesitated adding more links to avoid "making a mess". This suggests that aesthetic reasoning can influence concept map generation. Findings suggest that there are differences between expert and novice reasoning when generating concept maps.

Experts used model-based reasoning as they generated their maps according to their previously existing connections. They could step back and look at the broader patterns in their maps. Experts demonstrated their ability to move between the two modes of reasoning: They switched back and forth between the big picture view of model-based reasoning to plan (arrange and re-arrange their ideas into groups) and the more detailed view of constraint-based reasoning when creating individual links. Novices expressed less big-picture reasoning. The academically weakest student F showed the greatest difficulties and created a fragmented, mostly linear concept map. Because of her limited content knowledge, she accepted the given constraints without questioning and used a constrain-based approach by adding one idea at a time. She seemed more focused on task completion than using concept maps to express her ideas.

Apart from the initial assumptions, experts and novices showed several noticeable differences. The research-experts expressed greater difficulties generating their concept maps than the teacher-expert or the students. Several factors could contribute to this observation:

The research-experts had trouble expressing their complex and sophisticated understanding in the constrained format of a concept map. All experts showed a deep understanding of the given biology ideas. The final proposition was often a short-hand for several verbally explained intermediate steps, implying more background knowledge. Some final propositions would have to be considered invalid (for example "mitosis contributes to evolution"), without a verbal elaboration (for example, research-expert PM argued that without mitosis there would be no higher organisms and their evolution, as their bodies developed through mitotic cell division).

The teacher-expert C showed less difficulty representing ideas in the short-hand form of concept maps because concept maps are frequently part of biology textbooks. She differentiated between more complex 'research science knowledge' and simplified 'school science knowledge'. C designed her concept map as an instructional tool for high school biology and structured her map according to the textbook 'circle of life' model.

The teacher-expert C had the evolution content knowledge currently present, as it was currently the topic in her class. Through her teaching activity, she learned how to present this content in a clear and structured way. The research-experts saw the content from a researcher's perspective. Their last encounter with high school textbooks was over a decade ago.

Overall, concept maps can reveal differences in biology knowledge of experts and novices. Concept maps reveal different forms of knowledge than other assessment forms: Concept maps show a big-picture view of selected connections, and how ideas are structured and grouped. The short-hand form used to describe relationships between ideas allows keeping a clean big-picture view but limits the explanatory depth. Experts and novices often used the same words to describe a relationship between ideas, but verbal description revealed that experts often compressed more extensive thought processes in a short-hand description than novices.

F. Implications and Limitations

A case study, such as study 1A, can offer only limited insight. However, by referring to other studies, several suggestions for the classroom can be offered.

Findings suggest that concept maps can be used as assessment tools to track changes in students' integration of evolution ideas. Concept maps could be used as embedded or summative assessment tools. However, results from study 1A highlight the possible divergence between the concept map generation process and the finished product. During the generation process, most participants grouped structurally related terms together and/or followed a temporal flow. The final product in its network form made it difficult to see these structures anymore. A teacher or researcher, who will evaluate only the final product, will often not have this additional information. Concept maps elicit only a limited snapshot of a learner's integrated knowledge. Participants' oral explanations of their thought processes often diverged or expanded the reasoning leading to certain propositions. Some link labels might even have to be considered incorrect without the accompanying oral explanation by the learner. One way to triangulate this hidden understanding could be looking at written assessments or oral explanations that cover the same ideas. In such longer explanations, learners can express their understanding in more detail and provide supporting evidence.

Findings from study 1A suggest that effective learning environments should offer evolution ideas in alternative representations. Meira (2002) observed an evolution of students' external representations over time and suggests that teachers should not restrict students' production of their own representations (also see (Roth & Bowen, 2001)). Study 1A and 1B used a concept map form that represents a compromise between open and heavily constrained forms. Open-ended concept maps, where students can choose their own ideas, might reflect students' knowledge structures more accurately, but they are more difficult to compare, require more time, and could be more challenging especially for weaker students. This study found concept maps as assessment tools to have limits: More constrained concept mapping forms [See chapter 2: Types of Concept Map Tasks] can result in ceiling effect (Ruiz-Primo, 2000; Ruiz-Primo et al., 2001; Yin et al., 2005). Due to the constraints of the concept mapping task (for example: given list of ideas; only one relationship between two ideas), a high performing student's map can be difficult to distinguish from an expert's map. Many participants generated only short link labels (maybe due to graphical restrictions (limited space between two nodes)) that did not represent the same understanding as their oral elaborations. In addition, experts and students might use the same link labels to describe a relationship between ideas, but the words might represent different meanings. Ariew (2003) noted that experts often use vernacular expressions as a short-hand for more complex scientific ideas.

Findings from study 1A indicate that the concept mapping technique and concept mapping software is easy and quick to teach and learn. Despite never having used the concept mapping software 'Inspiration' before, all students showed no problems using the software. This observation is along findings by other studies, that concept mapping and concept mapping software can easily be taught and applied. Students should be familiarized with concept mapping throughout the curriculum by assigning them smaller, well-defined topics. Teachers could lead a classroom discussion to identify characteristics of good concept maps and demonstrate how to group and connect ideas.

G. Concept Map Analysis and Benchmark Maps

Expert-generated maps could be used as benchmarks for concept map evaluation [See chapter 2: Forms of Concept Map Analysis]. However, findings from study 1A suggest that there is no single ideal expert benchmark map. Expert maps can strongly differ from one another (Acton et al., 1994), even when using a limited number of given ideas, and show great variety. Findings from study 1A suggest that concept maps with more connections are not necessarily better. Experts do not generate every possible connection but make informed decisions. Novices need scaffolding to support their critical reflection on which connections are important.

Using expert-generated benchmark maps might suggest that there is only one correct answer (Kinchin, 2000a). From a constructivist perspective, concept maps should reflect the rich variety of students' repertoire of ideas. As concept maps allow only one connection between two ideas, experts might not agree on which connection to prefer.

Results from study 1A also raise the question of who is considered an expert. There are many different kinds of experts, for example researchers, practitioners, proficient amateurs, and science teachers (see (Hmelo-Silver et al., 2007)). An expert benchmark map can be generated by a single expert (Coleman, 1998), by the teacher, or by a group of experts (Osmundson et al., 1999). Ruiz-Primo (2001) suggests creating an aggregated expert-group map. More education research is needed to address the "expert problem" by providing better descriptions of what constitutes an "expert" and distinguishing different types of experts.

As an implication, this study suggests that scoring individual propositions using a knowledge integration rubric can reveal a greater variety of students' alternative ideas than a direct comparison to an expert-generated benchmark map (as examples for direct comparisons see (Herl, O'Neil, Chung, Dennis, & Lee, 1997; Chang et al., 2001; Rye & Rubba, 2002; Cline, Brewster, & Fell, 2009; Ifenthaler, 2010)). The Knowledge Integration concept map rubric acknowledges different ways ideas can be expressed.

Concept maps aim to represent only selected important connections. More connections do not necessarily mean a better map (as used in Novak's 1984 coding method (Novak & Gowin, 1984)). This study suggests scoring only a small number of essential connections instead of all propositions (weighted scoring) (also see (Ruiz-Primo et al., 2009)). Expert-generated benchmark maps can be used to identify such essential propositions and as a benchmark to determine a meaningful number of connections.. Especially links between ideas at different levels can be seen as indicators for more coherent understanding.

III. Study 1B: Essay vs. Concept Map as Summative Assessments

A. Study 1B Rationale

Many students leave school with a very fragmented knowledge of biology (Mintzes et al., 1998; Mintzes et al., 2000b; Wandersee, 1989) that does not allow them to understand complex scientific systems and connections to their everyday lives. Dynamic interactive visualizations, embedded into a scaffolding curriculum, promise to allow students to build a robust connected understanding.

The goal of this study is to explore concept maps as generative assessment tools implemented in a technology-supported learning environment with interactive visualizations designed to support a more coherent understanding of evolution that enables learners to explain real-life phenomena.

Comprehensive understanding of evolution requires simultaneous thinking on different levels and connecting different types of explanations: Explanations on an observable level describe changes in phenotype trait changes in organisms; and explanations on an non-directly-observable level describe changes in the genotype. Multiple representations of the same phenomena can facilitate learning and performance supporting different explanations of scientific phenomena (Ainsworth, 2006; Pallant & Tinker, 2004). Making the connections between different representations is challenging as they are connected through multiple dynamic relationships that are not intuitively obvious to the learner (Duncan & Reiser, 2005). These characteristics make complex systems difficult to understand (Feltovich, Coulson, & Spiro, 2001). Students have difficulties coordinating and connecting these types of representations and explanations, which leads to various alternative ideas and learning difficulties (Eylon & Linn, 1988; Harrison, 2000) [See chapter 2: Understanding Evolution].

The Knowledge Integration (KI) framework fosters construction of connections between ideas and effectively measures the quality of students' integrated knowledge (Linn & Hsi, 2000). Building connections in complex systems is fundamental to understanding science. Knowledge structure is an important component of understanding a domain, especially in science (Novak & Gowin, 1984). Being knowledgeable in a domain means having highly integrated conceptual structure among certain core ideas. Eliciting these interconnections can help learners to gain a deeper, more coherent understanding. Visualization methods such as dynamic computer visualizations or concept maps have been shown to facilitate learning for coherent understanding [See chapter 2: Concept Maps as Learning Tools].

Dynamic computer-based visualizations with scaffolded inquiry activities can help eliciting and generate connections between ideas (Spitulnik, Krajcik, & Soloway, 1998). BioLogica (Concord Consortium, 2006) is an exemplar of a well-established computer environment that offers students a challenging and interactive inquiry environment to learn genetics across multiple levels of organization (Tsui & Treagust, 2007).

To visualize knowledge structures for assessment, concept maps have been shown to be a valuable method [See chapter 2: Concept Maps as Assessment Tools]. Concept maps are one form of external representation used to visualize students' connections between ideas. Concept mapping (Novak, 1990; 1996) has been shown to be a technique that can enhance learning in the sciences, a) as a learning strategy, b) as an instructional strategy, c) as a strategy for planning curriculum, or d) as a means of assessing students' understanding of science concepts [See chapter 2: Concept Map as Tools].

B. Study 1B Theoretical Framework

In order to form coherent understanding in biology, students need to integrate and distinguish their alternative ideas. Research on learning suggests that students hold a repertoire of loosely connected ideas, rather than internally consistent scientific theories, and that students often fail to connect ideas from one context to another (diSessa, 1988). The Knowledge integration (KI) framework (Linn et al., 2004) [See chapter 2: Knowledge Integration] aims to help students to form meaningful connections among diverse ideas. KI builds on two central findings: First, learners hold multiple conflicting ideas about the world around them (diSessa 2000). These ideas are often contextualized, what explains the observation that students use different ideas in their everyday life and in the classroom environment. Second, learners sort out, link, connect, critique, reconsider, prioritize, select and organize their ideas (Piaget, 1971a; Vygotsky, 1962). The process of integrating knowledge includes creating a repertoire of ideas, adding ideas to the repertoire, sorting out the various connections among the ideas, and developing criteria for connections between ideas.

The scaffolded knowledge integration (SKI) framework translates the KI framework into four pedagogical meta-principles that promote knowledge integration within instructional design: *Making science accessible*, *making thinking visible*, *helping students learn from others*, and *promote autonomy and lifelong learning* (Linn & Hsi, 2000). Together, the four SKI tenets serve to provide students with opportunities to form meaningful connections between ideas from multiple contexts. These four meta-principles serve several purposes: As guidelines for instruction or curriculum design as well as rubrics for researches [See chapter 3: Scaffolded Knowledge Integration].

1) Study 1B Concept Maps

Study 1B uses concept maps as a summative assessment tool [See chapter 2: Concept Maps as Assessment Tools]. Concept maps allow eliciting students' connections between ideas. Concept mapping has been shown to effectively assess students' understanding of scientific ideas (or concepts) (Novak, 1990; Novak, 1996). Students' domain knowledge, represented in a concept map, was found to have a high correlation to predict their problem-solving performances in that domain (Gordon & Gill, 1983).

Concept maps are graphical tools for organizing and representing knowledge [See chapter 2: Concept Map Definition]. Concept mapping was originally developed as a research tool in 1972 by Novak to better represent children's knowledge, formerly assessed through clinical interviews (Novak & Canas, 2006). A concept map includes nodes (ideas), linking lines (usually with a unidirectional arrow from one idea to another), and linking labels, which describe the relationship between nodes. Two nodes connected with a labeled line are called a proposition.

Using concept maps as assessment tools have been found to highly correlate with multiple choice tests and have high inter-rater reliability. However, concept mapping offers several advantages over multiple-choice tests: 1) Concept mapping assessment is generative, not responsive. 2) It reveals a student's higher order structure of his knowledge organization. 3) Concept maps allow seeing cross-links between ideas from different levels. Cross-links represent creative leaps on the part of the knowledge producer (Novak & Canas, 2006). 4) The high degree of explicitness makes them an ideal vehicle for exchange of ideas in collaborative construction of knowledge. 5) Concept maps combine the effects of visual representations and written text. 6) Concept maps allow students to self-monitor their knowledge. This enables concept maps to be used both as a learning tool and an assessment tool. 7) The form of assessment directs students learning. A cognitive-based learning and assessment tool that assesses for understanding, like concept mapping, fosters students' learning for conceptual understanding. 8) Concept mapping as an assessment tool allows not only to see what a person knows about a topic, but also how that person's ideas are organized, constructed, stored, retrieved, and manipulated.

Study 1A compares concept maps against essays, another generative assessment form. Generating and scoring essays can be challenging and time-consuming. Concept maps might offer an effective alternative to essays.

C. Study 1B Research Questions

Study 1B aims to answer the research questions:

1) How did students' integration of evolution ideas change after using the WISE module *Meiosis - the next generation*?
2) How do the generative summative assessments methods concept mapping and essays differ in describing students' understanding of the connections between evolution ideas after the WISE module *Meiosis - the next generation*?
3) How can quantitative and qualitative concept map analysis methods (concept map topology, concept map accuracy score, and concept map convergence score) be used to distinguish different levels of knowledge integration?
4) How does the dynamic visualization BioLogica support knowledge integration of evolution ideas?

D. Study 1B Methods

1) Study 1B Curriculum Design

The curriculum for this study, *Meiosis – the next generation*, was created using WISE [See chapter 3: WISE] and the BioLogica Dragon Genetics visualization (Concord Consortium, 2006). The WISE module *Meiosis - the next generation* aims to elicit the connections between meiotic cell division, genetic diversity, and evolution processes [See structure of WISE module Meiosis - the next generation in chapter 3: WISE Environment: Study 1B WISE module structure]. Understanding meiosis is one of the most important ideas to understand genetic diversity and evolution (Kindfield, 1994). The WISE module *Meiosis - the next generation* aims to support cumulative learning by combining ideas covered by the WISE modules *Simple Inheritance* (Genetics), *Birds of a feather evolve together* (Evolution), and *Mitosis and Cell Processes* (Mitosis and Cancer).

The WISE module *Meiosis – the next generation* has been designed according to the four principles of the scaffolded knowledge integration framework: 1) Making science accessible, 2) Making thinking visible, 3) Supporting peer learning, and 4) Supporting lifelong learning [also see chapter 3: Scaffolded Knowledge Integration].

1) Making Science Accessible

A) Leading Question: The leading questions for the module are “Why does every child look different?” and “To what degree can the traits of a child be predicted?” These questions serve as the recurring motive and link to prior real-life experiences of the students. Students explore explanations for these questions on two different levels: On a genotype level, “What are the genetic reasons for individual differences?”, and on the phenotype level, “Why is genetic diversity beneficial?”. Placing meiosis into the context of evolution and real-life experiences is expected to help students add new ideas to their repertoire, connect new ideas to existing ideas, and distinguish alternative ideas. The module illustrates genetic diversity using topics of interest to students, such as cloning and conjoined twins.

B) Focus questions: Many students have difficulties identifying the important ideas in a text, lecture, or other form of presentation. Part of the reason is that many students learn only to memorize but not integrate and critically evaluate ideas. They fail to construct connections between ideas and see learning as “blur of myriad facts, dates, names, equations, or procedural rules to be memorized, especially in science mathematics and history” (Novak & Canas, 2006) (p. 24). As a consequence, students find these subjects boring and feel that they cannot master these fields. Focus questions on top of each page aims to model identifying central ideas, connect science ideas to real-life phenomena, and serve as prompts for generating explanations and seeking evidence [See figure 14].

C) Glossary: Important ideas in the WISE module are made salient through bold-type letters and a mouse-rollover pop-up glossary. The glossary presents a short description of the idea and a phonetic pronunciation [See figure 12].

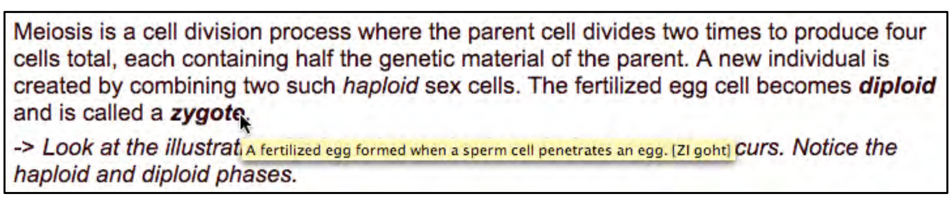


Figure 12: Roll-over glossary with phonetic pronunciation.

2) Making Thinking Visible

A) The WISE module *Meiosis - the next generation* uses a case study of human evolution. Scaffolded graphs, diagrams, videos, and dynamic visualizations show genetic, cell division, and evolution processes. Embedded notes with prompts ask students to generate explanations and revisit their existing ideas. [See figure 13].

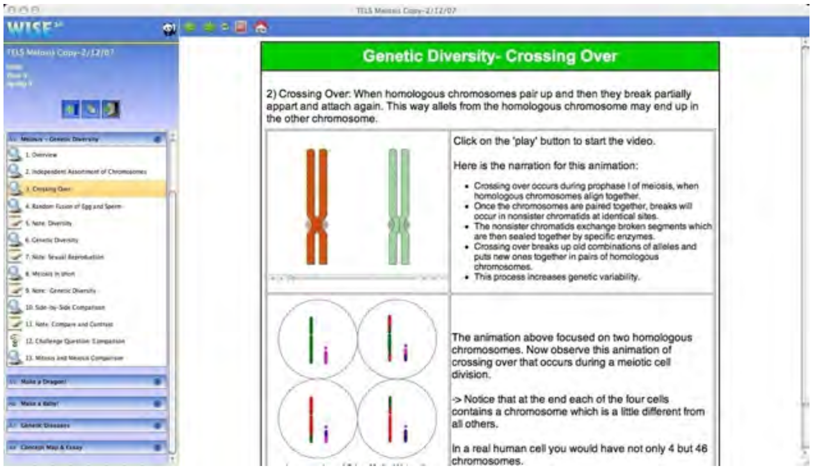
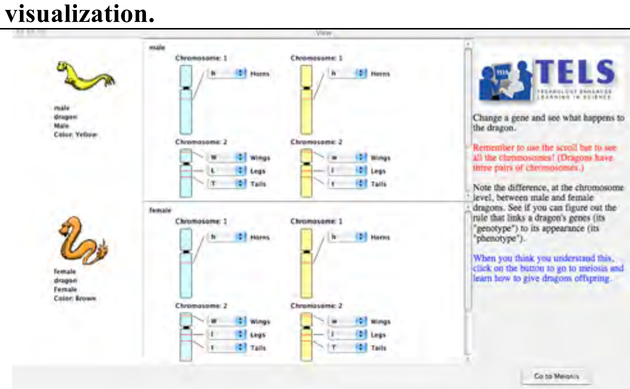
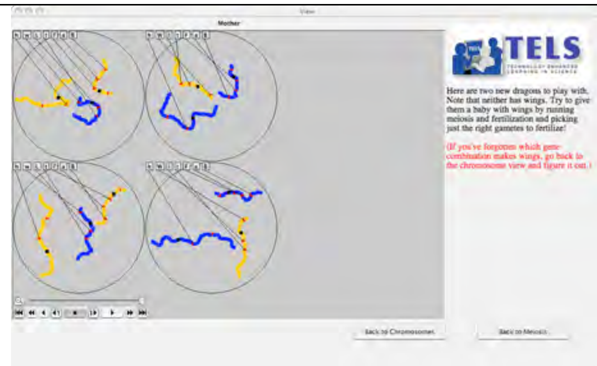
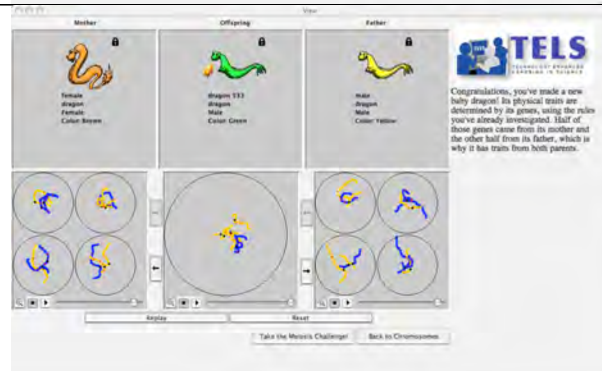


Figure 13: Inquiry map of WISE module "Meiosis - the next generation"

B) BioLogica Dragon Genetics is a (Concord Consortium, 2006) dynamic, interactive visualization that allows students to breed virtual organisms (dragons) and manipulate their genetic material. The visualization consists of three consecutive tasks: In the first task, students manipulate individual alleles and observe changes in the phenotype of the dragon. In the second task, students study animations of female and male gamete formation, choose chromosome of each for fertilization, and observe the effects on the phenotype of the offspring. The first two tasks can be repeated several times under varying conditions. The third task asks students to apply their knowledge from the first two tasks to create dragon offspring with certain specific traits. Ainsworth (1999) suggests that manipulating multiple interconnected representations could be beneficial for learning science ideas. In BioLogica, students explore genetic changes in the phenotype view, gamete view, and meiosis view [See table 18] to learn about the mechanisms that influence genetic diversity that is a pivotal idea to understanding evolution.

Table 18: Three different views in BioLogica visualization.

Genotype/ phenotype view	

Gamete view	
Meiosis view	

C) Embedded notes provide students with prompts to generate explanations using information presented in dynamic visualizations and existing ideas from real-life contexts. Teachers can score students' notes and provide feedback.

D) Challenge Questions: Some students, especially slow readers, tend to skip longer or complicated passages (Fishbach, 2005). Multiple choice questions after reading passages can give students immediate feedback and redirect them back to a previous evidence page, if required. This aims to model an effective self-monitoring of students' learning progress. Research indicates that challenge questions cause no drop in performance of high and medium literacy students, but a great increase in answer quality of low literacy students (Fishbach, 2005).

3) Supporting Peer Learning

Students work in dyads (both online and offline) to foster discussions of problems with a peer, development of a shared understanding, and hearing explanations in the words of a peer (see (Vygotsky, 1962)).

4) Supporting Life Long Learning

The WISE module introduces a female and a male character (Sue and Marc) as virtual guides [See figure 14]. They periodically ask questions that serve as starting points for students to generate explanations. The guides model the knowledge integration processes of asking questions about real-life phenomena, seeking evidence, distinguish ideas, and generate explanations. This strategy aims to support students' lifelong continuous learning of biology ideas.

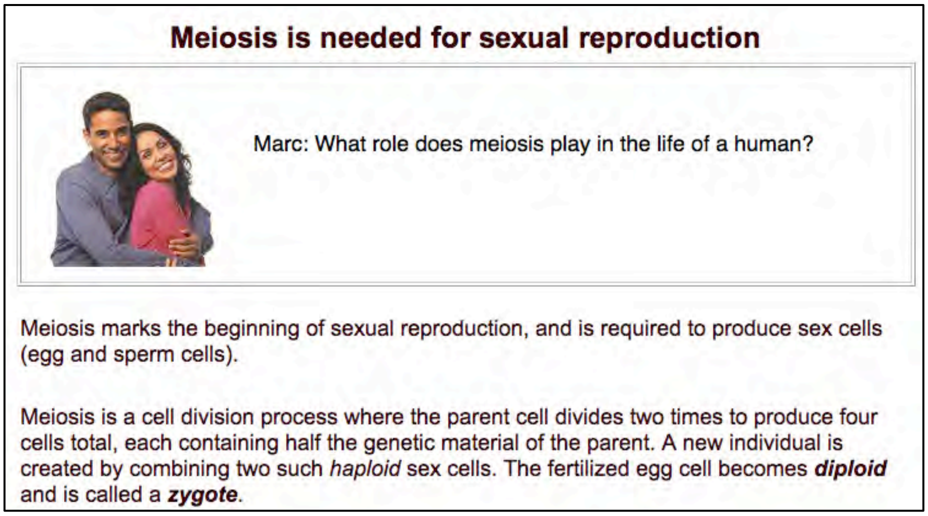


Figure 14: Focus question.

2) Study 1B Participants

The WISE module *Meiosis - the next generation* was implemented by three teachers in one public high school [See table 19]. Teacher A has a background in economics and had been a biology teacher for only year. All except one of his 9th and 10th grade classes were college-preparation classes. All classes had a diverse student population. Each class had about 30 students on average. Students spent two periods each day for one week with WISE module.

Table 19: Overview of study 1B participants.

Teacher	Prior experience with WISE	Researcher present in classroom	Number of classes	Number of students
A	No prior experience; attended WISE summer teacher workshop	Fulltime	4	96
B	Experienced WISE teacher; attended WISE summer teacher workshop	Part time	5	185
C	Experienced WISE teacher; attended WISE summer teacher workshop	Not present	4	126

More than 340 students in 13 classes participated in the *Meiosis – the next generation* module. Students in all three classes received an introduction to genetics in their previous grade. All students were in 9^{th} and 10^{th} grade and were ethnically and socioeconomically diverse. Teachers B and C as well as some students had previous experience with other WISE projects. All three teachers attended a WISE summer workshop and received support by an experienced teacher mentor.

3) Study 1B Data Sources

(i) Summative Assessments

(a) Pretests and Posttests

A pretest-posttest design was used to assess students' prior knowledge and learning gains. The assessments items targeted students' understanding of connections between cell biology, genetics, and evolution ideas. Individual pretests were completed prior to the project, and posttests were completed after finishing the project. The pretest-posttests consisted of five identical questions, each composed of a multiple choice item followed by a short-essay item that asked students to provide an explanation and evidence for their multiple choice answer [See table 20].

Sample item: "*Does sexual reproduction have an advantage over asexual reproduction*?"

a) Choose one: Yes/ No
b) Explain your choice by providing supporting evidence.

Table 20: Study 1B student's sample answer.

Pre-test answer	Post-test answer
"When organisms reproduce sexually they can pass on traits that are better and leave the weaker ones behind."	*"Meiosis (sexual reproduction) leads to genetic variation which allows natural selection to choose from these new combination of traits."*

(b) Concept Maps and Essays

To compare changes in knowledge integration, each class was assigned to one of two different generative summative assessments, either a concept mapping or an essay task. Essays and concept maps were used to assess the level of complexity of student's connections between cell biology, genetics, and evolution ideas.

Concept map task come in a wide variety [See chapter 2: Types of Concept Mapping Tasks], from open-ended free drawing to highly constrained forms where students have to fill in ideas out of a given list into a given network. The concept mapping task designed for study 1A seeks a balance between the extremes by providing students with a list of ideas while allowing them to freely choose their own labels and links (task type #2). Both concept mapping and essay tasks were constrained by the same list of ideas which all had to be used. The list included 18 different ideas from genetics, cell biology and evolution [See appendix chapter 4: Study 1B], and aimed to model what experts consider important ideas. Using the same ideas for concept maps and essays allows for a comparison of students' connections in each assessment form. Study 1A used paper-and-pencil concept maps.

(ii) Embedded Assessments

Embedded assessments allow teachers and researchers to track student learning progress during the module. Unlike summative assessments, embedded items provide a more detailed on-time view and inform teachers where exactly their students need more support. Embedded assessments during the module consisted of several open-ended questions. Student dyads answered all embedded questions electronically. The teachers scored embedded notes and made them part of the students' final grade. Students had the opportunity to revise their answers after they received feedback from the teacher.

4) Study 1B Analysis Methods

(i) Pretest/Posttest Analysis

Pretests, posttests, and selected embedded notes were scored using a 0-5 scale Knowledge Integration (KI) rubric (Linn et al., 2006) [See table 21]. Overall pretest and posttest scores weighted each item equally [See specific KI rubrics in appendix chapter 4: study 1B]. A total pre- and posttest score of all five explanation-items was calculated.

Table 21: Knowledge Integration rubric

Score	**Knowledge Integration**
0	No answer
1	Off task
2	Incorrect Non-normative ideas or links
3	Partial Idea without elaborate links
4	Basic One scientifically valid link between two relevant and normative ideas
5	Complex Two or more scientifically valid links

(ii) Concept Map Analysis

Literature research suggests that evaluating concept maps is no trivial task. Concept maps are highly individual representations of selected connections between ideas. Concept maps can be analyzed either quantitatively or qualitatively [see chapter 2: Forms of Concept Map Analysis].

(a) Quantitative Concept Map Analysis

Concept maps contain several elements that can be quantitatively evaluated: Links, ideas (or concepts), hierarchy levels, and propositions. Links and ideas can be easily counted but their amount provides little insight into a student's understanding. A higher number of links does not mean that the student understands the topic better as many links might be invalid or trivial (Austin & Shore, 1995b; Herl, Jr., Chung, & Schacter, 1999; Lomask, Baron, Greig, & Harrison, 1992) [See chapter 2: Quantitative Concept Map Analysis].

Evaluating the number of hierarchy levels has been suggested by Novak (1984). The existence of hierarchies can be linked to a higher level of expertise, but hierarchy levels are difficult to differentiate and many students create non-hierarchical but valid maps.

Propositions, the composite of two ideas and a labeled arrow, are the most promising element of a concept map to be evaluated in order to learn about students understanding. It can be decided to evaluate all ideas equally, to weight certain propositions more than others (Rye & Rubba, 2002), or to analyze only certain core ideas (Ruiz-Primo et al., 2009; Yin et al., 2005). Yin (2005) suggested that scoring each individual proposition on a four-point individual proposition scale, summed up to a 'total accuracy score', provided the best validity: 0 for scientifically wrong or irrelevant propositions, 1 for partially incorrect propositions, 2 for correct but scientifically 'thin' propositions, and 3 for scientifically correct and strong propositions. The 'total accuracy score' allows comparing the overall quality of students' concept maps. The disadvantage of this method is its time consumption and equal evaluation of links that show deeper understanding and trivial links.

Yin (2005) compared the total accuracy score to a second concept map scoring method, the convergence score. Propositions of the students' concept map are compared to a domain-expert generated criterion map. The convergence score is the proportion of accurate propositions out of all possible propositions in the criterion map. The criterion map used for study 1A represent a combination of the maps generated by the domain-experts who participated in study 1B. The criterion map included 30 propositions [See figure 15]. Only student-generated propositions that ranked 3 or 4 on the individual proposition scale were considered accurate. Yin found that the total accuracy score provided the higher validity than the convergence score but lacked in time efficiency. The shortcoming of the convergence score is that it equally values high-ranking propositions and does not weigh central ideas higher.

To address the two shortcomings of both the total accuracy and the convergence method, a new concept map scoring method, based on the KI rubric, has been developed for this study: Six core propositions were identified and a five level KI rubric created for each one. The central idea, which links cell biology, genetics, and evolution, has been identified as 'genetic variability'. Three factors contribute to genetic variability: Crossing over, random segregation of chromosomes, and random fusion of gametes. Genetic variability is the basis for natural selection, which reduces genetic variability by eliminating less well-adapted organisms out of the gene pool. Both genetic variability and natural selection are required to allow evolutionary changes.

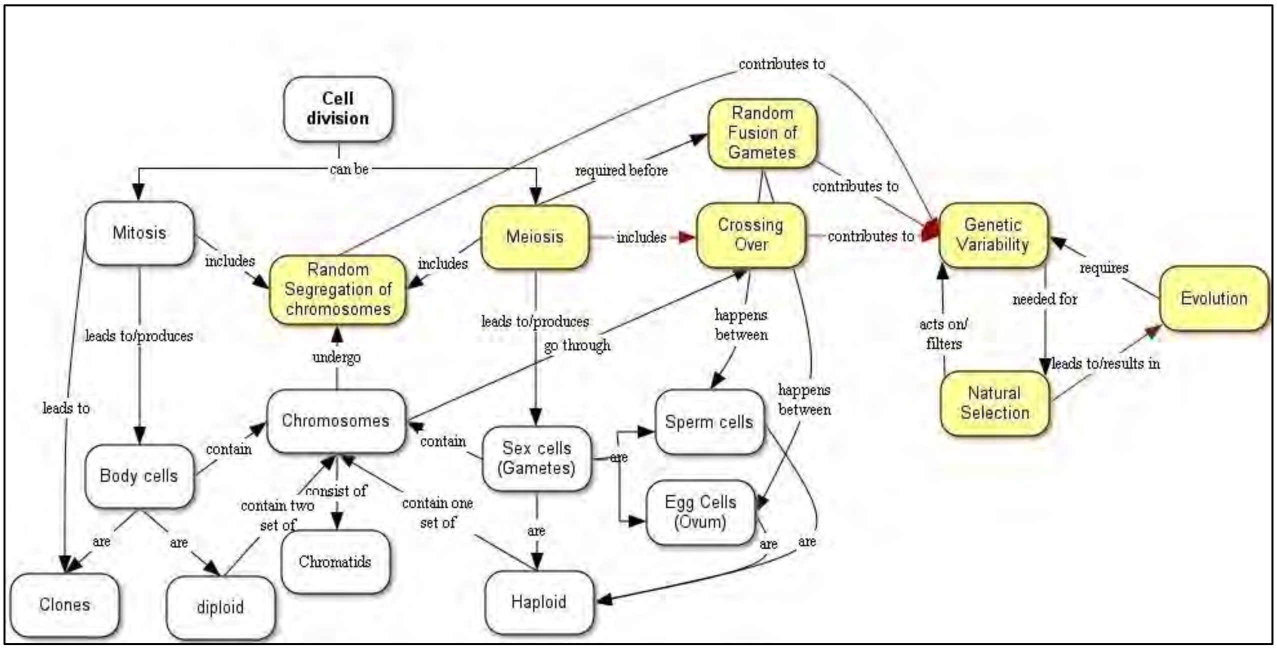


Figure 15: Expert concept map: Core ideas (yellow), core propositions (red).

The KI concept map rubric identified six core propositions.

- Crossing over contributes to genetic variability.
- Random segregation of chromosomes contributes to genetic variability.
- Random fusion of gametes contributes to genetic variability.
- Natural selection requires genetic variability.
- Evolution requires natural selection.
- Genetic variability is the basis of evolution.

The KI concept map rubric focuses on cross-links that show a coherent understanding across topics. This KI rubric promises to be significantly more time efficient than both other scoring methods, an important factor for large-scale assessment [See KI concept map rubric in appendix chapter 4: study 1B].

(b) Qualitative Concept Map Analysis

Kinchin (2000b; 2001) suggested a framework of four classes (simple, chain/linear, spoke/hub, net) that refer to the major structure of a concept map. This quick way to categorize concept maps can be used at the beginning of a lesson to pair students accordingly. According to Vygotsky's "zone of proximal development", it is beneficial to pair students of different ability levels (Vygotsky, 1978). Students who create a "network" show a more coherent prior understanding than students who create a simple map or a chain.

Yin (2005) suggested two additional classes (tree, circle):
(0) Simple: Mostly isolated propositions
(1) Linear/chain propositions, which are chained together;
(2) Circular propositions, which are daisy-chained with the ends joined;

(3) Hub or spoke propositions, which emanate from a center idea;
(4) Tree propositions, a linear chain that has branches attached; and
(5) Network or net propositions, a complex set of interconnected propositions.

A ranking of these categories is only possible at the extreme ends, with simple and chain at one end and networks at the other. All others classes fall in between.

This study used Yin's framework to quantitatively classify student's concept maps. The research question was whether there is a connection between students pretest performance and the concept map class.

(iii) Essay Analysis

Essays were scored by the same KI rubric as concept maps by translating the text into concept maps. This allowed visualizing students' connections between the six core ideas. Explanations were coded for connections between ideas on a score ranging from 0 to 5, a higher score indicating a more complex connection [see table 21].

E. Study 1B results

The results of study 1B consists of a *quantitative* analysis of data gathered through pretests and posttests, embedded challenge questions, concept maps, and essays [See appendix chapter 4: study 1B] and a *qualitative* description based on field notes by the researcher during the module run in teacher A's classroom.

1) Quantitative Observations

Study 1B used three different methods for summative assessments: Posttests, concept maps, and essays. In total, 330 pretests, 330 posttests, 330x12 items challenge questions, 78 concept maps, and 56 essays were evaluated.

(i) Pretest/Posttest Results

Paired t-tests of pretest and posttest scores indicate that students in all three classes achieved significant gains in their ability to link and connect explanations of cell division and genetics to evolution. Analysis by essay item suggests significant gains, especially on the first two items that test for students' knowledge of the connections between topics (cell biology, genetics, and evolution) [See figure 16].

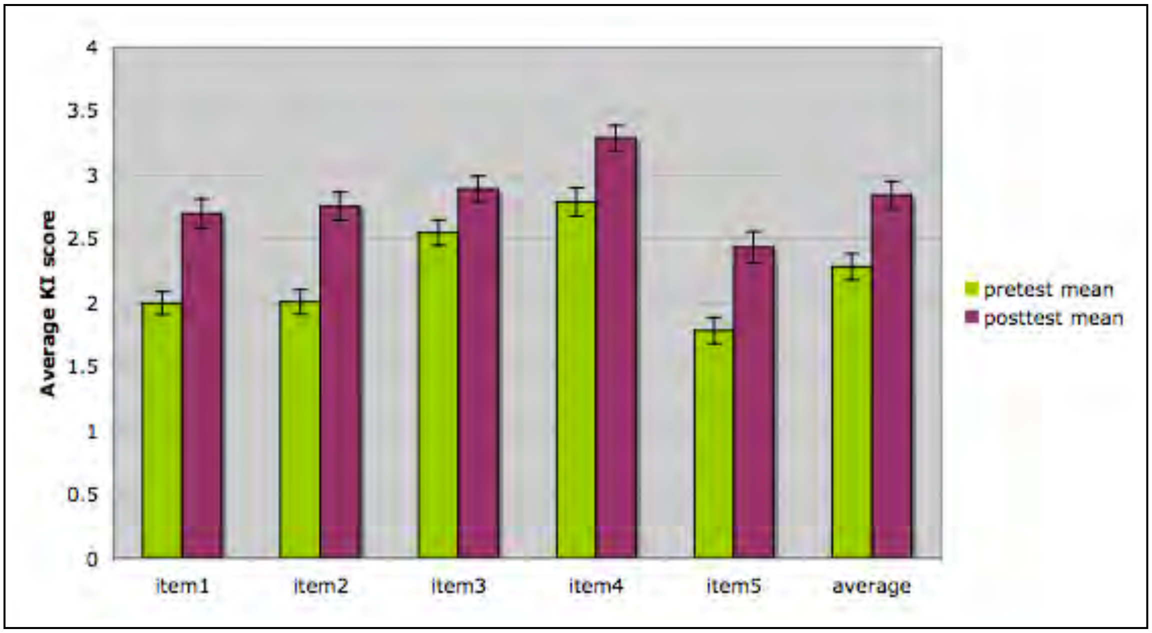


Figure 16: Average KI score by explanation item. Significant gains in knowledge integration in all five explanation pre/post-test items and total average KI score.

Each explanation item was preceded by a multiple choice question. Results suggest that students improved in their knowledge integration from pretest to posttest. Of particular interest is the increase in performance in item 2 that asked students about the core idea of the module ("How asexual and sexual reproduction contributes to evolution"). Items 3 and 4 that assessed more isolated factual knowledge showed less improvement [See figure 17].

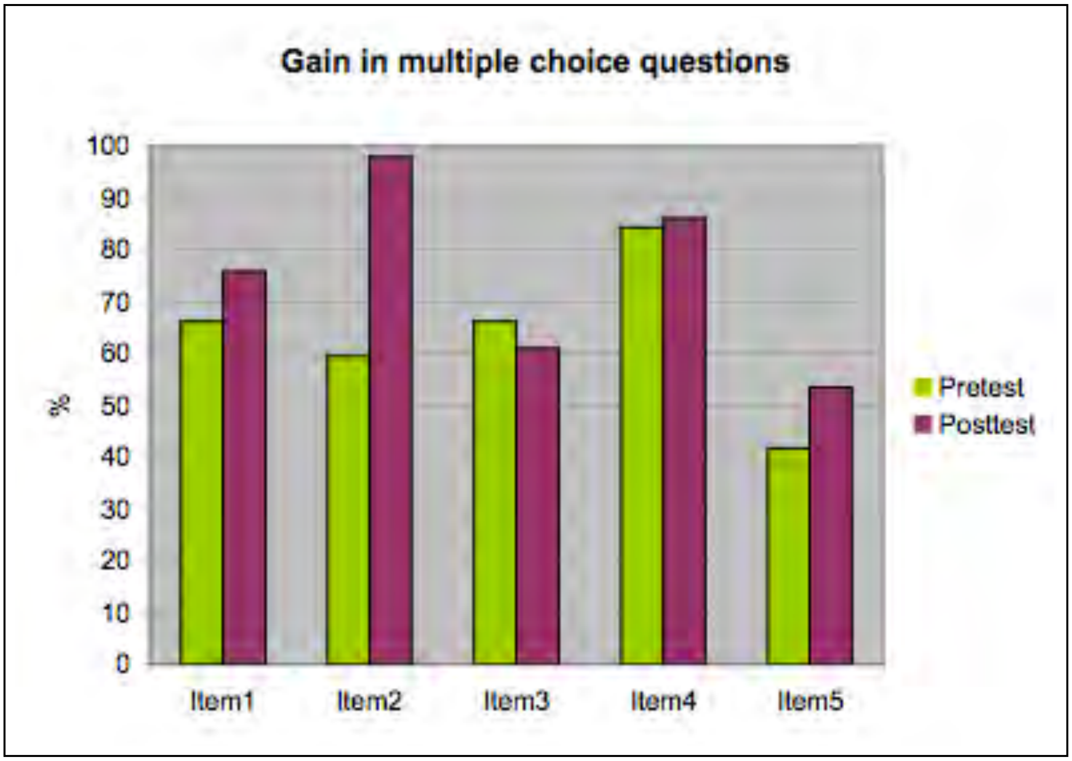


Figure 17: Gain in multiple choice items (in percent)

Results indicate that students improved in the multiple choice items from pretest to posttest [See figure 17].

Comparison by class indicates that students in all three classes gained from pretest to posttest [See figure 18].

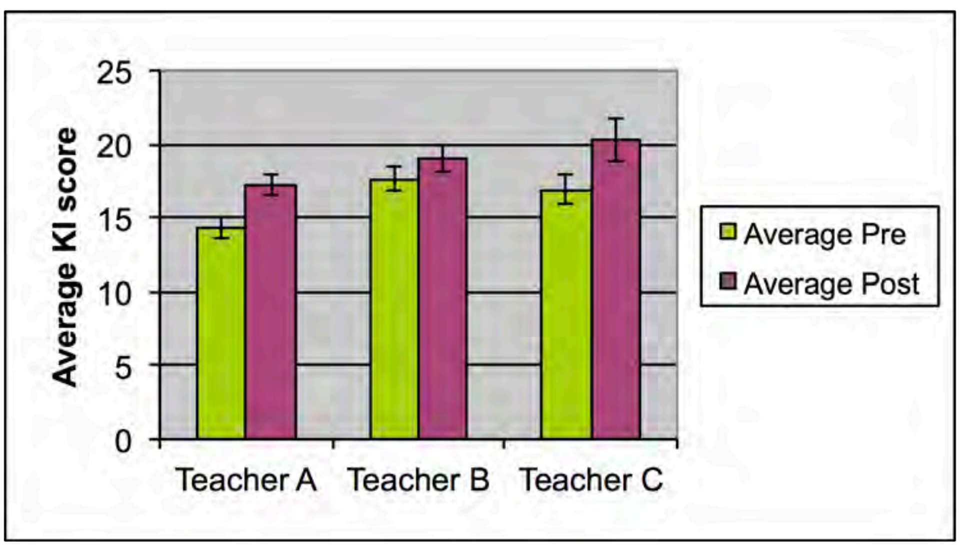


Figure 18: Average KI score by class.

Overall, 166 female and 175 male students participated in study 1B. Students of either sex showed significant gains from pre- to posttest. The curriculum therefore addresses female and male students equally well [See figure 19].

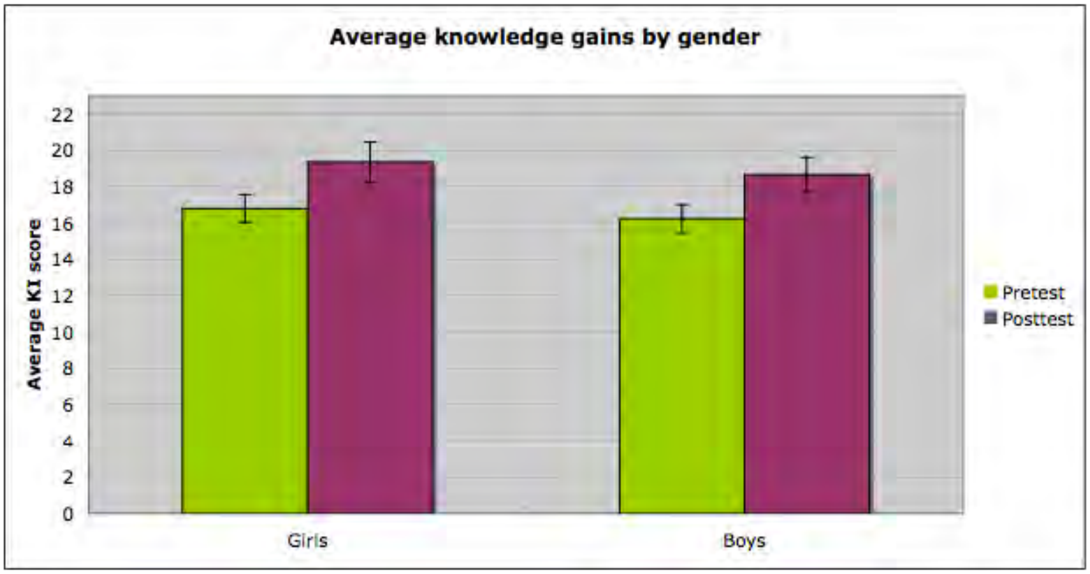


Figure 19: Average KI score by gender.

To investigate how students of different academic abilities gained from the curriculum, students were stratified into three groups according to their prior knowledge as measured by the pretest.

Low Group *(N=110): Pretest Mean=12.3 (SD=2.6), Posttest Mean=15.2 (SD=6.6), t(109)=4.3, p<0.001, ES=0.578*
Medium Group *(N=111): Pretest Mean=17.4 (SD=1.1), Posttest Mean=19.2 (SD=4.8), t(110)=4, p<0.001, ES=0.517*
High Group *(N=109): Pretest Mean=21.3 (SD=1.9), Posttest Mean=22.3 (SD=6.5), t(108)=1.7, p<0.001, ES=0.209*

Cohen's d effect sizes for t-tests have been calculated. Effect sizes for the low and medium group indicate a strong relation (0.578 and 0.517). The lower effect size of the high performance group could be due to a ceiling effect [See Figure 20].

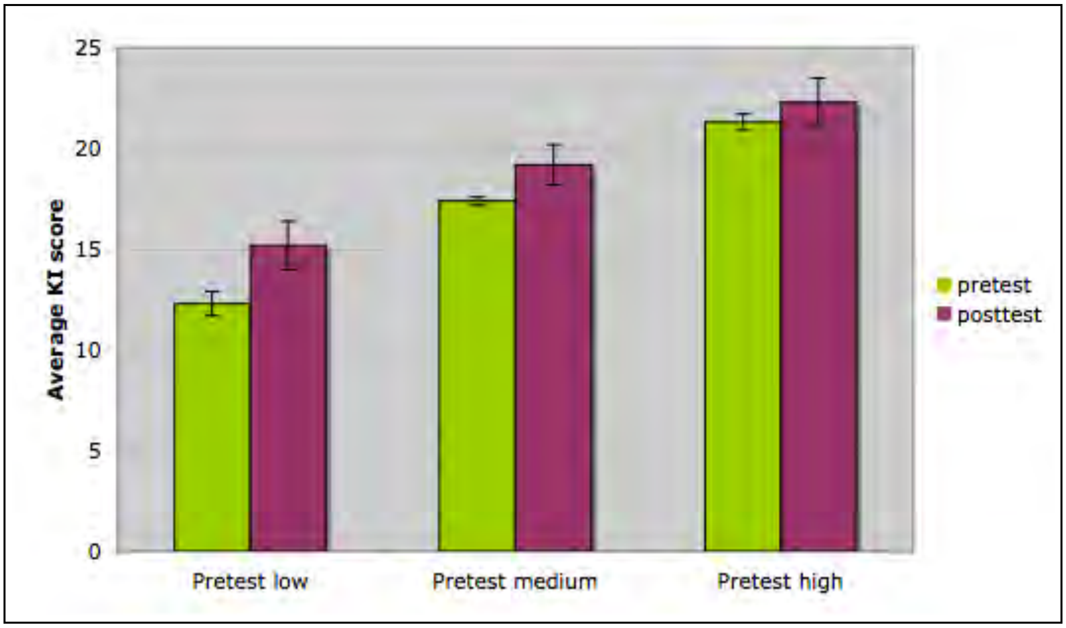


Figure 20: Average KI score gains by pretest performance.

Results suggest that students in each group (pretest low, medium, and high) gained from pre- to post-test. Students with low to medium pretest scores made the most gains. The lower learning gains of high performing students could be due to a ceiling effect of the assessment [See figure 20]. These findings are consistent with research on prior WISE modules.

(ii) Embedded Challenge Questions

The average score of all embedded challenge question items was calculated. Students' average challenge question scores were distinguished by pretest performance [See figure 21].

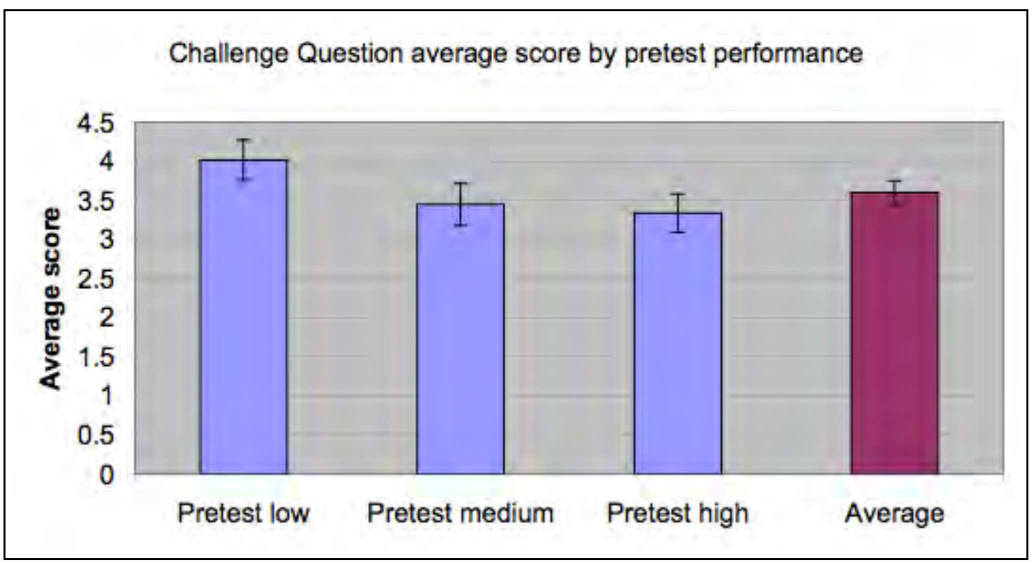


Figure 21: Embedded challenge question scores by pretest performance.

The pretest low performance group achieved above average challenge questions scores, while the medium and high group preformed around total average. In general, all three pretest performance groups showed high performance in the challenge question items.

(iii) Concept Maps

Study 1B used concept maps as summative assessment form. The concept maps have been analyzed qualitatively according to the classification suggested by Yin (2005) and qualitatively by determining the total accuracy score and KI score.

(a) Quantitative Concept Map Results

Grouping students by their pretest performance shows that the low group achieved a total accuracy score and convergence score significantly below average, the medium group at average, and the high group above average [See figure 22 and 23].

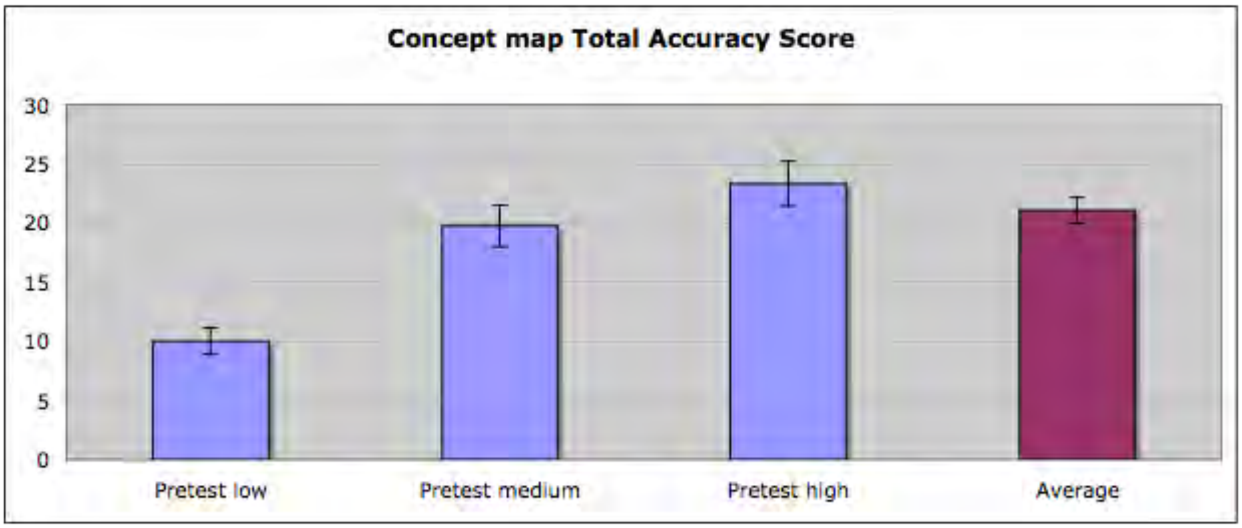


Figure 22: Concept map total accuracy score by pretest performance.

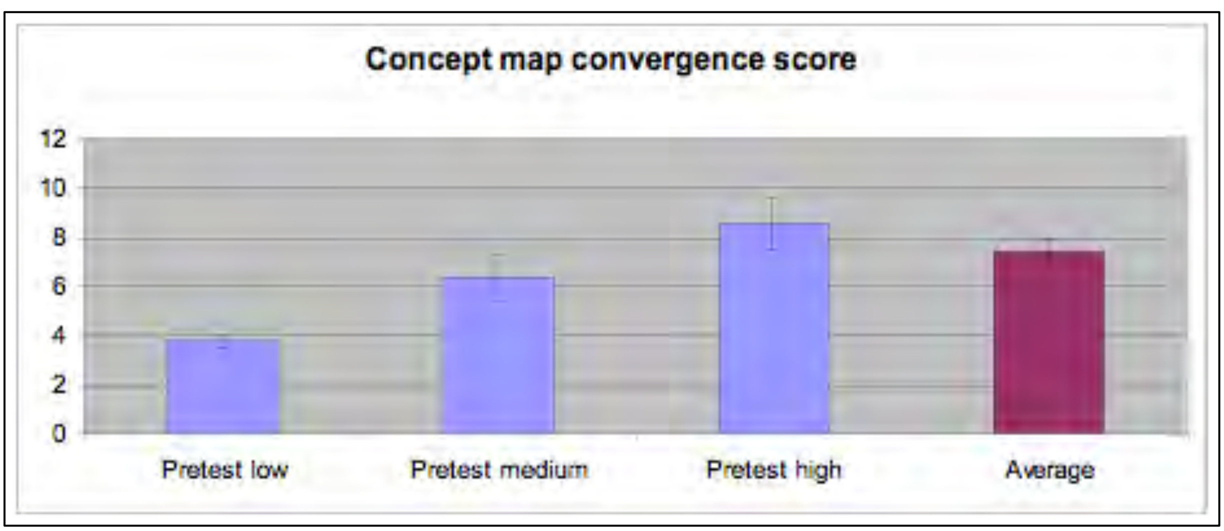


Figure 23: Concept map convergence score by pretest performance.

KI concept mapping scores show a very similar result than the total accuracy score. Students with low performance in the pretest achieved significantly below average KI scores, the medium group at average, and the high group above average [See figure 24].

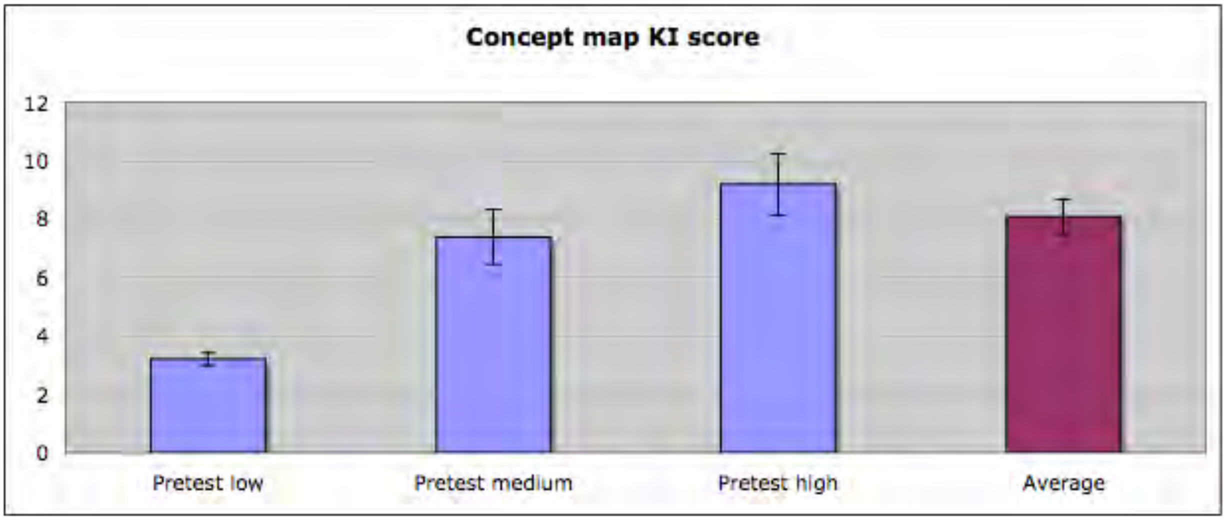


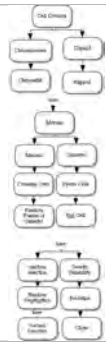
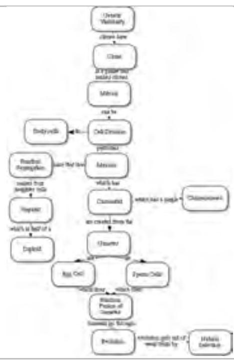
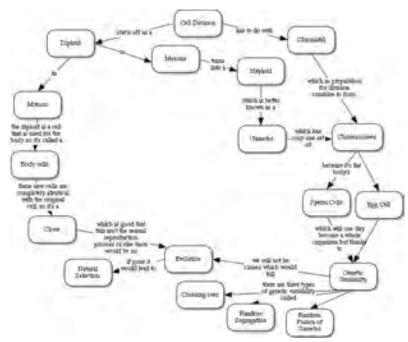
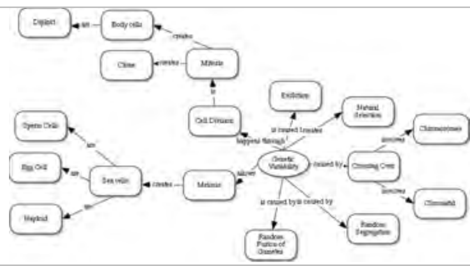
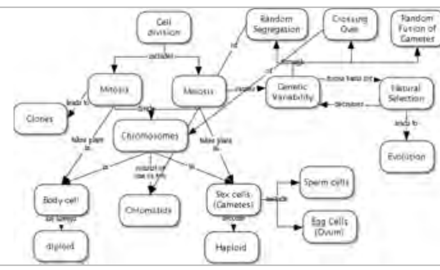
Figure 24: Concept map KI score by pretest performance.

(b) Qualitative Concept Map Results

Students generated a wide variety of different forms of concept maps [See table 22]:

- "Simple" concept maps with isolated groups of concepts without cross-connections between them showed very fragmented understanding.
- "Chain" concept maps were often based on temporal rather than functional connections between concepts. Frequently found temporal link labels were for example "then", "leads to", and "follows". Only few students created high scoring chain concept maps.
- "Circular' concept maps were rare and showed mostly the same temporal connections as in chains maps.
- "Tree" concept maps are closely related to chain maps, but showed often more functional relationships and branch off into subgroups.
- "Hub" concept maps showed that the student successfully identified a core concept, often "genetic variability" or "cell division", around which arranged concepts of lesser importance. The ability to identify a core concept can be seen as deeper understanding.
- "Network" maps achieved the highest total accuracy and KI scores due to their higher number of cross-links. They show a coherent systemic view between concepts of different levels and topics.

Table 22: Samples of students' concept map classes (Redrawn electronically by the author to improve clarity).

Simple	Chain
	
Tree	**Circular**
	
Hub	**Network**
	

Frequency analysis shows that chains (37%) are the most common concept map type, followed by hub (22%) and network (22%) [See figure 25].

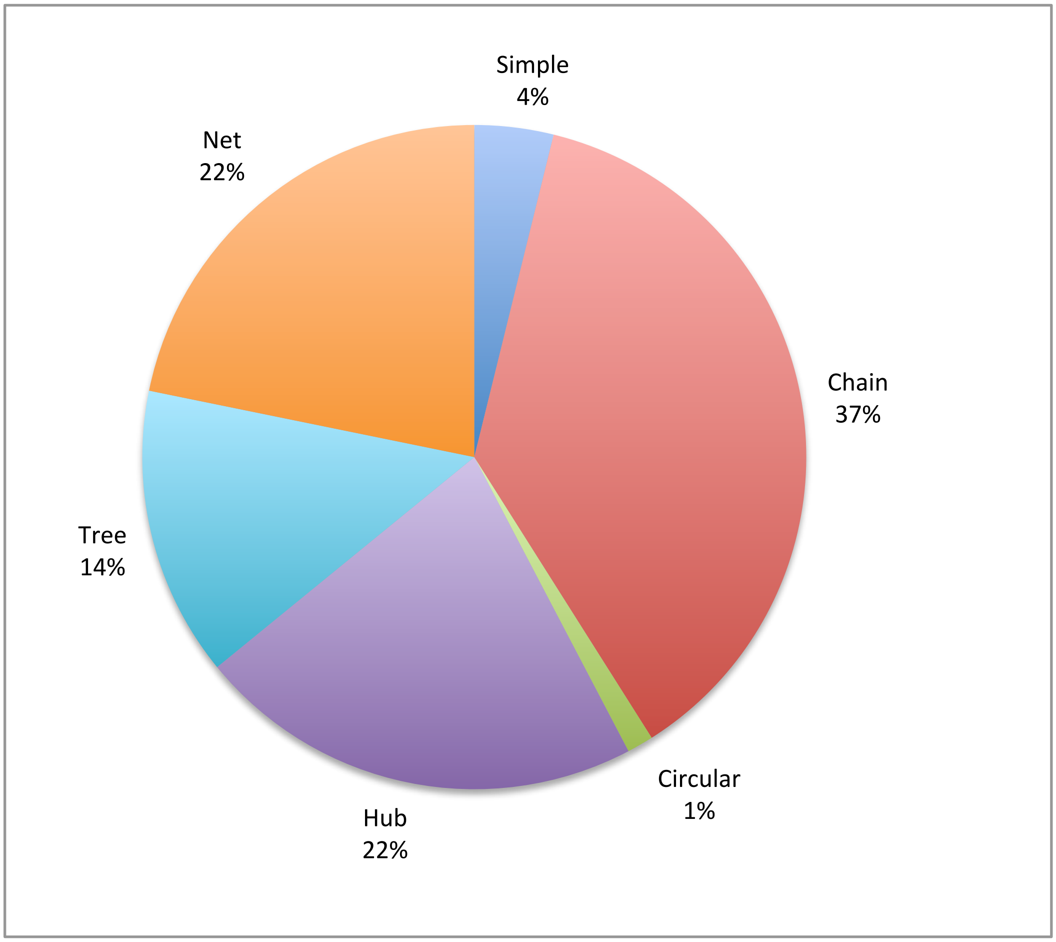


Figure 25: Frequency of different concept map classes.

Students with low pretest performance generated only simple or chain-class concept maps. Medium and high pretest performance students generated chain-class, hub-class, tree-class, and network-class concept maps [See figure 26].

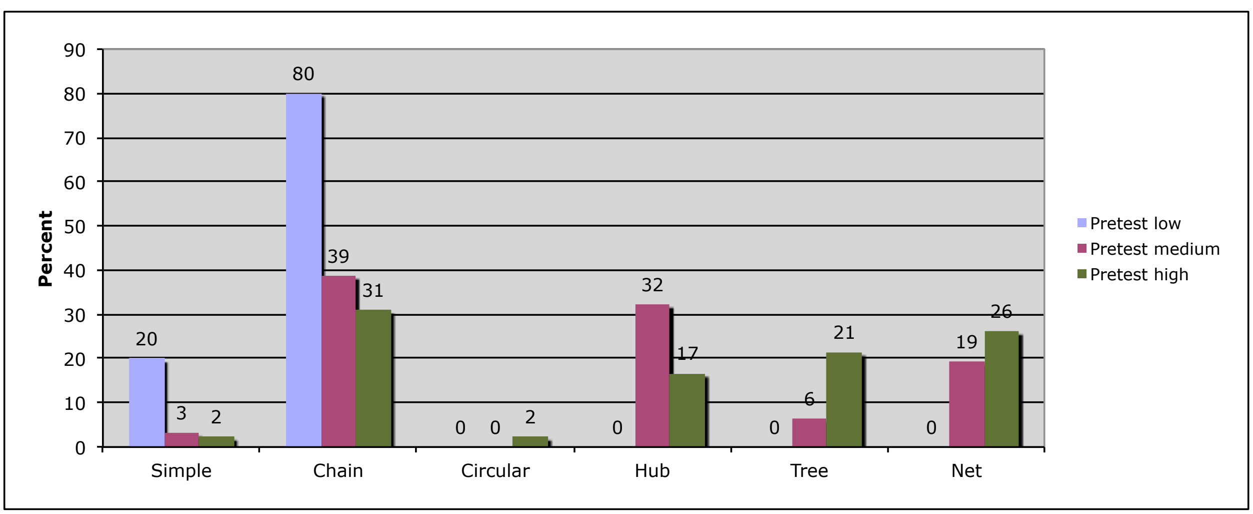


Figure 26: Concept map classes by pretest performance.

Concept maps revealed several interesting alternative ideas students hold about the field:

- "Natural selection helps an individual to adapt and survive": The normative view is that natural selection does not favor any individual or group. Individuals that show a phenotype with favorable traits for the current environment have a higher chance to survive and ensure the ongoing existence of their group.
- "Meiosis happens *to* sex cells": The normative view is that meiosis is the cell division process that *leads* to sex cells.
- "Meiosis leads to better adapted offspring": The normative view is that meiosis increases genetic diversity in a group that may or may not include better-adapted individuals.
- "Meiosis leads to more genetic diversity because it is more complicated": The normative view is that meiosis does not have an increased mutation rate over mitosis. Nevertheless, meiosis leads to more genetic diversity through crossing over and random segregation of chromosomes.

(iv) Essays

Similar to the quantitative concept map analysis, students pretest performance is reflected in their essay scores: Students in the pretest-low group achieved average essay scores below average, the medium group at average, and the high group significantly above average [See figure 27].

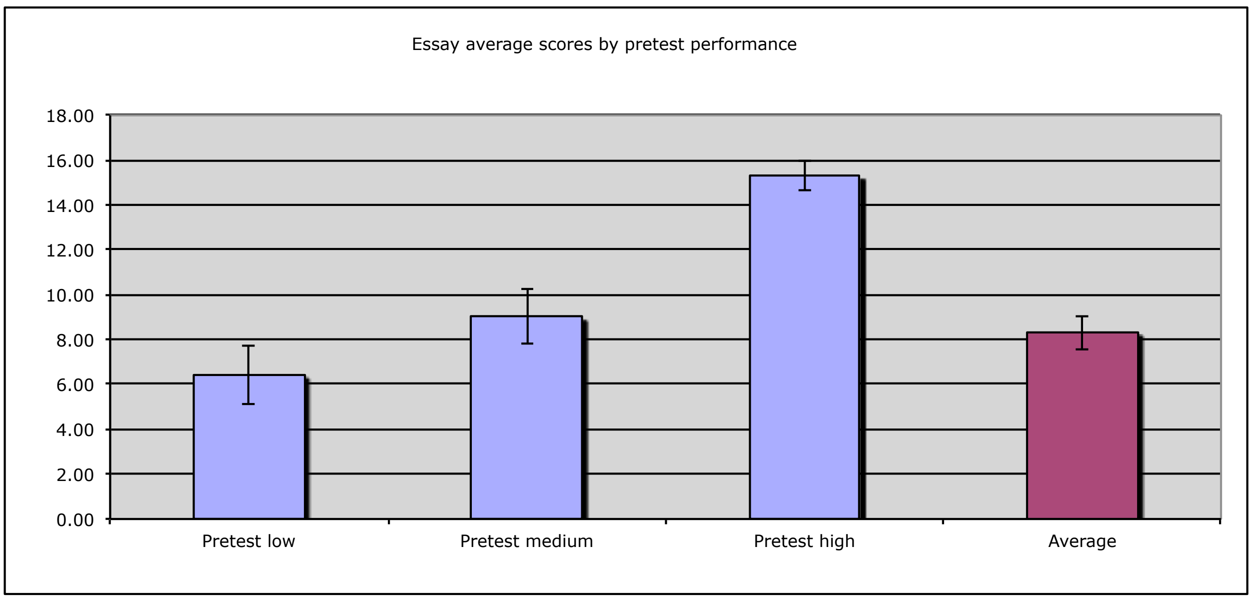


Figure 27: Average essay KI score by pretest performance.

Pearson's correlation analysis showed significant correlations with the posttest on the 0.01 level for all three concept mapping and essay scores [See table 23].

The three concept map scoring methods differ from each other in several ways. First, they differ in the way they weigh each proposition. The total accuracy score consists of the scores of all propositions without weighing. The convergence score includes only accurate (=high scoring) propositions. The convergence score is the proportion of accurate propositions in the students' map to the number of all possible propositions in the criterion map. The KI concept mapping score focuses exclusively on six core propositions. The six propositions are evaluated according to a KI rubric.

The three scoring methods differ also in their time demands. The total accuracy score is the most time demanding as every proposition is scored. The convergence score is more time efficient than the total accuracy score, but using an expert map as a 'correct' answer can limited the variety of alternative ideas that concept maps can capture. The KI score was found to be the most efficient of the three scoring methods used, while capturing a wide variety of alternative ideas [See study 1A: Concept Map Analysis and Benchmark Maps].

As the total accuracy score provided the highest validity in Yin's study, it can be considered the benchmark to compare other scoring methods against. The total accuracy score, convergence score, and KI score predicted the posttest score at the same level and are all positively correlated (0.329, 0.281, and 0.309). The KI score and the total accuracy score have a correlation significant at the 0.01 level of 0.618. The high correlation of 0.928 between the total accuracy score and the convergence score can be explained by the use of the same individual proposition scoring method. Convergence score and KI score both score only selected propositions, but use different scoring methods. They show a strongly positive correlation of 0.543.

A shortcoming of the total accuracy score is that students might reach the same score in different ways, for example through a map with a few high scoring propositions or a map with many low scoring propositions. The total accuracy score cannot differentiate between those maps. Yin (2005) suggested to either set a limit for the allowed number of propositions or score only key propositions. Scoring only key propositions, also called core connections, allows students more freedom as they can still construct a number of propositions of their own choosing. The KI concept map score incorporates these described features. The newly developed KI concept mapping score is a promising method that could be used in large-scale assessments. It could be considered the most time efficient concept map scoring method available to date. Its focus on core propositions assesses students' deeper understanding of the underlying principles.

Essays had a higher correlation with the posttest score than concept maps scores (0.431). As a trend, essays showed fewer but higher scoring KI propositions than the concept maps.

Table 23: Pearson's correlations between summative assessment methods.

	Post-Sum	Total Accuracy Score	Convergence Score (Compared with Criterion Map)	KI Core concept Score	Essay KI	
Post-Sum	Pearson Correlation	1	0.329(**)	0.281(*)	0.309(**)	0.431(**)
	Sig. (2-tailed)		0.003	0.011	0.005	0.001
	N	365	82	82	82	56
Total Accuracy Score	Pearson Correlation	0.329(**)	1	0.928(**)	0.618(**)	
	Sig. (2-tailed)	0.003		0.000	0.000	
	N	82	87	87	87	0
KI Core Ideas Score	Pearson Correlation	0.309(**)	0.618(**)	0.543(**)	1	
	Sig. (2-tailed)	0.005	0.000	0.000		
	N	82	87	87	87	0
Convergence Score (Compared with Criterion Map)	Pearson Correlation	0.281(*)	0.928(**)	1	0.543(**)	
	Sig. (2-tailed)	0.011	0.000		0.000	
	N	82	87	87	87	0
Essay KI	Pearson Correlation	0.431(**)				1
	Sig. (2-tailed)	0.001				
	N	56	0	0	0	56

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

2) Qualitative Observations

Day1: Teacher A introduced meiosis in the week prior to the WISE module. The students had learned about mitosis in middle school. He started each period with a 'warm-up' question reviewing last weeks lesson that the students had to answer with a short essay. An experienced WISE mentor introduced the module to the class and distributed the pretest. Students focused on the pretest for 5-10 minutes. Setting up the laptops and online accounts took about 20 minutes. The teacher allowed students to choose their own partner but advised them to pick someone they know 'they are productive with'. Students spent the remainder of the lesson finishing the first activity of the module.

General observations: Some classes proved to be more competitive than others by continuously comparing their challenge question scores. Student dyads progressed at significantly different speeds and showed different carefulness reading the provided information.

Several changes in the module were made according to observations in the classroom: Pictures and videos were uploaded to the WISE server, instead of using external links, to improve loading times and availability. The point value of the challenge questions has been reduced from 20-15-10-5 to 5-4-3-2-1 in order to decrease competitiveness among students.

Day 2: Teacher A started class by reading out an article about stem cells to the students. The students had to write a short essay about their personal opinions about stem cell research. A classroom discussion did not take place. Students continued with the second activity in the WISE module. Teacher A interrupted the class after he felt a majority reached the section about twins to show them a video about conjoined twins, followed by a short classroom discussion. The majority of the students were engaged and focused with the module. Student pairs showed different levels of interaction: Only a few students actively discussed the presented evidence with each other; some students read texts aloud to each other; many students took turns interacting with the module. The student were very excited about the challenge questions: Many shouted out load after answering correctly on the first try and gave each other high-fives. Several students had to learn how to use the Mac OSX environment.

Several changes were made after the observations of the second day: Additional scaffolding for several notes was implemented. Students received more specific instructions on how to navigate through the activity.

Day 3: Several students, especially careful readers, used the roll-over glossary. The teacher interrupted the class to play a rap song about mitosis (provided by the author of the module). Students were very enthusiastic about this activity and started to sing along the lyrics. The students filled out blanks on a worksheet with the lyrics. Expect for the short classroom discussion following the song, the teacher did not interact often with his students and spent most of his time on his computer to grade and comment on students' notes from the previous day. In agreement with the researcher, Teacher A decided to skip the 'make a baby' activity because of time shortage.

Day 4: Teacher A instructed students to revise their notes from the previous days according to his comments. He informed them that unrevised notes would lead to a lower total grade for the module. Several of the school laptops could not run the Concord Dragon Genetics visualization due to outdated software. Students formed temporarily bigger groups to work with the visualization. Teacher A demonstrated the Dragon Genetics visualization on a projector and gave instruction about how to handle the software.

Day 5: Teacher A observed that a specific pair of students, which usually did not work well together cooperated very well during the WISE module. This student pair showed great interest in the topic and asked several questions. Teacher A gained more confidence and expertise teaching the WISE curriculum with each additional class. At the end of the lesson, Teacher A instructed students to finish the remainder of the module individually at home. Three classes were assigned the concept mapping task and two the essay task as homework due by the next week. The posttest was issued in the first lesson of the following week.

F. Study 1B Discussion and Conclusions

Study 1B aimed to answer the questions:

1) How the WISE module *Meiosis - the next generation* helped students integrate evolution ideas?

The rich, authentic data gathered from thirteen classes indicates that students in all three groups (low, medium, high pretest performance) showed more integrated knowledge of evolution ideas after using the WISE module *Meiosis – the next generation.* Building connections between ideas from different fields (genetics, cell biology, and evolution) is essential to understand evolution phenomena.

2) How do the generative summative assessments methods concept mapping and essays differ in describing students' understanding of the connections between evolution ideas after the WISE module *Meiosis - the next generation*?

Study 1B implemented concept maps as generative summative assessments to track changes in students' integration of evolution ideas.

a) Comparison concept map and essay: Study 1B compared two forms of generative assessments: Essays and concept maps. In each treatment, students received the same seed ideas to include in their work. Results indicate that essays and concept maps can both effectively measure students' knowledge integration of evolution ideas, but focus on different forms of knowledge (also see (Ruiz-Primo, 2000; Shavelson et al., 2005; Yin et al., 2005)). As a trend, essays showed fewer but higher scoring KI propositions than the concept maps. Concept maps use each idea only once and elicit connections leading to or from that idea in the same place. Concept maps constrain the description of connections between ideas to short expressions. Essays allow for more detailed descriptions of connections, but the same idea is often used multiple times in different sections of an essay that can make it more difficult to get a big picture overview. Due to task constraints, concept maps require students to elicit the nature of relationships between ideas, which can be hidden or left ambiguous in essays. Findings suggest that concept maps are effective tools to elicit connections between ideas in a big picture view, while essays are efficient tools to elaborate on ideas and connections in more detail. Results indicate that concept maps are highly correlated with posttests and essays (also see (Stoddart et al., 2000)). This study suggests that concept maps can be a valuable addition and alternative to other generative summative assessment methods, such as essays.

b) New concept map scoring method: Study 1B compared three different concept map scoring methods: Total accuracy score, convergence score, and the novel KI concept map score. The total accuracy score consists of the scores of all propositions without weighing. The convergence score matches students' propositions to an expert-generated concept map. Both scoring methods have shortcomings: The total accuracy score is time-consuming and can include made trivial connections. The convergence score is more efficient but using an expert map as the "correct" answer can limited the variety of alternative ideas that concept maps can capture [See study 1A: Concept Map Analysis and Benchmark Maps].

The novel KI scoring method aims to alleviate both shortcomings: The KI concept map score uses expert-generated concept maps to identify important connections and ideas. Instead of matching the student map directly with the expert map as in the convergence score, the KI score uses a five scale KI rubric for each connection that allows for a wide variety of alternative ways to express ideas. Results from study 1B indicate that the KI score was the most efficient of the three scoring methods used, while capturing a wide variety of alternative evolution ideas

3) Can qualitative concept map analysis be used to distinguish different levels of knowledge integration?

Kinchin (2000b; 2001) and Yin (2005) suggested using the topology of the major structure of concept maps to categorize concept maps. Different than quantitative analysis that isolates individual propositions, topology analysis takes the overall structure of a concept map into account. Results from study 1B suggest that the concept map topology is correlated with students' academic performance (pretest score). Based in these findings, concept map topology can be used to describe concept maps and serve as indicators for the quality of concept maps.

4) How does the dynamic visualization BioLogica support knowledge integration of evolution ideas?

The BioLogica Dragon Genetics visualization activity allows learners to directly manipulate alleles and observe phenotypic changes. However, the BioLogica visualization is limited in several ways: The mechanism between the genetic level (chromosomes) and phenotype level is not explicit but appears as a black box. Many students understand genes as "trait-bearing particles" (Lewis & Kattmann, 2004) that directly control or contain phenotypic traits. Students who hold such a view do not see a necessity to distinguish between phenotype and genotype. Genes are difficult to understand because of their dual ontology, being both a physical particle and genetic information (Duncan & Reiser, 2007). Shea suggested that students need to learn about the role of proteins as the connecting element between genes and phenotypic traits (Shea & Golan Duncan, 2010). Learners need to be made aware of the assumptions and limitations of visualizations [See table 24].

Table 24: Similarities and differences between BioLogica visualization and human genetics.

BioLogica Visualization Limitations	**Real life**
Dragons have only 4 chromosomes	Organisms have larger numbers of chromosomes, e.g. humans have 23
Each trait controlled by only one/two alleles	Many traits controlled by several alleles in concert
Limited number of traits + all visible in phenotype	Large number of traits + many not directly visible in phenotype
Random reproduction	Non-random (sexual) selection
Embryo development omitted	Pregnancy and embryo development require time
All genes actively expressed all the time	Only some genes are actively expressed at times

IV. Study 1: Overall Discussion

Technology-supported science instruction environments, such the WISE module *Meiosis – the next generation*, allow presenting up-to-date scientific information. Using humans as a pivotal case for genetic diversity and evolution allows connecting scientific ideas to real-life phenomena. Dynamic visualizations, such as BioLogica, can elicit the dynamic relationships between genotype and phenotype ideas. Dynamic visualizations allow students to learn through inquiry-based activities to add new ideas to their repertoire and connect ideas across different contexts.

Findings suggest that concept maps can be used as generative assessment tools for evolution ideas. The new concept map analysis rubric was found to be a more efficient scoring method than previously proposed methods while having a similar diagnostic power. Focusing on core ideas instead of scoring all connections allows for a much more sensitive measurement of change over time than a total score that may include a large number of correct but non-essential connections. These findings are supported by a study by Ruiz-Primo (2009). Concept maps scores were strongly correlated with essay scores, which suggests that concept maps as a valid alternative method to measure students understanding. Different than essays, concept maps were found to show clusters of related ideas, and reveal both existing and missing links. Using a single one-shot generation activity is common usage in classrooms. Study 1A and 1B found that concept maps need often several revisions to reflect one's understanding more accurately.

A. Implications for Study 2

Study 1A and 1B explored concept maps as summative assessment tools. Findings suggest that concept maps can be valuable assessment tools. The strength of concept maps lies in allowing students to generate visual big-picture representations of their connected understanding. Study 1A explored the differences in concept map generation of biology experts and novices. Study 1B implemented concept maps as summative assessment tools after the WISE module *Meiosis - the next generation*. Study 1B compared the generative assessment tools concept maps and essays to measure gains in knowledge integration of evolution ideas. Findings suggest that concept maps require revision after the initial generation step. Study 2 explores concept maps as embedded learning tools for evolution. The visual form of concept maps can support collaborative learning [See chapter 2: Concept Maps as Collaborative Tools], for example students can collaboratively generate concept maps and critique peers' maps. Critique activities aim to generate criteria that allow distinguishing alternative ideas of evolution.

Study 1A suggests that concept map generation and critique activities require carefully designed instruction. Learners need adequate scaffolding to effectively generate and revise concept maps.

Study 1B used paper and pencil concept maps. For future iterations of the WISE module, a web-based concept mapping tool, similar in function as the offline tool 'Inspiration' used in study 1A, could be used. This tool would make it easier for students to re-arrange ideas into groups, provide a repository of ideas and labels to be used, and scaffold students with prompts to label all their links. This would decrease the risk of students forgetting to use certain ideas or draw unlabeled links between them. An electronic concept mapping tool can improve readability of the maps and allow for possible automated scoring to provide additional feedback to the students about their learning progress.

Study 1 used concept maps as summative assessment tools. Pankratius (1990) suggests that using concept maps as embedded learning tools can be more effective then using concept maps only at the end of a unit [See study 2]. On the other hand, when continuously revising concept maps throughout a unit, students might not revise their initial superstructures (Cheng 2001; Kinchin et al., 2005). Instead, students could be asked to create several smaller concept maps from scratch.

Results from study 1A indicate that concept maps can be improved through peer review. Peer review of concept maps could be mutually beneficial for both parties: The reviewed receives valuable feedback while the reviewer gets insight into another person's concept map, which can support revisiting his or her own alternative ideas. Students can internalize the role of the critic and improve their self-reflections about their own work, similar to the reciprocal teaching approach (Brown & Palincsar, 1989) [See study 2].

Study 1A successfully introduced concept map critique activities. Critiquing concept maps instead of or in addition to generating concept maps could be used as an efficient way to assess learners' understanding. Critiquing ideas is a central step in knowledge integration [See chapter 2: Knowledge Integration] [See chapter 2: Critique]. Concept maps with deliberate errors based on common alternative ideas could be used as learning tools to help learners revisit their own ideas, generate criteria to distinguish ideas, and sort out alternative ideas [See chapter 2: Concept Maps as Metacognitive Tools] and [See study 3].

CHAPTER 5: STUDY 2: KNOWLEDGE INTEGRATION MAPS AS LEARNING TOOLS: GENERATION AND CRITIQUE

I. Study 2 Abstract

Understanding evolution requires learners to connect genetic, cellular, and population level ideas. Students can hold a rich repertoire of alternative ideas that are often fragmented and disconnected [See study 1]. Concept maps aim to help students develop connections between ideas within and across different levels. Students need to learn how to critically distinguish alternative ideas. This study explores the effect of generating and critiquing concept maps on students' ability to build relationships between evolution ideas. Ideally, this activity would contribute to an integrated understanding of evolutionary change. A novel concept map form, called "Knowledge Integration Map" (KIM), structures the drawing area into biology-specific levels (DNA/cell/organism & population). Students receive a list of ideas to sort into the corresponding levels, and connect ideas with each other. The concept map activity was part of a technology-enhanced learning environment on genetic diversity and human evolution. Four classes of high school biology students (total n=81) generated concept maps and were then randomly assigned to two different treatments: Students in one group compared their concept maps to an expert-generated map, while the other group compared their maps to a peer-generated map. Pretest-posttest changes indicate that the learning environment lead to significantly improved understanding of evolutionary mechanisms for both treatment groups. However, the two groups developed different criteria: The expert-map group focused mostly on surface level criteria such as idea placement while the peer-map group used more conceptual criteria like directionality and missing connections. Findings suggest that generating and critiquing KIM activities can lead to a more integrated understanding of evolution.

II. Study 2 Rationale and Theoretical Framework

A. Fragmented Understanding of Biology

Based on study 1, study 2 explores concept maps as embedded learning tools in the WISE evolution module. Concept maps aim to help students develop connections between ideas within and across different levels. Students need to learn how to critically distinguish alternative ideas. This study explores the effect of generating and critiquing concept maps on students' ability to generate relationships between evolution ideas. Ideally, this activity would contribute to an integrated understanding of evolutionary change.

To understand evolution, students need effective learning tools to generate and elicit connections between ideas across different levels (for example genetic, cellular, and natural selection of phenotypic traits). This study aims to connect the following biological ideas [See figure 28]:

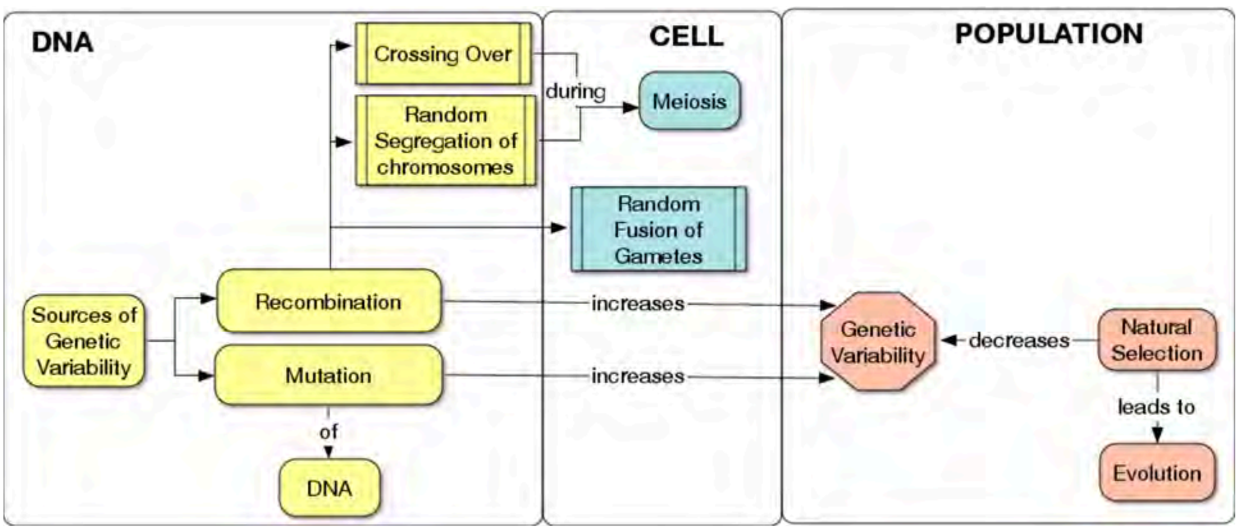


Figure 28: Biological ideas within and across levels.

B. Knowledge Integration

Learners develop many alternative ideas of the same phenomenon that are often highly contextualized and fragmented [See study 1]. Knowledge Integration (Linn & Hsi, 2000; Linn, Eylon, & Davis, 2004) explains this persistence by the amount by which an idea (or concept) is connected to existing ideas and applied in multiple contexts [See chapter 2: Knowledge Integration]. Alternative ideas, for example the idea "need", are often concrete and have been used in many different contexts for long periods of time. In contrast, scientific ideas, for example "natural selection", are often abstract and were introduced in a short time period in a formal instructional context. The lack of integration of scientific ideas hinders learners from applying them in everyday life context.

Knowledge Integration describes learning as the process of adding new ideas to the existing repertoire of ideas, making ideas and connections explicit, developing criteria to distinguish ideas from each other, and applying ideas to multiple contexts. Developing critical thinking is pivotal to learning scientific ideas as it allows students to distinguish different ideas in their repertoire (Linn, 2008). To develop critical thinking, learners need to elicit connections between existing and new ideas and develop their own criteria to distinguish alternative ideas (Linn et al., 2004).

This project aims to supports students' knowledge integration through two complementary tools: Dynamic visualizations that engage learners in exploring evolution ideas using inquiry processes. Knowledge Integration Maps that elicit connections between different levels (Duncan & Reiser, 2007).

C. Dynamic Visualizations

Computer-based visualizations can make biological ideas visible and accessible (Hegarty, 2004). The term "visualization" refers to the many different forms that make scientific ideas visible, for example animations, videos, models, and simulations. Seeing the same idea in different visualizations can support learners to distinguish, sort out, and integrate them into their existing understanding, or vice versa (Linn et al., 2004).

Many biological ideas, such as mutations and evolution, are often not directly observable because of time and space restrictions (Ainsworth & VanLabeke, 2004). For example, mutations happen on a micro-scale and very quickly, while evolution happens as a statistical effect in populations over long periods of time.

Dynamic computer-based visualizations allow students to investigate scientific ideas through scaffolded inquiry activities (Spitulnik et al., 1998). Dynamic interaction with visualizations can support learning by allowing direct manipulation of biological processes (Tversky, Morrison, & Betrancourt, 2002).

D. Concept Maps and Evolution Education

Comprehensive understanding of evolution requires simultaneous thinking in and connection of several levels. Complex systems can be understood by explaining the interactions between multiple components (Hmelo-Silver & Azevedo, 2006). Building the connections between ideas can be challenging as they are connected through relationships that are often not intuitively obvious to the learner (Duncan & Reiser, 2005). Eliciting these interconnections can help learners adding and distinguishing ideas.

This study explores using concept maps as embedded learning tools to support students' integration of evolution ideas [See chapter 2: Evolution Instruction]. Concept maps (Novak & Gowin, 1984) are a versatile type of graphic organizer. They consist of ideas (or concepts) connected by labeled arrows. Concept maps form semantic networks of visuo-spatially arranged text (Fisher, 2000).

Concept maps can elicit the relationships between existing and new alternative ideas of the learner (Shavelson et al., 2005). Concept maps constrain connections in two ways: First, concept maps show not all possible connections but only a meaningful selection. Learners need to generate criteria to decide which relationships they consider important ones (Schwendimann, 2007). Second, learners can only generate one single connection between two ideas. When working collaboratively in groups, learners need to negotiate which relationship they want to generate. Negotiating can encourage students to revisit their ideas and critically reflect upon the relationships.

E. Novel Type of Concept Map

Knowledge needs to be structured to be meaningful (Bransford, 2000a). Evolution ideas come from different fields (such as genetics, cell biology, and evolution. The novel concept mapping form, Knowledge Integration Map (KIM), uses the levels “DNA”, “cell”, and “population/organism” [See figure 29].

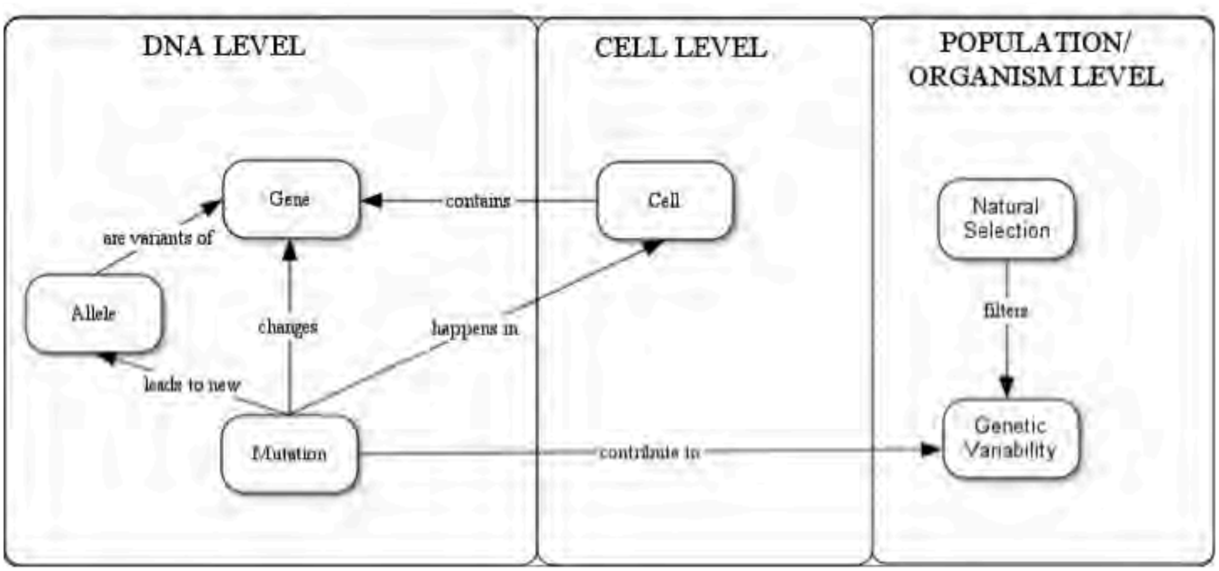


Figure 29: Study 2 Knowledge Integration Map.

KIMs can be described by the following characteristics [See table 25]:

Table 25: Characteristics of evolution-specific KIM.

Evolution-specific drawing levels	This characteristic combines aspects of concept mapping with aspects of Venn diagrams. The concept map drawing area is divided into several biology-specific vertical levels (genetic, cellular, organism/population). This arrangement requires learners to a) generate criteria and categorize ideas, b) sort out and spatially arrange ideas into corresponding levels (clustering), and c) generate connections between ideas within and across levels. Sorting out and grouping ideas spatially according to semantic similarity requires learners to generate criteria and make decisions about information structure that is latent in texts (Nesbit & Adesope, 2006). This is expected to support knowledge integration by showing ideas in contexts to other ideas and eliciting existing (and missing) connections within and across

	levels. Placement of ideas adds an additional level of information to the concept map activity. Cross-connections in students' knowledge are often invisible and difficult to identify in other knowledge representations, for example in traditional essays (Schwendimann, 2007). The divided levels of the concept map elicit connections within and across levels. Cross-level links are especially desirable as they can be interpreted as "creative leaps on the part of the knowledge producer" (Novak & Canas, 2006) and support reasoning across ontologically different levels (Duncan & Reiser, 2007). An increase in students' cross-connections can be interpreted as an indicator for a more integrated understanding of evolution.
Given list of ideas, but free labels and links	Ruiz-Primo et al. (2000) compared concept mapping tasks with varying constraints and found that constructing a map using a given list of ideas (forced choice design) [See table 4 in sub-chapter Types of concept map tasks: Task #2] reflected individual student differences in connected understanding better than more constrained fill-the-map forms. Evolution consists of a large number of ideas that make it often challenging for novices to identify key ideas [See chapter 2: Difficult Use of Terminology]. Providing students with a list of expert-selected key ideas can serve as signposts and model expert understanding. Concept maps generated from the same set of ideas allow for better scoring and comparison. Students' alternatives ideas are captured in the idea placement, link labels, and link direction.
Concept map training activity	Students need initial training activities to learn the concept mapping method and generate criteria for concept map critique [See study 2: Concept Map Training]
Focus question	The biology-specific focus question guides the construction of the concept map as learners select ideas and generate links to answer the focus question (Derbentseva et al., 2007).
Collaborative concept map activity	Concept maps are generated collaboratively in dyads. As each proposition is constrained to only one link, students are required to negotiate which connection to revise or generate. Students are required to generate criteria [See chapter 2: Concept Maps as Metacognitive Tools] and negotiate with their partner [See chapter 2: Concept Maps as Collaborative Tools].
Generation and Critique	After generation, concept maps often need several revisions to adequately answer the focus question [See study 1B]. Students get few opportunities for critique or revision [See chapter 2: Critique]. Providing students with concept maps made by a peer (or a faux-peer) allow students to revisit their ideas by adding to, critiquing, or revising an existing concept map.

Feedback and Revision	Feedback and revision supports students' knowledge integration through revisiting, reflecting, and revising existing and new ideas.

F. Learning through Generating and Critiquing

Concept map generation activities are often used as one-shot summative assessment activities (Trowbridge & Wandersee, 1998). Adding a critique activity following the generation of concept maps can foster students' revision of their ideas (Schwendimann, 2007) [See study 1B]. Critique activities require students to use or generate criteria to distinguish ideas (Chi, 2000b; Linn & Eylon, 2006) [See chapter 2: Critique]. Critiquing encourages the elaboration and revision of ideas and conjectures. Asking students to critique has been found to support the development of more coherent and generative criteria (Lehrer & Schauble, 2004). Critique activities can potentially help learners to monitor their own work, which can support the development of lifelong autonomous learning (Linn et al., 2004).

The study aims to compare critique of expert and novice KIMs:

Expert-generated KIMs offer normative relationships between evolution ideas (Hmelo-Silver et al., 2007). Expert maps can be used as good solutions for comparison. However, critiquing one's own work has been found often more difficult than evaluating other people's work (Linn & Clancy, 1992a).

Peer-generated maps might be easier to compare to one's own because of the use of familiar language and build on similar prior knowledge (Keppell, Au, Ma, & Chan, 2006). Peer evaluation can be mutually beneficial for the giver and the receiver (Topping, 2005). Peer critique can motivate students to improve their work and better understand what might be refined (Hoadley, 2004). However, peer critique might introduce or reinforce non-normative ideas.

In this study, students integrate evolution ideas through the collaborative generation of concept maps: Student dyads in one treatment group compare their own concept maps to an expert-generated map. Student dyads in the other treatment group provide critique for a peer-generated concept map [See table 26]. Students in both treatment groups were required to develop their own criteria, make decisions on how to change selected connections, and provide an explanation for their decision.

Table 26: Study 2 treatment groups and conditions.

Groups	Training	Criteria resources (what they use to compare to perform the critique)	Objects to Critique	Object to Revise	Purpose	Criteria used to critique
Expert map comparison group	Training worksheet	Expert Maps	Own Maps	Own maps	Correctness/Accuracy of one's own map	Generated by dyads
Peer review group	Training worksheet	Own Maps	Peer Maps	Own maps	Distinguish and sort out alternatives	Generated by dyads

G. Research Questions

This study compares two different ways to help students connect biology ideas and form an integrated view of evolution. In this study, students built coherent understanding of evolution by using a dynamic computer-based inquiry environment and an embedded biology-specific Knowledge Integration map generation and two different critique activities.

The research questions this study addresses are:

Did the two treatment groups differ in their integration of evolution ideas after using the WISE module *Space Colony*? How did students in each treatment group place the given ideas into the corresponding levels in their Knowledge Integration Maps? What connections did students in each treatment group generate in their Knowledge Integration maps? How did students in each treatment group generate criteria when critiquing expert or peer KIMs? How did students use the critique activity to revise their KIMs?

III. Study 2 Methods

A. Study 2 Curriculum design

1) WISE Environment

The evolution module designed for this study used the Web-based Inquiry Science Environment (WISE). WISE offers numerous scaffolded inquiry tools such as simulations, drawing, graphing, data tables, online discussions, and student journals (Linn et al., 2003; Linn et al., 2004) [See chapter 3: WISE]. The module created for this study, *Space Colony - Genetic diversity and survival*, was designed by a partnership of teachers, researchers and programmers. It includes scaffolded inquiry activities using the dynamic visualizations Dragon Genetics

(Concord Consortium, 2006) and Evolution Lab (Leif, 2005). Students worked collaboratively in dyads sharing one computer and spent 5 hours to complete the module. [See structure of WISE module Space Colony in chapter 3: WISE Environment: Study 2 WISE module structure].

(i) Design Features

The WISE module *Meiosis - the next generation* [See study 1B] was found to be effective in integrating ideas of human genetic diversity. Using a case study of human evolution allowed identifying genetic variety in human phenotypes and connecting to students' real-life experiences [See chapter 2: Human Evolution as a Pivotal Case]. However, the WISE *Meiosis – the next generation* module did not explain why genetic diversity can be advantageous for surviving changing environmental conditions. To place human genetic diversity in the context of evolution by natural selection, a new guiding story based on humans colonizing space was developed. The WISE *Space Colony* module was driven by the story of a group of human colonists who are planning to colonize planets with different environmental conditions [See figure 30]. Students needed to collect evidence to support their decision to either sending out a genetically diverse or genetically homogeneous group of colonists. Exploring this guiding question aimed to connect genetic, cell biology, and evolution ideas. The leading questions of the module were "What are the sources of genetic diversity?" and "Under which circumstances is genetic diversity beneficial?" The major sources of genetic diversity - mutation and recombination - were placed into the bigger context of evolution to help students understand the purpose of genetic diversity.

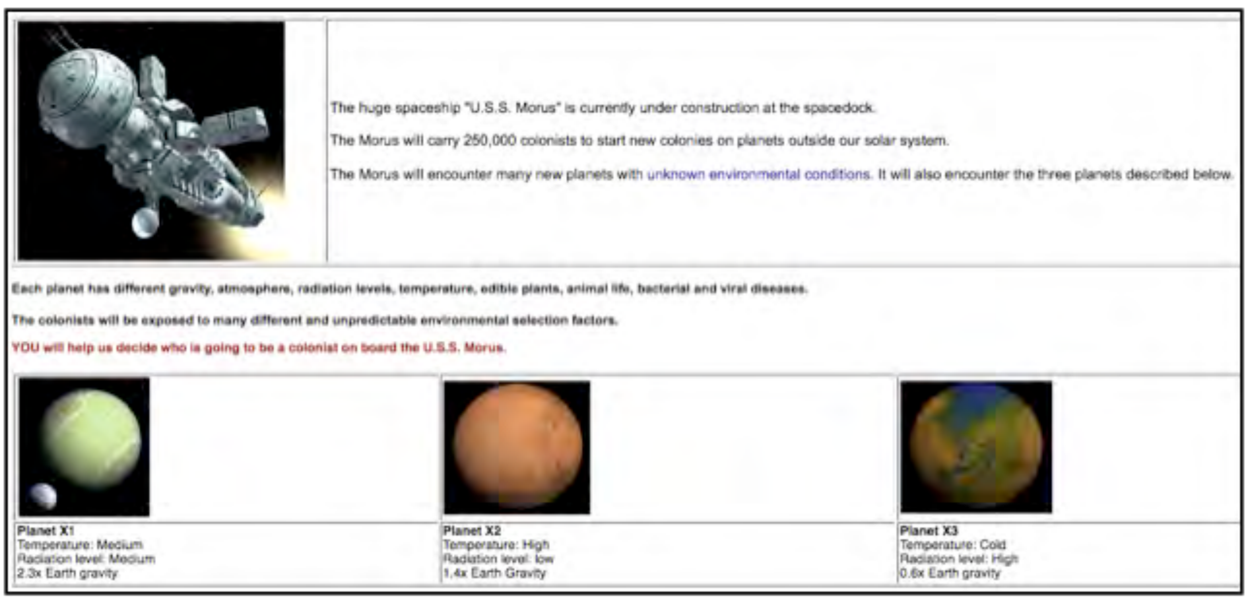


Figure 30: WISE module "Space Colony".

In addition to a revised guiding story, several changes have been made from the WISE module *Meiosis - the next generation*:

- To better elicit students' alternative ideas, active reading, and revisiting of ideas, self-assessment items were added to the pages.

- Pages were revised to reduce the amount of text and streamline the content with the key ideas outlined in the KIMs. Additional mouse-over glossary elements were added to provide optional supporting information.
- The names of the meiosis steps were removed because a) this is expected to encourage a focus on a conceptual understanding of meiosis instead of a rote memorization of the steps, and b) because the names are not included in the California state standards.
- Novices find it often difficult to identify underlying ideas and tend towards simple explanations of complex phenomena (Hmelo-Silver & Pfeffer, 2004; Perkins & Grotzer, 2000). One reason for this is that novices tend to focus on surface features rather than underlying ideas. To model expert reasoning and make central ideas salient, each page of the WISE *Space Colony* module presents a guiding question that is explored in the subsequent page [See figure 31].
- Each activity includes multiple choice questions and prompted open-response questions that scaffold reflection and revision of alternative ideas.

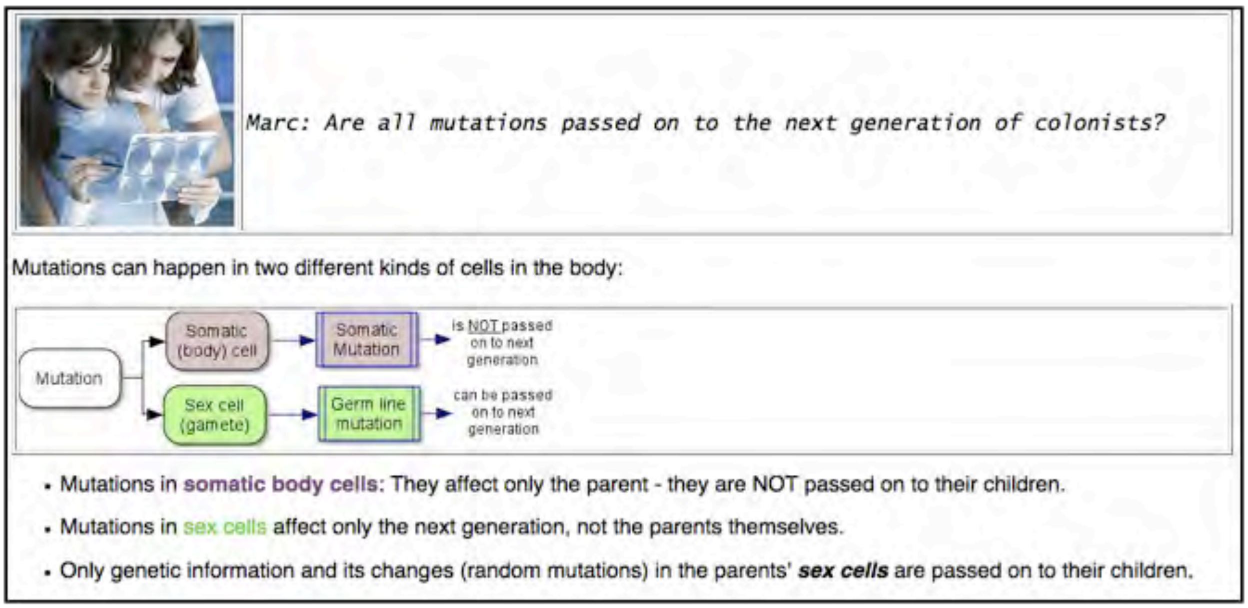


Figure 31: Study 2 guiding leading question.

Particularly in biology, students have to think in different levels, for example DNA, cell, organism, and population. Duncan and Reiser (2007) described how students often fail to recognize different biological levels. To scaffold construction of coherent connections between ideas, each page in the WISE *Space Colony* module shows an indicator of the current focus level (DNA, cell, organism, and population) [See figure 32]. These "focus pyramid" indicators aim to illustrate different levels on which evolution takes place.

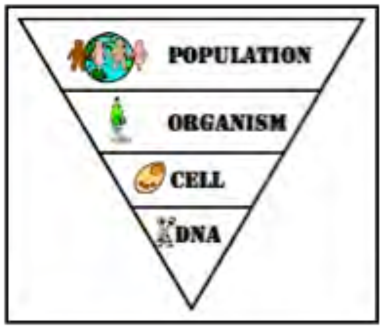


Figure 32: Study 2 focus pyramid.

2) Dynamic Visualizations

Students can learn evolution ideas through guided inquiry activities [See chapter 2: Evolution Instruction]. In addition to a revised version of the BioLogica visualization that was included in the WISE *Meiosis – the next generation* module, a new dynamic visualization "Evolution Lab" was added to the WISE *Space Colony* module to illustrate the connections between genetic diversity and natural selection. The WISE module *Meiosis - the next generation* focused on meiosis and mentioned the idea "mutation" only in passing. Interviews with biology experts [See study 1B] and the California science standards informed the inclusion of "mutation" as a central idea in the WISE module *Space Colony*. The WISE module distinguishes between somatic and germ line mutation as well as positive, negative, and neutral mutations.

A) The dynamic visualization "Evolution Lab" aims to help students sort out the common alternative ideas that mutations are always negative or lead to targeted improvements of an organism [See chapter 2: Alternative Ideas for Sources of Variation] (in activity 2). The population genetics visualization "Evolution Lab" (Leif, 2005) allows students to investigate the effects of mutations and natural selection on the evolution of a population of fictitious organisms [See figure 33]. Student dyads conduct four scaffolded inquiries with varying settings of selection strength and mutation rate. Students record the frequency of phenotypic changes over several generations and generate graphs to answer several given research questions. Randomly occurring mutations change the fitness of the organisms to catch food and reproduce. The Evolution Lab visualization aims to illustrate the connections between mutations (DNA level) and their effects on individuals (organism level), and the whole population (population level).

The learning goals of the Evolution Lab inquiry activity are:

- Mutations (DNA level) are the source of genetic diversity (population level).
- Mutations are random and can lead to both beneficial and harmful changes.
- Without natural selection, there would be no evolution of a population towards improved fitness.

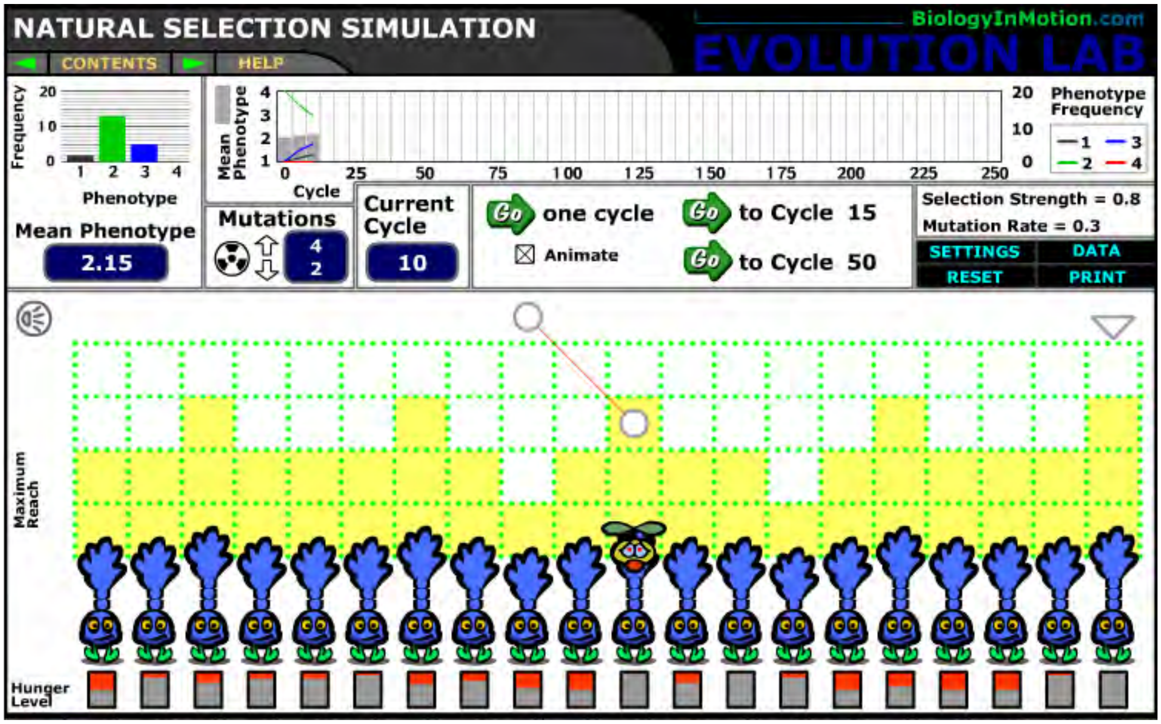


Figure 33: Evolution Lab visualization.

B) The BioLogica Dragon Genetics visualization (Concord Consortium, 2006) is a dynamic, interactive visualization that allows students to breed fictitious organisms (dragons) and manipulate their genetic material (in activity 5). In BioLogica, students explore genetic changes in the phenotype view, gamete view, and meiosis view [See table 18] to learn about the mechanisms that influence genetic diversity that is a pivotal idea to understand evolution. Ainsworth (1999) suggests that manipulating multiple interconnected representations could be beneficial for learning science ideas. The BioLogica Dragon Genetics visualization was revised from the WISE Meiosis module version to include a series of increasingly more challenging tasks. The visualization consists of three consecutive tasks: In the first task, students manipulate individual alleles and observe changes in the phenotype of the dragon. In the second task, students study animations of female and male gamete formation, choose chromosome of each for fertilization, and observe the effects on the phenotype of the offspring. The first two tasks can be repeated several times under varying conditions. The third task asks students to apply their knowledge from the first two tasks to create dragon offspring with certain specific traits. This selective breeding task builds upon Charles Darwin's observation of selective animal breeding that stimulated his conception of the idea of "natural" selection.

The learning goals of the BioLogica Dragon genetics visualization activity are:

- Understand the relationship between alleles (genetic level) and phenotypic traits (phenotype level)
- Identify random assortment of chromosomes and random selection of gametes as a source for genetic diversity in offspring
- Apply the idea of dominant and recessive alleles to breed offspring with specific traits.

3) Novel Type of Concept Map

(i) Map Activity Structure

The KIM activities in study 2 followed the structure “generation” -> “critique” -> “revision” [See figure 34].

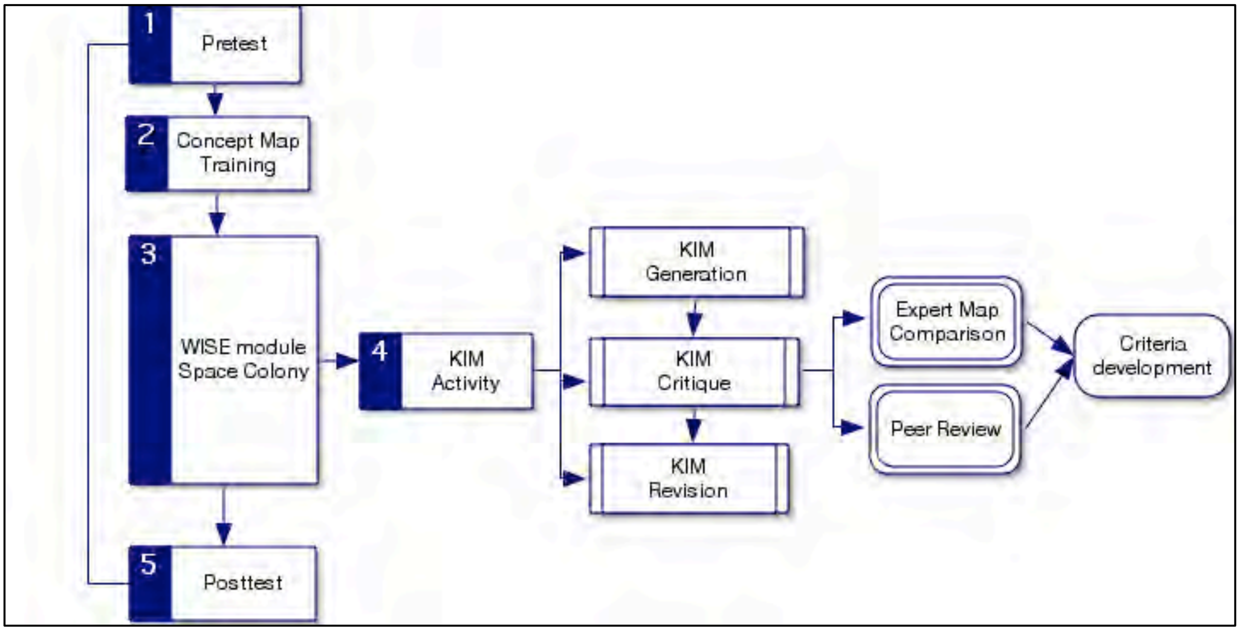


Figure 34: Study 2 KIM activities structure.

(ii) Map Training

Shavelson (1994) described the importance of an initial concept map-training phase. A concept map training worksheet has been developed for this study that uses a context familiar to students: Students worked in dyads to create a concept map that illustrated what it takes to get a pizza delivered to one’s home. After completion, students compared their work against a worked-out example and discussed differences with the whole class. This activity aimed to familiarize students with the concept map technique and illustrate how to compare and critique concept maps.

(iii) Map Generation Activity

A paper-and-pencil concept map activity was administered at the end of activity 2. Yin (2005) found that a forced choice design with a given list of expert-selected ideas to choose from allowed for a better comparisons between maps than free choice of ideas. Students had free choice in which ideas to connect, arrow direction, idea placement, and linking labels.

Working in dyads, students created a Knowledge Integration map (KIM) from six given ideas: Gene, allele, mutation, cell, natural selection, and genetic diversity. The number of given ideas has been kept small to reduce working time and limit complexity. Student dyads spent about 20 minutes on generating their Knowledge Integration map.

Knowledge Integration Maps have several distinct features:

1) Each KIM worksheet had a focus question to guide the map generation. Derbentzeva (2007) found that focus questions are important to concept map construction as they explicitly define the question the map is designed to answer.

2) The KIM drawing area was divided into three distinct levels: DNA level, cell level, and organism/population level. These levels were also used in the focus pyramid indicators throughout the project. First, students were asked to sort out and place each idea into the corresponding level. This can be seen as an indicator for the students' association of an idea with a certain level. Second, students connected the ideas with labeled mono-directional arrows. The connections could be between ideas within the same level or across levels. Especially connections across levels can be seen as an indication for a more integrated understanding [See figure 35].

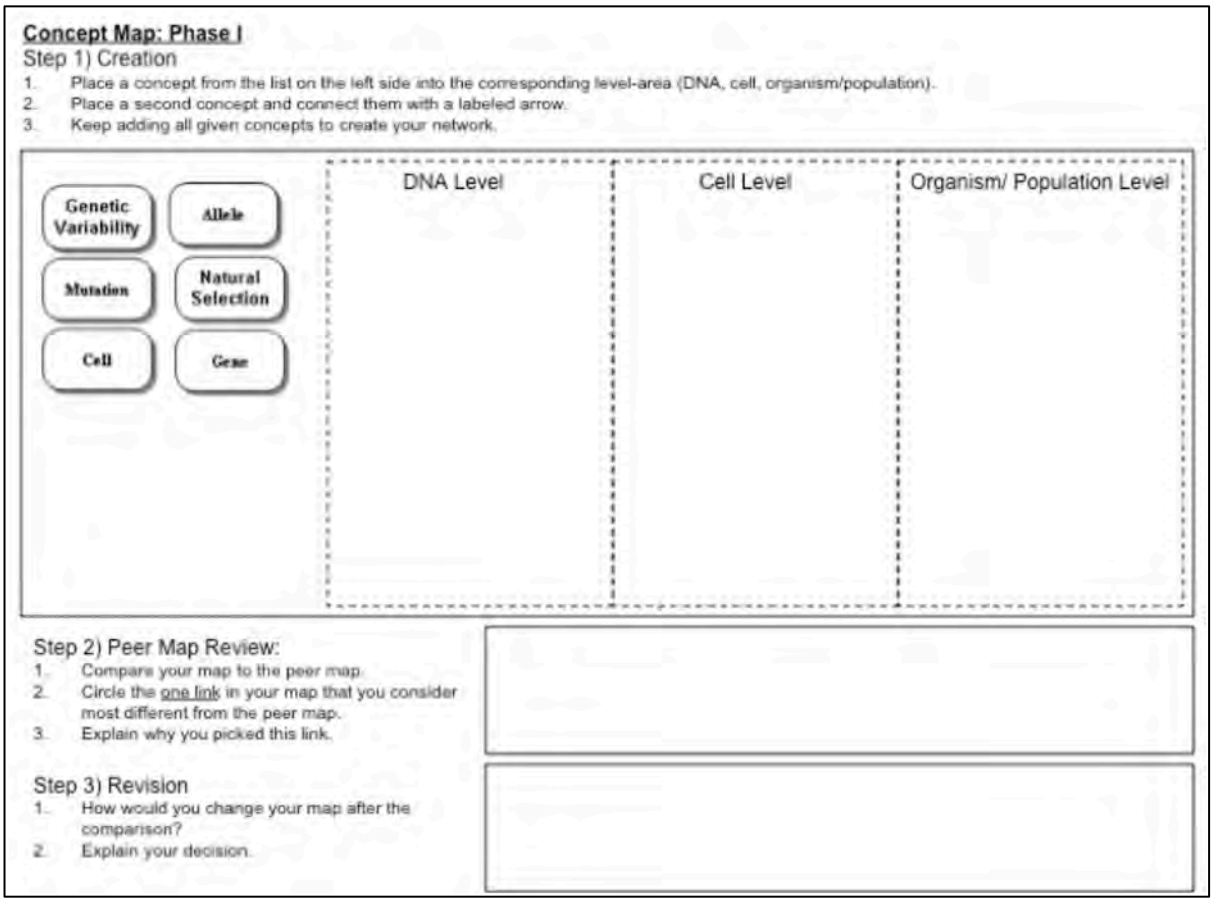


Figure 35: Study 2 Knowledge Integration Map worksheet.

(iv) Map Critique Activity

Students were instructed to compare the Knowledge Integration Map to a reference map – either an expert-generated map or the map of an anonymous peer. Students were instructed to identify and critique one element that they considered most different and in need of revision. Students were asked to mark the element in the map itself as well as to provide an explanation for their critique [See figure 35].

(v) Map Revision Activity

Students were instructed to respond to the critique by suggesting one possible revision. They were asked to provide supporting evidence for their revision [See figure 35].

B. Study 2 Participants

The WISE module *Space Colony – Genetic diversity and survival* was implemented by two teachers, each with two classes in the same San Francisco Bay Area public high school. One class from each teacher was randomly selected for either treatment (expert map or peer-review) [See table 27]. All students (n=81) were in 9th and 10th grade and came from a variety of ethnic and socioeconomic backgrounds.

Table 27: Study 2 participants.

Teacher	# of students (m/f)	Pretest average	Treatment
A	21 (10m, 10f)	9.9	Expert-Map
	17 (9m, 8f)	9.8	Peer-Map
B	20 (10m, 10f)	10.1	Expert-Map
	23 (17m, 6f)	10.4	Peer-Map

Description of Teachers

Teacher A is an experienced science teacher with more than 8 years of teaching experience. Teacher B has worked as a biology high school teacher for three years. Both teachers used WISE modules before and attended WISE teacher workshops. Both teachers can be considered technology-savvy.

C. Study 2 Data Sources and Analysis

1) Assessment

Study 2 used three different data sources: Pre- and posttests, embedded Knowledge Integration Maps, and qualitative field notes.

A pretest-posttest design was used to measure student's prior knowledge and illustrate learning gains. The assessment items were designed and scored using a Knowledge Integration rubric (Linn et al., 2006) [See table 28] to measure students' abilities to connect genetic, cell biological, and evolution ideas. Students individually filled out the paper-based pretest on the first day of the project and the posttest immediately after finishing the project. The pretest and posttest consisted of five identical items, each composed of a multiple choice item followed by a short essay item that asked students to explain their choice and provide supporting evidence.

The assessment items were designed to address common alternative ideas:

- Asexual organisms never change as they produce only clones. -> Normative view: Mutations also happen in asexual organisms, but changes happen slower because there is less genetic diversity.
- Mutations/Evolution lead to improvements for better adaptation/survival of the organism. -> Normative view: Mutations happen randomly and mostly decrease an organism's fitness.
- Natural selection/adaptation helps individual organisms to survive -> Normative view: Natural selection has no preference for certain individuals. The survival of the whole group is of importance.
- Meiosis happens to sex cells after fertilization -> Normative view: Meiosis is the cell division process which leads to sex cells
- Mutations/Genetic disorders happen more often in meiosis because the cell division process is more complicated/longer -> Mutation rate is the same in mitosis or meiosis.

2) Pretest/Posttest Analysis

Pretests and posttests were scored according to a five-scale Knowledge Integration rubric (Linn et al., 2006) [See table 28]. Explanations were coded for the number of connections between ideas on a score ranging from 0 to 5, a higher score indicating a higher number of connections. Each explanation item of the pre- and posttest was weighted equally. A total pre- and posttest score of all five explanation-items was calculated.

Sample essay question: *"Why do grapes (with seeds) that reproduce sexually have a greater chance to survive a new disease than (seedless) grapes that reproduce asexually?"*

Table 28: Study 2 Knowledge Integration rubric.

Knowledge Integration	Example
No answer	None
Off task	I don't know
Incorrect	Because they have seeds to fight off the disease
Partial	The seedless grapes are all genetically identical.
Basic	Seedless grapes are all the same, but grapes with seeds have better chance and traits to survive.
Complex	Grapes that reproduce sexually have more genetic diversity in their gene pool that allows for a greater array of organisms from which natural selection may choose – allowing some to survive.

3) Map Analysis

A Knowledge Integration rubric was developed to evaluate the quality of propositions in the Knowledge Integration maps (Schwendimann, 2008). The KI rubric scores each proposition on a scale from 0 to 5 by distinguishing between the link label and the link arrow direction [See table 29]. A higher KI score indicates a more complex integration of ideas. In KIMs, ideas are represented by arrows (directionality of connection), labels (quality of connection), idea placement in designated levels (DNA, cell, or organism/population), and cross-links across levels (indicating understanding connections between levels). Each proposition was weighted equally. A "total KI concept mapping score" before and after the revision was calculated. The "total KI concept mapping score" is a composite of three sub-scores:

- *"Idea placement score"* indicates how many ideas have been placed in the corresponding level (DNA, cell, organism/population).
- *"Total proposition score"* is the sum of all propositions scored individually by the five-scale KI concept map rubric. The student maps were compared against the expert concept map to establish the proposition validity.
- "Cross-link score" is the sum of the proposition scores of valid cross-links. Cross-links indicate connections between different levels.

The difference between the pre and post-revision KIM was calculated as the "*Total concept map improvement score"*.

Table 29: Study 2 KIM Knowledge Integration rubric.

KI Score	**Link label quality**	**Link Arrow**	**Example**
0	None (missing connection)	None	
1	Wrong label	Wrong arrow direction	*Genetic variability – includes -> mutation*
2	a) Only line b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow direction	*a) Mutation --- genetic variability* *b) Genetic variability –contributes to -> mutation* *c) Mutation – includes -> genetic variability*
3	Only arrow (no label)	Correct arrow direction	*Mutation --> genetic variability*
4	Partially correct	Correct arrow direction	*Mutation – increases -> genetic variability*
5	Fully correct	Correct arrow direction	*Mutation – causes random changes in the genetic material which in turn increases -> genetic variability*

A nine-scale concept map critique rubric was developed to categorize the different forms of critique [See table 30].

Table 30: Study 2 KIM critique rubric.

Kind of critique	**Description**	**Example**
None	No critique given	
Off-Topic	Comment unrelated to biology or concept mapping	*I am tired.*
General	General critical comment	*Make more links between your ideas.*

Remark	without giving specific feedback	
Critique of idea placement	Critique that an idea is placed in the wrong level (DNA/Cell/Organism/Population level)	*Mutation' should be in DNA-level.*
Critique of missing idea	Critique that one or more of the given ideas have not been used	*You forgot to add 'mutation.*
Critique of link direction	Critique of the direction of an existing link (while keeping the same label)	*Your arrow should go in the other direction.*
Critique of missing link	Critique that an important link has not been created.	*You missed to connect mutation and allele.*
Critique of missing label	Critique that one or more links have not been labeled (blank line).	*You should add a label for the link mutation and allele.*
Critique of existing label	Critique of the label of an existing label (while keeping the same direction)	*Connection between allele and mutation should be "leads to" instead of "includes".*

IV. Study 2 Results

A. Study 2 Quantitative Results

1) Study 2 Research Question 1

Results include both quantitative and qualitative data [See study 2: Qualitative Observations] that was analyzed using knowledge integration methods.

Research question: Did the two treatment groups differ in their integration of evolution ideas after using the WISE module *Space Colony*?

Students in both treatment groups gained significantly from pretest to posttest, t(80) = 4.15, p<0.001; Effect size (Cohen's d)=0.52 (SD pretest=2.78, SD posttest=3.17)]. Paired t-test analysis indicates that the pretest knowledge did not significantly differ between the classes of the two different teachers [t(80) = -0.67, p=0.5075 [See figure 36]. A paired t-test suggests that the students gained significantly in their understanding from pre- to post test, t(80) = 4.151, p<0.001 [See figure 36]. No significant difference overall of the posttest performance of the two critique groups was found: t(79) =0.8868 , p=0.3779. This suggests that the main activities were effective and the form of Knowledge Integration Map activity does not influence performance differentially. Additionally, these findings are influenced by the short duration of the treatment and the nature of the critique activities that lead to more reflection in both treatment groups. Research question 2 and the qualitative observations provide a deeper analysis of students' actual critiques. Multiple regression analysis suggests that an improvement in KIM scores through subsequent revision is associated with an estimated increase in the mean posttest score by 2.5 (on

KI rubric score). Significant at p<0.001. This indicates that the KIM revision activity can have a positive learning effect on the posttest performance. Comparing the students' Knowledge Integration Maps before and after the revision to the expert map indicates that the two treatment groups did not significantly differ from each other. The expert map group did not copy the expert map to replace their own [See appendix chapter 5: study 2].

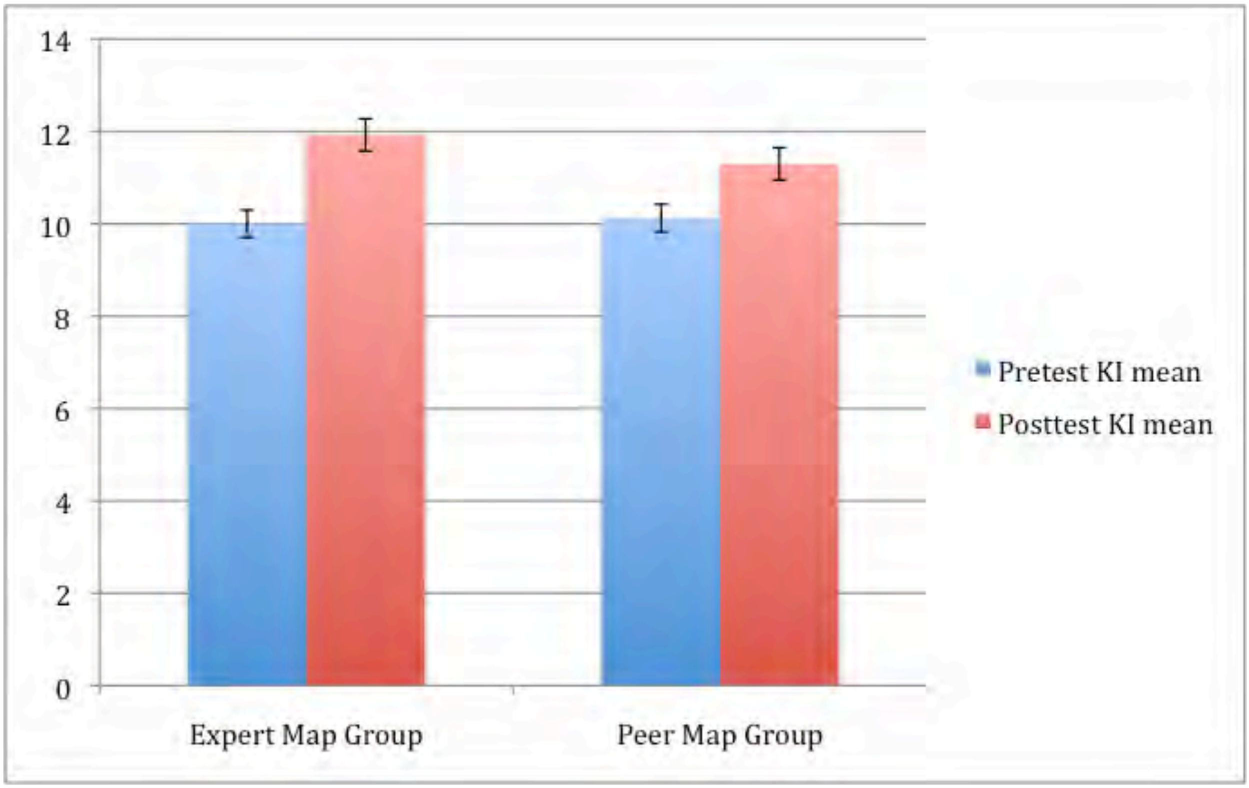


Figure 36: Average KI score gains by treatment.

2) Study 2 Research Question 2

Research question: How did students in each treatment group place the given ideas into the corresponding levels in their KIMs?

The idea "cell" was the most correctly placed idea (100% and 95%) in the pre-revision Knowledge Integration maps of both treatment groups (which is not surprising as the corresponding level was labeled "cell") [See figure 37]. "Genetic variability" (32% and 48%) and "mutation" (66% and 53%) were placed incorrectly most often. Many students associated the population-level idea "genetic variability" with the DNA level because of the association with the idea "gene". "Mutation" was frequently placed in the organism/population level: Follow-up interviews suggest that many students placed "mutations" in the organism/population level because "mutations change traits of organisms". This understanding corresponds with findings by Duncan (2007) and Shea (2010) that suggest that genetic ideas are difficult to understand because students connect them directly with phenotypic phenomena without proteins as connecting elements [See chapter 2: Inheritance and Genes]. Interviews also indicate that some students did not understand the idea "allele" and placed it in levels different than the DNA level.

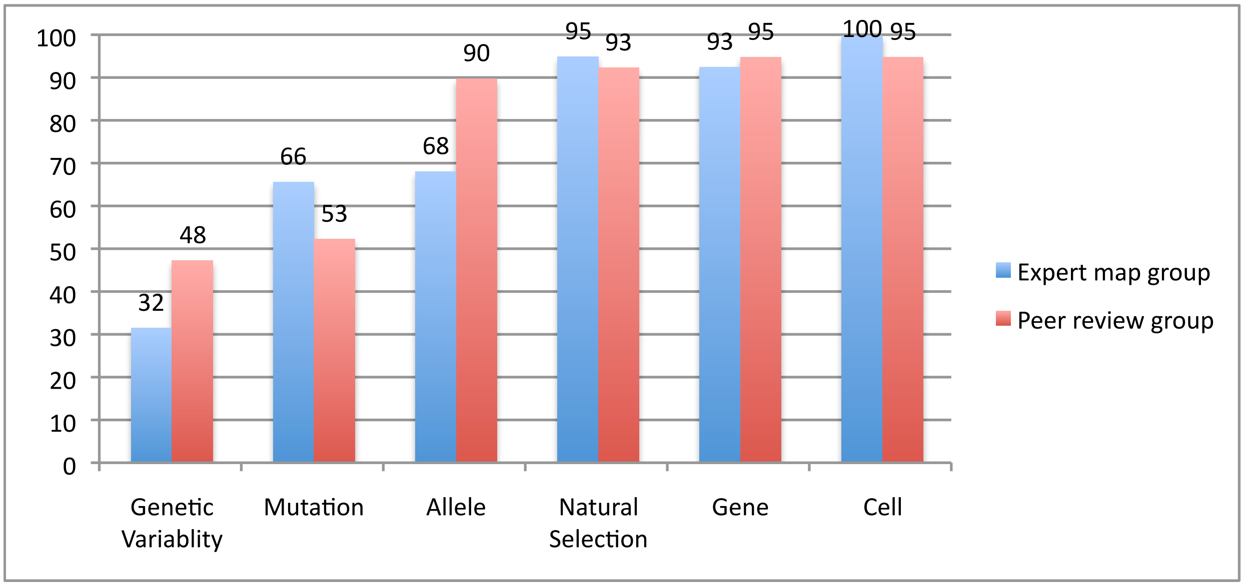


Figure 37: Initial idea placement (in percent).

3) Study 2 Research Question 3

Research question: What connections did students in each treatment group generate in their KIMs?

After instruction in the WISE module *Space Colony*, student dyads most frequently connected ideas learned in the same curricular context in the embedded Knowledge Integration Map, for example “allele and gene” (genetics context) or “genetic variability and natural selection” (evolution context) [See yellow area in figure 38]. However, students also connected ideas across one level (for example “mutation and cell”) and two levels (for example “genetic variability and mutation”) [See blue and purple area in figure 38]. These results suggest that the WISE module *Space colony* effectively helped students in both treatment groups making connections within and across levels.

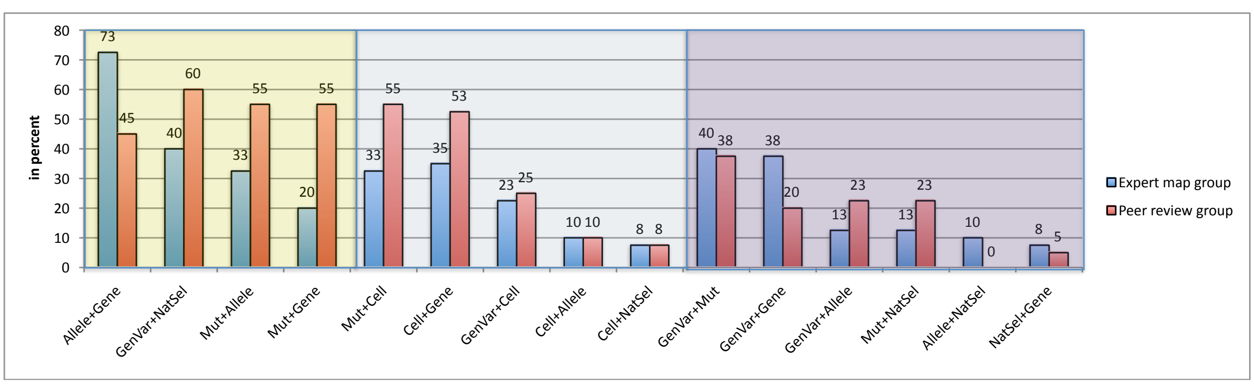


Figure 38: KIM connections (after revision) (in percent). Yellow = within level connections; Blue = connections across one level; Purple = connections across two levels.

Cross-link analysis: The two variables number of cross-links and total score of the revised Knowledge Integration Map are strongly correlated, $r(79) = 0.9951$, $p<0.001$. This positive correlation suggests that students with a high number of cross-links have also a high mean concept map score. These findings suggest that cross-link scores can be used as indicator variables for the overall quality of Knowledge Integration Maps. Regression analysis indicates that the peer map group created more cross-links after the revision than the expert map group (while keeping the coefficient for the initial number of cross-links constant), R^2=0.9917, F(2,78)= 4680.91, p=0.025.

4) Study 2 Research Question 4

Research question: How did students in each treatment group generate criteria when critiquing expert or peer KIMs?

Students' criteria have been coded using the rubric shown in table 30. Results indicate that students generated a broad variety of criteria to review different aspects of concept maps [See figure 39].

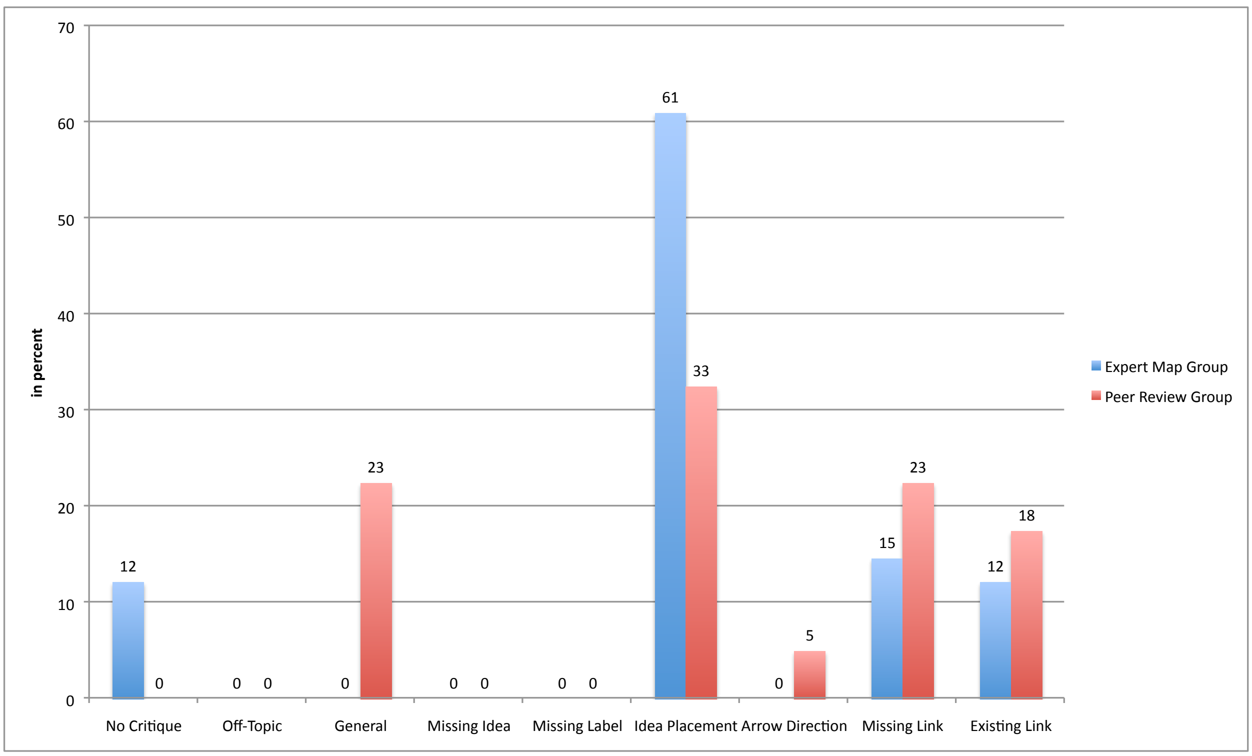


Figure 39: KIM critique criteria by treatment (in percent of total responses of each treatment group (n=81).

Students in the expert map group critiqued mostly idea placement (61%), missing links (15%), and existing link labels (12%). Students in the peer map group showed a different distribution: Only 33% critiqued idea placement, but 23% critiqued missing links, 18% existing link labels, and 5% link direction. No student critiqued a missing idea or a missing label. This might be explained by the explicit instructions to use all given ideas and label all connections.

The student-generated criteria can be grouped in three categories [See table 31]. This study interprets critiquing a different connection or a new connection as a more in-depth reflection than the identification of a misplaced idea.

Table 31: Categories of student-generated criteria.

Non-relevant criteria =No Critique + Off Topic + General	**Non-relevant criteria** include missing, off-topic, and general comments.
Superficial criteria = Idea Placement + Missing Idea + Missing Label	**Superficial criteria** allow for a quick visual comparison between Knowledge Integration Maps without necessary conceptual reflection (for example "Is idea placed in corresponding level?"; "Is an idea from the given list missing?"; "Are some connections not labeled?")
Specific criteria = Arrow Direction + Missing Link + Existing Label	**Specific criteria** provide conceptual feedback by identifying an important missing connection, pointing out that an arrow direction should be reversed, or suggesting the revision of an existing label.

The two treatment groups differed in their use of criteria [See figure 40]: Students in the expert map group generated more superficial criteria (61%) that allows for a quick comparison with the expert map. Aligned with their criteria, most students in the expert-map group revised their idea placement. Students in the peer review group generated fewer superficial criteria (33%) and more specific criteria (45%) instead. Aligned with their criteria, students in this group focused their revisions on improving propositions labels and directions.

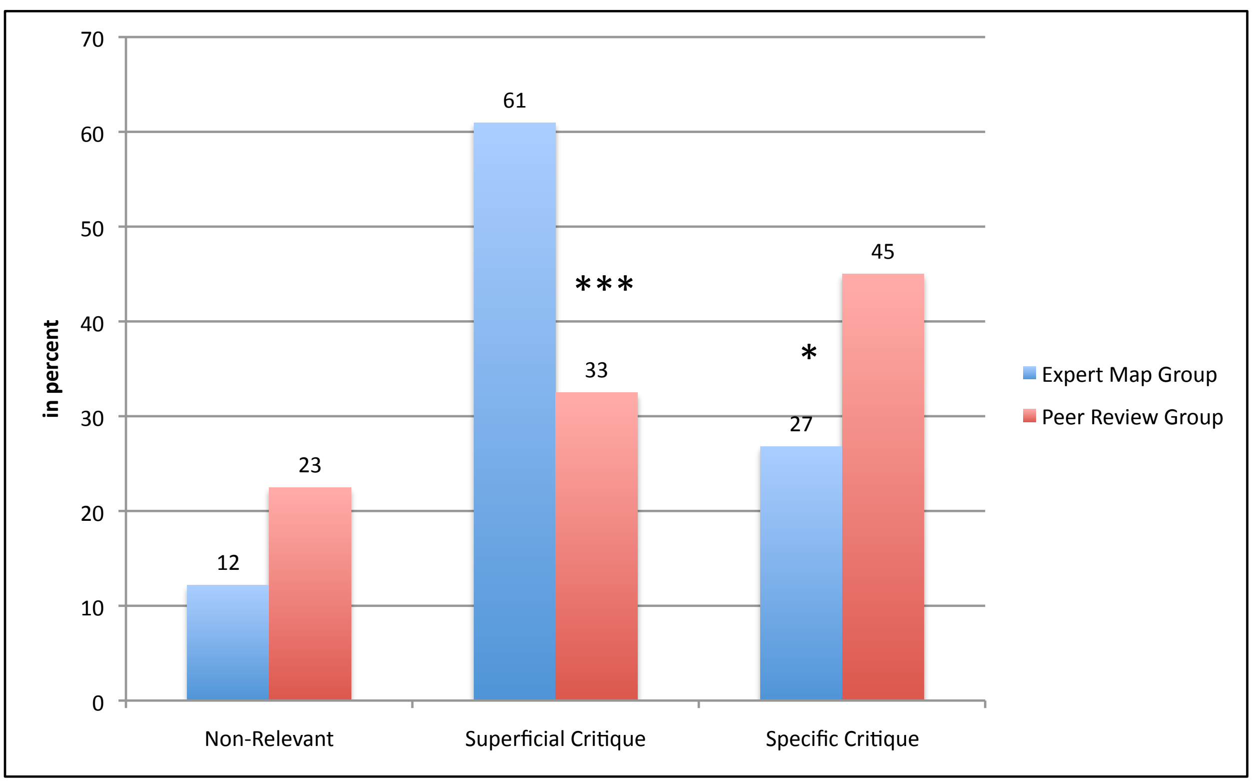


Figure 40: KIM critique criteria by categories (in percent of total responses of each treatment group (n=81). * = significant at p<0.05; ** = significant at p<0.01; * = significant at p<0.0001.**

Z-scores were computed for raw scores in the critique data set. The differences in proportions of the criteria categories between treatment groups are statistically significant: Superficial critique (z=2.97. p=0.001) and specific critique (z=1.68. p=0.0457).

5) Study 2 Research Question 5

Research question: How did students use the critique activity to revise their KIMs?

What specific revisions did students in the two treatment groups suggest in their critique? Students in both treatment groups suggested revising the placement of specific ideas, for example the placement of "genetic variability" (15% and 20%) [See table 32]. These suggestions correspond with the frequent incorrect placement of the idea "genetic variability" [See figure 37]. Several students in the peer review group, but none in the expert map group, suggested revising connections to the central idea "mutation", for example "mutation and allele" (8%) and "mutation and natural selection" (5%).

Table 32: Revision suggestions by student dyads after the critique activity (in percent of each treatment group). Only review suggestions with at least one entry are shown.

	Expert map group	**Peer review group**	**Total**
No revision	15	30	22
Genetic Variability + Allele	0	5	2
Genetic Variability + Gene	12	0	6
Mutation + Cell	0	3	1
Mutation + Allele	0	8	4
Mutation + Natural Selection	0	5	2
Mutation + Gene	0	5	2
Cell + Allele	5	0	2
Cell + Natural Selection	5	0	2
Cell + Gene	0	5	2
Natural Selection + Gene	5	0	2
Placement of Genetic Variability	15	20	17
Placement of Mutation	7	20	14
Placement of Allele	34	0	17
Placement of Gene	2	0	1

Were the specific revision suggestions scientifically accurate? Students in the expert map group generated over 50% correct revision suggestions, compared to only 33% for students in the peer review group. As anticipated, a number of peer review feedbacks were incorrect (28%), as they did not have an expert map for reference [See table 33].

Table 33: Correctness of student dyads' revision suggestions (in percent of each treatment group).

	Expert map group	Peer review group	Total
Empty	12	0	6
No specific suggestion	37	40	38
Incorrect	0	28	14
Correct	51	33	42

How did students in the two different treatment groups decide to revise their KIMs after the critique activity? In accordance with the most frequent form of critique (idea placement critique) [See table 32], most students in the expert map group decided to revise their idea placements (51%). It is interesting to note that no student in the expert map group, but 28% of students in the peer review group expressed confidence in their own maps and decided not to revise them.

Table 34: Student dyads' revision decisions after the critique activity (in percent of each treatment group).

	Expert map group	Peer revision group	Total
Missing Response	22	5	14
Non-specific comment, for example "I disagree"	0	13	87
General comment, for example "I would add more links"	10	10	10
Revise idea placement	51	30	41
Add missing idea	0	3	1
Add missing link	12	13	12
Revise existing label	5	0	2
Decision not to follow the revision suggestion and keep own idea	0	28	14

Findings suggest that both treatment groups significantly improved their Knowledge Integration Maps after the critique activity, $t(80) = 4.13$, $p<0.001$ (two-tailed)]. Regression analysis indicates that an improvement in the KIM score after the revision was positively associated with an estimated increase in the mean posttest score of 2.5; $p<0.001$. For the peer review group, tables 33 and 34 suggest that is was not the feedback students received that lead to the improvement of their Knowledge Integration Maps, as 28% of them chose to ignore the received feedback and keep their own ideas. These findings suggest that students' self-explanation and generating critique contributed more to their learning gains than receiving feedback. Critical comparison of Knowledge Integration Maps seems to strengthen students' confidence in their own ideas, while comparing to an expert map decreases that confidence. These findings are consistent with Chi's (1994) observations that generating explanations of a text or diagram, whether for oneself or for others, can be more effective for learning than receiving explanations.

B. Study 2 Qualitative Results

1) Study 2 Qualitative Observations Teacher A

Curriculum structure: Teacher A organized his curriculum from the top-down, starting with the big picture of evolution before discussing cell biology and genetics. The WISE module Space Colony was placed between cell biology and genetics. The students did not know yet about DNA structure, alleles, transcription, translation, mutation, phenotype, genotype, and Mendelian inheritance. He uses the WISE module as an introduction to cell biology and genetics and as a bridge to evolution.

1) Expert map comparison treatment group

Day 1: The teacher started the class by issuing the paper-based WISE pretest. The students spent ten minutes on the pretest. The class worked concentrated and quietly. The teacher gave a brief introduction to concept mapping by showing a several examples on the whiteboard. Most students were not yet familiar with the concept mapping method. The teacher walked the students step-by-step through the concept map training worksheet [See appendix chapter 5: study 2]. He gave several examples for the term "hierarchy". After this ten-minute introduction, the students worked on the concept map training worksheet for ten minutes. In this activity, the students constructed a concept map about a familiar topic ('What does it take to get a pizza delivered?'). While the students were working, the teacher walked around the classroom and gave individual feedback to student groups. He finished the activity by showing the 'expert map' on the projector for comparison. The students used the expert map as a model to critique their own training maps. Similar to the embedded activity in the WISE module, students were asked to identify one own proposition that differs most from the expert map and suggest a possible revision. After receiving the laptops from the cart, the login process took about 25 minutes. This run was the pilot run for the new WISE 3 portal. The loading time for the WISE3 module took only about 2-5 minutes, thanks to a broadband connection and pre-downloaded WISE packages on the students' laptops. Once the majority of the students reached the Evolution Lab visualization, the teacher demonstrated the activity on the projector. At the end of the two-hour period, students completed the embedded Knowledge Integration map activity. Teacher A finished the period by showing the expert map on the projector for comparison. He asked students which link differed most from their own or which idea they would place in a different level.

Day 2: The laptops were set up on the students' desks by the research team. Nevertheless, it took about twenty minutes to get all students back to the WISE module as several student groups encountered difficulties (for example Wi-Fi connection problems or forgotten passwords). Teacher A started the period by demonstrating the Evolution Lab activity on his computer on the projector for ten minutes. He asked students about their understanding of genes, mutations, and phenotypes. He provided students with a short overview over the key terms, as they will learn genetics in detail only after the WISE module. The teacher walked the students through the Evolution Lab worksheet: For each experiment, first make a prediction, reset and change the settings, observe the mean phenotype of each generation, draw line graph of your results, and answer the follow-up questions. The teacher decided to give individual students an Evolution Lab worksheet because he wanted to learn about their individual graphic skills. The Evolution Lab activity lasted for about 25 minutes. While students worked on the activity, the teacher and members of the research team provided individual support to the students. At the end of the period, students spent ten minutes on the second knowledge integration map activity. The teacher showed the expert map on the projector for comparison. Several students reacted surprised by the complexity of the expert map compared to their own. Several students could be observed sorting out ideas in the three levels without linking them. The dividing lines between the three levels on the worksheet might falsely suggest that connections cannot cross the line. After prompting by the teacher, most student groups started linking ideas across levels.

Day 3: The students had only one more hour to finish the project, as they had to attend a school-wide information workshop. The total duration of the WISE module was five hours.

2) Peer review treatment group

Day 1: Teacher A gave the same introduction to both treatment groups but improved his concept map introduction by stressing the point that there is not only one way to create valid concept map propositions. He gave more detailed examples at the whiteboard. Students spent ten minutes on the concept map training worksheet. The teacher showed the expert map on the projector followed by a brief classroom discussion.

The login process took less time than in the other treatment group. The students were engaged and motivated. Student groups worked at different paces. After the majority of the students reached the Evolution Lab activity, the teacher interrupted the class to give a 15-minute demonstration of the visualization on the projector. Students then spent the remainder of the period with the Evolution Lab worksheets. They finished the graphing part but did not complete the questions. Despite a detailed worksheet with instructions, the Evolution Lab activity requires detailed demonstrations by the teacher and continuous individual support for the students. Once students became familiar with the interface, they had only few problems running the experiments. The teacher welcomed the combination of online and paper-based activities of the module.

Day 2: The initial login time could be reduced to ten minutes by having all computers already on standby and the WISE module loaded. The teacher started the class by asking students to finish the Evolution Lab activity they begun last time. The majority of students finished after 15 minutes.

Teacher A decided to walk students through the concept map activity after some students in the expert map treatment needed additional individual support. Students worked pairwise on the Knowledge Integration map activity and finished the construction phase in ten minutes. After the construction phase, the concept map worksheets were randomly distributed to another group for peer-review. Each student group generated their own criteria to analyze the Knowledge Integration map. They marked the issue in question on the map and provided feedback in a text-box. Students were more engaged looking at their peers' maps than the students in the expert map comparison group. After the peer-review, the worksheets were returned to the original groups for revision. The whole peer-review took 15 minutes. In a future iteration of the project, the peer-review process could be improved by using an electronic concept mapping program that allows for automated distribution of maps to other computers. After the worksheets got collected, the teacher demonstrated the Dragon Genetics visualization on the projector. He used pairs of shoes as an analogy to chromosome pairs. The students spent 15 minutes on this visualization. The module includes a number of self-test questions that follow visualizations. Students could be observed to look more closely at the videos and replaying them several times after having tried to answer the self-test questions.

Day 3: The students had only one more hour to finish the project, as they had to attend a school-wide information workshop. The total duration of the WISE module was five hours.

2) Study 2 Qualitative Observations Teacher B

1) Expert map comparison treatment group

Day 1: Teacher B started the lesson by administering the paper-based pretest. He asked the students to work with a partner they could be productive with. He instructed the students how to set up their accounts in the WISE3 environment. The login process took about 20 minutes. The class was very quiet and focused. The students were on task most of the time. When the majority of students reached the Evolution Lab activity, the present researcher provided an introduction to the Evolution Lab activity and explained the worksheets. Students spent 30 minutes on the Evolution Lab activity, guided by the worksheet. After this activity, the teacher introduced the concept map training worksheet. Students spent about five minutes placing the provided ideas in the corresponding level on the worksheet and connecting them. Before the teacher could show the expert map on the projector, a fire alarm interrupted the class. This way, the class ended 10 minutes early and the students had to finish the concept map activity at he beginning of next class. The concept map-training example with the pizza delivery service worked well as the situation was familiar to all students. The only disadvantage of the example was that it led to mostly circular concept maps. At first, many students did not label their connections. After prompting by the teacher, most students had no problems adding labels to their links. The teacher suggested that providing a list of labels could be beneficial.

Day 2: Teacher B started the period by asking the class a review question about the cell cycle (events during S, G1, G2 phase) and a one-question quiz “What is an allele?”. Several students used the description for alleles given in the WISE module. The students set up the computers quickly by themselves.

During the login procedure, the students were not able to log onto the WISE3 server. After a call to the WISE tech group, the class was informed to use a different server address, which resolved the problem. Resolving this server issue took almost an hour. While students were waiting for their login, the teacher finished the concept map-training phase and handed out the worksheets for the KIM I activity. Teacher B discussed the expert map on the projector with the class. By the end of the lesson, most students reached the Dragon Genetics activity. The teacher wanted to give a demonstration of the Dragon Genetics on the projector, but was unable to run WISE3 using Microsoft Internet Explorer (as WISE3 was optimized for Firefox only). However, the students encountered very few problems understanding the Dragon Genetics activity using the embedded scaffolding. They were very engaged creating different baby dragons. Several students spent additional time with the visualization creating dragon babies with different specific features.

Day 3: Teacher B noted that concept mapping is a beneficial learning method for his class and developed two additional training examples for his class (“rock-paper-scissors” and “Taking a date to a movie”). He assigned a concept map about mitosis as homework. Teacher B started the period with a short quiz in which students had to describe what the teacher looks for in a good concept map. The teacher wanted to stress the point that concept map connections should all be labeled arrows (instead of blank lines). Setting up the computers and signing in took ten minutes. The students continued with the Dragon Genetics activity. Students who finished early worked on the optional WISE activity about genetic diseases for extra credit.

2) Peer review treatment group

Day 1: Teacher B started the period similarly to the expert map treatment group. After distributing the concept map training worksheets, he discussed several examples of possible connections with the students. He stressed the point that labeling the arrows with link words is important because an un-labeled arrow does not show the nature of that relationship. The students worked for ten minutes on the training maps. The teacher showed the expert-map on the projector and asked students to compare this map with their own map. He stated that this expert-map should be considered only as one of many possible ways to construct this concept map and that concept mapping is not about right or wrong. Before starting with the computer work, the teacher rearranged several student groups to achieve more productive pairings. When a majority of the students reached the Evolution Lab activity, the teacher stopped the class to demonstrate the visualization on the projector. He asked students several questions about different elements of the visualization. Students spent about 30 minutes to finish the Evolution Lab activity. A few students needed additional instruction how to create the line graph in the worksheet. Students spent fifteen minutes working on the Knowledge Integration map peer review worksheet. Teacher B discussed several examples where to place an idea on the map. The students spent five minutes in their dyads generating the KIM out of the given six ideas. The maps were then collected and randomly redistributed for peer-review. Student dyads did not put their names on the worksheets but used randomly assigned identification numbers. This allowed an anonymous review process. After five minutes of peer-review, the maps were returned to the authoring group to allow them to make a revision suggestion. Students in the peer review group seemed more engaged analyzing other student's maps than students' in the expert map comparison treatment group.

Day 2: Teacher B started the period similarly to the expert map treatment group. Using the alternative server address from the beginning, the login worked without delay. The teacher noticed that several students who were usually unfocussed and disinterested in his science classes, were now engaged and on task during the WISE module activities. Students liked the constructive feedback from the self-assessment questions. However, only few students chose to revise their initial answers. Teacher B interrupted the class to demonstrate the Dragon Genetics activity on the projector.

Day 3: As the computers were already set up from the previous class, the students could start right away. Most students took turns operating the computer while working in their dyads. A few student dyads were observed reading the texts of the WISE module aloud to each other. After most students finished the WISE module, the teacher briefly reviewed the mitosis concept map homework assignment that students were to finish by today. The total duration of the project was six hours. Feedback by the teacher: He liked that the interactive inquiry activities in the WISE module and the combination of online and offline activities. He considered the concept map peer review activity as being a helpful learning activity.

Overall, the WISE projects went as planned, expect for initial login problems with the new WISE3 portal (which could be resolved) and the interruption by a fire alarm. Students in all classes worked focused and on-task.

V. Study 2 Discussion and Implications

A. Study 2 Discussion

The WISE module *Space Colony* consists of a combination of elements that were designed to scaffold students' connecting evolution ideas across levels (DNA, cell, organism/population), for example Knowledge Integration Maps, focus pyramids, guiding questions, essay questions, and dynamic visualizations. Results indicate that the concerted effects of all these elements contributed to a more integrated understanding of genetic diversity and evolution from pretest to posttest. Findings suggest that the WISE module *Space colony* helped students in both treatment groups to successfully make connections between ideas within and across levels. Cross-link (connections across levels) scores showed strong correlation with the overall Knowledge Integration Map score and could be used as indicators for changes in the quality of a map.

Knowledge Integration Maps fostered eliciting connections between ideas across different levels. Generating KIMs allows students to become knowledge producers instead of knowledge consumers. In addition learning from generating connections between ideas, student dyads critiqued their ideas. Results indicate that students in both treatment groups significantly improved their KIMs through the critique activity. Both critique activities (expert and peer map comparison) led to productive reflection and revision, and resulted in similar posttest performances. The similarities between treatment groups could be explained by the limited time of the critique activity and by the constraint to revise only one single element in the KIM. The focused comparison of only one element can reduce the complexity of the critique activity. Another explanation might be that Knowledge Integration Maps' visual form serves as an effective medium for collaborative critique activities [See chapter 2: Concept Maps as Collaborative Tools]. Different than essays, Knowledge Integration Maps present each idea only once and show all relationships to or from that idea in one place [See chapter 2: Concept maps and Knowledge Integration]. Knowledge Integration Maps cluster ideas into groups, which can encourage critical reflection about relationships between ideas within and across levels.

The treatment groups differed from each other in the different kinds of criteria generated to review their maps.

The expert map group received a trustworthy reference intended to serve as a model. Results, however, indicate that students interpreted the expert map not as one of many possible maps but as the "right" answer. Consequentially, student in the expert map group focused mostly on superficial criteria that allow for a quick visual comparison (for example "idea placement"). Critiquing one's own work can be more difficult than evaluating other people's work. Students need to be reminded that there is no single correct solution for a Knowledge Integration Map, and that even experts create many different maps [See study 1B] (Schwendimann, 2007). Students should be encouraged to value their own ideas.

The peer review group compared their own maps against maps generated by their peers. Therefore, the peer review group had to critique two maps, both their own and their peers. Some student dyads even looked for evidence in the WISE module to distinguish between their own and the peer map. The peer-map critique activity engaged students to develop and use more specific criteria, for example missing links, link direction, and link labels. Classroom observations indicate that students were more motivated during the peer-review activity than the expert map comparison. One explanation for this observation might be students' interest in work by peers and being in an equal position to critique each other's work. Providing anonymous critique can reduce personal bias and reluctance to critique others. One initial concern for the peer review activity was that it might reinforce non-normative ideas. Results indicate that some peer feedback consisted of non-normative ideas, but students rightfully discarded such critique and expressed confidence in their own ideas. This could be further addressed by asking students to provide supporting evidence for their critique. Comparing their own ideas against those of their peers can help students to value their own ideas while developing criteria to critically review them.

B. Study 2 Implications and Outlook

This study identified an effective design pattern for critique activities: Make existing ideas explicit through Knowledge Integration Map generation -> Create criteria -> Compare alternative ideas in Knowledge Integration Maps using criteria -> Distinguish ideas to decide which one to use (based on evidence). Both critique activities lead to criteria generation and revision. Critical reflection can support students' knowledge integration and self-monitoring of their learning progress. Self-monitoring is an important skill for autonomous life-long learning (Linn et al., 2004). Many different forms of critique are important for learning. Using expert or peer-generated work for critique comparison, or a combination thereof, can target specific forms of critique towards a more coherent understanding of evolution. The combination of KIM generation, critique, and revision was quite time-consuming. As time during WISE modules is limited, future iterations of the Knowledge Integration Map activity could focus on generation or critique activities alone [See study 3].

The peer review activity took more time than the expert map comparison activity, mostly because collecting, shuffling, and distributing the paper-based KIM worksheets took additional time. In the future, web-based Knowledge Integration mapping software could be used to generate and anonymously distribute students' work for review. The critique activity could be extended by having several embedded critique activities and by allowing students to revise more than one element.

The dynamic visualizations Evolution Lab and BioLogica allowed exploring evolution ideas through guided inquiry activities. However, both visualizations showed certain limitations.

The Evolution Lab visualization has a complex visual interface that demands time-intensive demonstrations and support by the teacher. Students struggled to make sense out of the multiple connected graphs of the simulation. Future iterations of the WISE module could include a population genetics visualization with simpler graphs and a more intuitive interface.

The BioLogica visualization allows students to select alleles that are linked to certain phenotypes. As identified in study 1B, the BioLogica visualization has certain limitations because of the simplified genetic model. In addition, the visualization does not include the intermediary steps how alleles lead to phenotypic traits, for example by producing certain proteins. This might reinforce the alternative idea that genes are "trait-bearing particles" (Lewis & Kattmann, 2004) that directly control or contain phenotypic traits. Students who hold such a view do not see a necessity to distinguish between phenotype and genotype levels [See chapter 2: Inheritance and Genes]. The current version of BioLogica does not include a population view that would allow students to explore the effects of genetic diversity in the context of natural selection. A future iteration of the WISE module could include a population genetic visualization that allows guided inquiry activities.

The guiding story of the WISE module *Space Colony* followed groups of settlers in a futuristic spaceship on the way to colonizing new planets. While this guiding story was of interest to a number of students, it provides an abstract setting that has few connections to students' everyday life experiences. Following the Knowledge Integration principle of using real-life examples, future iterations of the WISE module could use a guiding story that builds on students' existing personal experiences. Additionally, the WISE module *Space Colony* focuses only on the evolutionary mechanism of natural selection. Future versions of the WISE module can also include other elements of the Hardy-Weinberg model, for example genetic drift and migration.

Findings suggest that generating and critiquing KIMs can support Knowledge Integration of evolution ideas. However, the combination of the two activities can be time-consuming. As results indicate that students gained more from providing feedback than receiving feedback, a follow-up study could analyze the effects of critiquing KIMs with deliberate errors. Critiquing KIMs could be a more efficient alternative to generating KIMs, give students an opportunity to critically reflect on their ideas, and provide more scaffolding than generating a KIM from scratch.

CHAPTER 6: STUDY 3: KNOWLEDGE INTEGRATION MAPS AS LEARNING TOOLS: GENERATION VERSUS CRITIQUE

I. Study 3 Abstract

Students' hold a rich repertoire of alternative ideas of evolution that are often quite resistant to change. One cause could be a disconnection between genotype and phenotype level ideas. Making these connections explicit might help students building a more coherent understanding of evolution. This study investigates how two different treatments (generation or critique) of a novel form of concept map, called Knowledge Integration Map (KIM), can support students' learning from an inquiry-based technology-enhanced evolution curriculum. KIMs used in this study divided evolution ideas into genotype and phenotype levels. Findings indicate that either generating or critiquing Knowledge Integration Maps effectively supports knowledge integration of evolution ideas. Results suggest that critiquing KIMs can be used as a more efficient alternative to generating KIMs. The findings from this study are valuable for the design of effective and efficient learning environments to support more integrated understanding of evolution ideas.

II. Study 3 Introduction

The theory of evolution is a unifying theory of modern biology, and notoriously difficult for students to understand (for example (Alters & Nelson, 2002; Bishop & Anderson, 1990; Boggs et al., 2003; Catley et al., 2005; Hmelo-Silver et al., 2007)) [See chapter 2: Nature of Evolution Ideas]. Evolutionary theory is difficult understand because it is, to some degree, counterintuitive (Evans, 2008; Mayr, 1982; Wolpert, 1994). Our intuitions are formed throughout our childhood. In an early stage, a child sees the world filled with tendencies and intentions (Piaget et al., 1977) [See chapter 2: Evolution and Development]. Children apply this teleological understanding to biology; For example, they develop their own criteria to distinguish living (for example animals) from non-living things (Keil, 1994) by attributing to them a vital force (Inagaki & Hatano, 2002), or "needs" (goal-directed behavior) (Carey, 1985) [See chapter 2: Need; Intentionality]. Southerland (2001) and Shtulman (2006) identified "need" as a central element in people's reasoning about evolutionary change.

Another difficulty with understanding evolutionary theory is that students tend to think "typologically" by seeing individuals as representative of an entire population (for example (Greene, 1990)) [See chapter 2: Individual Variation vs. Essentialism]. Such a view makes it difficult to see the importance of individual variation, which is crucial to understanding the explanatory power of the theory. Besterman (2007) suggested using human examples to teach evolution as people relate better to humans than animals. Another advantage is that a case study of human evolution can build on our existing knowledge of human variability. Study 3 extends that argument and uses a case study of human evolution to demonstrate evolutionary change to connect to students' existing knowledge of human variability and to build on the human ability to observe individual differences in humans [See chapter 2: Human Evolution as a Pivotal Case; Contextualization and Human Exceptionalism].

Study 3 poses the hypothesis that the continued use of the alternative idea “need” to explain evolutionary change is caused by a disconnection between phenotype level and genotype level ideas [See figure 41]. Students who understand evolution only on a phenotypic-level might use the idea “need” instead of the genotype-level idea “mutation”.

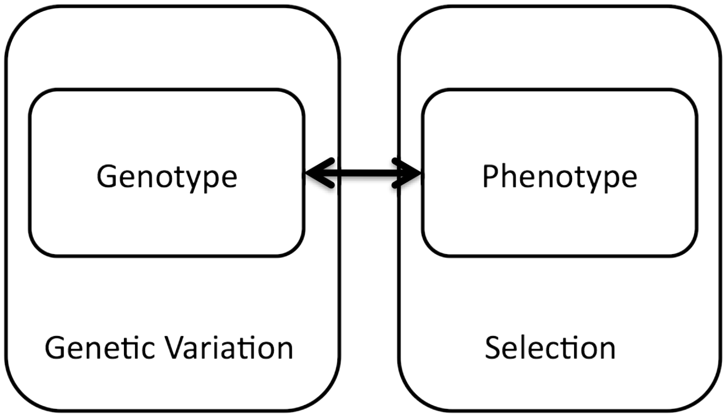


Figure 41: Study 3 genotype-phenotype levels.

The distinction between phenotype and genotype level ideas is fundamental to the understanding of heredity and development of organisms (Mayr, 1988b) [See chapter 2: Evolution Ideas on Different Levels].

- Genotype level ideas describe the genetic material and its changes over time, for example genes and mutations.
- Phenotype level ideas describe the phenotype of an organism and its interactions with the environment, for example natural selection and fitness.

An integrated understanding of evolution requires simultaneous thinking in and connections between both levels. Research suggests that students have difficulty reasoning across different levels (Hmelo et al., 2000; Marbach-Ad, 2000a; Penner, 2000). Different levels, like phenotype or genotype, use different vocabulary and focus on different (but related) key ideas. The connections are often not directly observable and not made explicit in curricula. Additionally, the current curriculum structure in many schools teaches genetics and evolution in isolated units that do not encourage students to construct links between these core ideas.

In order to form coherent understanding in biology, students need to integrate their various ideas about biology. The Knowledge Integration (KI) perspective on learning suggests that students hold a repertoire of loosely connected ideas, rather than internally consistent scientific theories, and that students often fail to connect ideas from one context to another (Computer As Learning Partner: Revised Annual Report, 1995; Linn, 2008; Linn et al., 2006) [See chapter 2: Knowledge Integration]. The goal of KI instruction is to support students to make their existing alternative ideas and the connections between them explicit, critically sort them out by comparing them against scientific evidence, and apply scientific ideas more frequently in multiple contexts. Students who build a strong integration of ideas of these two different levels might better distinguish important evolution ideas from less important ones. For example, students with more integrated evolution ideas might use the idea "mutation" more frequently in their explanations than students who have a disconnected understanding.

Building on the findings from study 1 and 2, study 3 uses KIMs as a learning tool to help students visually generate relationships between genotype and phenotype level ideas that are otherwise often not salient.

Results of study 2 [See study 2 Results] indicate that a combination of generating and critiquing Knowledge Integration Maps can effectively support integrating evolution ideas, but was time-consuming. As time in the science classroom is precious, study 3 aims to identify and develop more efficient KIM activities by distinguishing the learning effects from either generating or critiquing Knowledge Integration Maps.

III. Study 3 Research Questions

Study 3 aims to answer the following research questions:

Specific research questions:

A) Overall changes in students' Knowledge Integration of evolution ideas

1) How does the WISE module *Gene Pool Explorer* change students' integration of evolution ideas?
2) How does the WISE module *Gene Pool Explorer* help students to integrate evolution ideas across contexts (plants and humans)?

B) Changes in knowledge integration of evolution ideas of treatment groups

3) How do treatment groups (critique and generation) differ in generating KIMs after the WISE module *Gene Pool Explorer*?
4) How do treatment groups (critique and generation) differ in cross-links between genotype and phenotype level ideas in their KIMs after the WISE module *Gene Pool Explorer*?
5) How do treatment groups (critique and generation) differ in qualitative changes of connecting ideas in their KIMs after the WISE module *Gene Pool Explorer*?
6) What variables can track changes in students' evolution ideas in KIMs?
7) How do treatment groups (critique and generation) differ in integrating core evolution ideas in their KIMs after the WISE module *Gene Pool Explorer*?
8) How do treatment groups (critique and generation) differ in changes of the topology of their KIMs after the WISE module *Gene Pool Explorer*?
9) How do treatment groups (critique and generation) differ in critiquing KIMs after the WISE module *Gene Pool Explore*r?
10) Is generating or critiquing KIMs a more time efficient knowledge integration activity to learn about evolution ideas?

IV. Study 3 Theoretical Framework

A. Study 3 Knowledge Integration

This study uses the Knowledge Integration framework (Linn, Eylon, & Davis, 2004; Linn & Hsi, 2000) as its operational framework to build and evaluate a curriculum that focuses on the connection between genotype and phenotype ideas [See chapter 2: Knowledge Integration].

The Knowledge Integration framework suggests that scaffolding students to better integrate their ideas will support conceptual changes in students' understanding of evolution. Knowledge integration focuses on connections between ideas and includes the processes of eliciting a repertoire of ideas, adding ideas to the repertoire, sorting out the various connections among the ideas, and developing criteria for connections between ideas. The knowledge integration framework informs curriculum design and has proven effective in design of rubrics for scoring items reliably and consistently and in creating scales that have excellent properties of discrimination, reliability, and validity across the full range of performance.

The Knowledge Integration framework states that existing ideas are not simply replaced by more normative ones but continue to coexist. Knowledge Integration explains the resistance for change of alternative ideas by them having been used for longer periods of time and in more different contexts than a newly introduced scientifically normative idea. Additionally, alternative ideas are often more concrete while scientific ideas are often abstract. In curriculum design, Knowledge Integration connects scientific ideas with everyday life situations where they can be applied more frequently and more diverse contexts than only in the science classroom. New ideas need to be applied across multiple contexts to be more frequently chosen when forming explanations. Inquiry activities provide learners with evidence to critically evaluate their different ideas against. This allows students to develop criteria to distinguish the relevance of different ideas.

B. Study 3 Concept Mapping

Knowledge Integration aims to make students' repertoire of diverse ideas and their connections explicit in order to allow critical reflection and distinction. Study 3 uses a novel form of concept maps, called Knowledge Integration Maps (KIM) [See study 3: Novel Concept Map Type], as embedded learning and summative assessment tools to support and track the integration of evolution ideas [See chapter 2: Concept Maps and Learning Evolution]. The Knowledge Integration Map developed for this study requires students to divide ideas into genotype and phenotype level ideas. This structure requires learners to categorize and spatially group related ideas. Cross-connections in students' knowledge are often invisible and difficult to identify in other knowledge representations, for example in a traditional essay format (Schwendimann, 2007). KIMs make connections within and across levels explicit. Cross-level connections are especially desirable as they represent connections between ideas at different levels.

Knowledge Integration Maps cannot only be used as cognitive tools that help eliciting ideas [See chapter 2: Concept Maps as Learning Tools], but also as social artifacts through which students communicate [See chapter 2: Concept Maps as Collaborative Tools]. When KIMs are collaboratively constructed, they become shared social artifacts that can make existing and missing connections explicit and can spur discussion among students and teachers. As each connection between two ideas can consist of only one link, students need to negotiate which connection to make. This constraint requires student dyads to negotiate and make decisions about which connection to revise or add, which creates an authentic need for effective criteria and supporting evidence to distinguish among ideas in students' repertoires (Berland & Reiser, 2009). The KIM becomes a social support for prompting students to articulate their understanding and integrate their knowledge through reflection. This social process of reaching agreement is critical in shaping and sharing reflections of connections between ideas (Brown, 1994; Scardamalia & Bereiter, 2006).

V. Study 3 Methods

A. Study 3 Curriculum design

1) WISE Gene Pool Explorer activities

The WISE *Gene Pool Explorer* module aimed to present the modern synthetic view of evolution by focusing on changes in the gene pool and contrasting phenotype processes (for example natural selection and genetic drift) with genotype processes (for example mutations) [See chapter 2: History of Modern Evolution Theory]. The WISE *Gene Pool Explore*r module shifted back and forth between genotype and phenotype level ideas and focused on the connections between ideas of the two levels [See figure 42]. Many students do not understand the relationships between ideas of the two levels are. Duncan (2007) and Shea (2010) suggested that students needed to learn about the role of proteins as the connecting element between genotype and phenotype level ideas. To address this issue, the WISE *Gene Pool Explorer* module focused on the production of the enzyme lactase that breaks down the milk sugar lactose [See study 3: Case Study for Human Evolution Development].

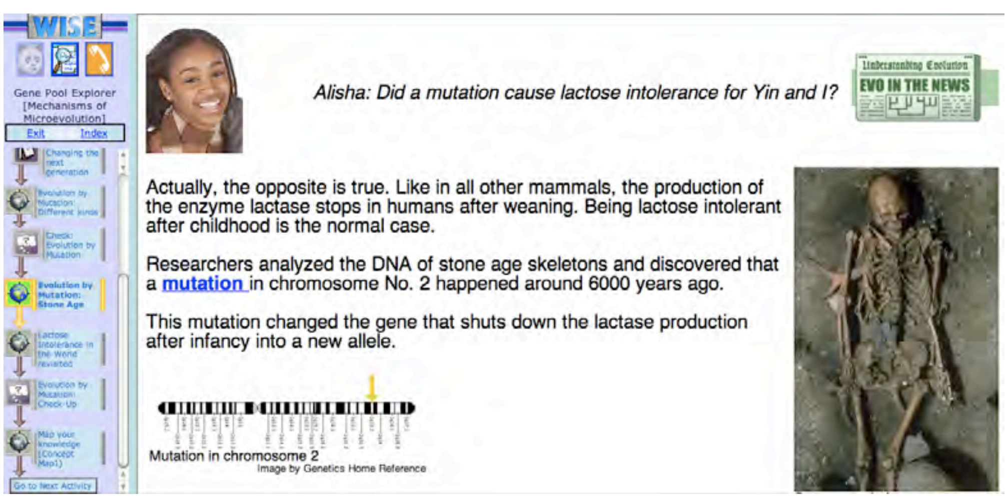


Figure 42: Study 3 WISE module "Gene Pool Explorer".

B. Design principles

The WISE module was created using a set of theory-based biology-specific curriculum design principles (See (Cummins et al., 1994)):

- Make evolutionary time (deep time) explicit. Show that evolution happens as a statistical effect in populations over many generations.
- Show that evolution consists of two connected processes - sources of variation and selection.
- Sources of variation (for example mutation and recombination) are random. Selection processes are a consequence of different phenotypes meeting the environment.
- Natural selection affects both differences in survival and reproductive success. The crucial factor is differences in fitness (reproductive success).
- Connect the underlying genetic processes that lead to diversity to phenotypic selection processes.
- Evolution needs to be discussed on various levels of organization.

Evolutionary biologist Steven Jay Gould frequently cautioned that there is more to evolution than natural selection (Gould & McKeever, 1987) (p. 344); (Gould, 1990) (p. 256); (Gould, 2002) (p. 1464). To address Gould's concern, the WISE module aimed to support students' conceptual understanding of the Hardy-Weinberg principle of population genetics (without introducing the mathematical formula): Mutations, natural selection, genetic drift, and migration (gene flow). This focus on changes in the gene pool is expected to help students understand evolution as a statistical change in allele frequencies and integrate genotype and phenotype ideas [See chapter 2: Entities: Genotype and Phenotype]. Understanding evolution requires thinking on 1) individual levels, and 2) on a population levels. Both levels can be understood on a genotype or a phenotype level [See table 35]. The WISE module aimed to help students distinguish and connect evolutions within and across these levels.

Table 35: Study 3 connections between levels.

	Genotype Level	**Phenotype Level**
Individual Level	Individual genetic variations	Individual phenotypic traits
Population Level	Variations in the gene pool of a population	Differences between the phenotypic traits in a population

C. Curriculum Structure

The WISE *Gene Pool Explorer* module was delivered using the web-based inquiry science environment (WISE) (Linn & Hsi, 2000)[See chapter 3: WISE Environment]. WISE allows delivering content to students over the web, providing them electronically with feedback, and collecting all embedded student data in real time. During the weeklong module, students worked collaboratively in dyads sharing one computer.

Before the WISE *Gene Pool Explorer* module starts, students learn how to generate and critique Knowledge Integration Maps (KIM) through individual and collaborative exercises [See chapter 2: Knowledge Integration Map Training] [See figure 43]. Students individually complete knowledge integration assessment (delivered through WISE) before (pretest) and after posttest) the module [See Study 3 Data Sources]. The individual assessment includes a KIM generation and a KIM critique activity that includes both genotype and phenotype level ideas.

In the WISE *Gene Pool Explorer* module, students start with a phenotypic real-life observations (1) Introduction: Lactose intolerance and 2) Introduction: Gene Pool), exploring the underlying genetic mechanisms (3) Mutation), investigate changes in the gene pool over time (4) Natural Selection and 5) Genetic Drift), and explain the differences in phenotypic traits (6) Lactose intolerance treatment) [See figure 43]. The first three activities focus on changes in the genotype: The first activity introduces the human lactose intolerance case study. The second activity introduces the idea "gene pool". The third activity consists of an overview of the connections between mutations and genetic variability in the gene pool. The fourth activity presents two guided inquiry activities using the population genetics visualization "Allele A1" to explore the connections between mutations, natural selection, and genetic diversity. The fifth activity introduces the idea of genetic drift as an additional selection process and explores the effects of small population sizes on genetic drift in "Allele A1". Students generate or critique a concept map on phenotype concepts. The last activity discusses treatment and dietary options for people who are lactose intolerant [See structure of WISE module *Gene Pool Explorer* in chapter 3: WISE Environment: Study 3 WISE Module Structure].

The WISE module aims to connect genotype and phenotype level ideas:

I) Sources of genetic diversity (genotype level): Gene pool, mutation, recombination (Hardy-Weinberg principle) [See chapter 2: Sources of Variation]

II) Effects of genetic diversity (phenotype level): Natural Selection, fitness, genetic drift, migration (gene flow) [See chapter 2: Selection of Variation]

The WISE module aimed to contrast the two selection processes, natural selection and genetic drift, as well as mutations through several scaffolded inquiries using a dynamic population genetics visualization [See study 3: Dynamic Visualization]. These experiments aim to address two common alternative ideas about evolution: First, evolution always leads to individual improvements; and second, evolution happens because of individual needs [See chapter 2: Need].

After completing the genotype section (activities 1-3), student dyads either critique or generate a genotype level KIM using the electronic concept mapping tool Cmap [See chapter 2: Concept Map Activity Design]. After completing the phenotype section (activities 4-5), students dyads either critique or generate a phenotype level KIM.

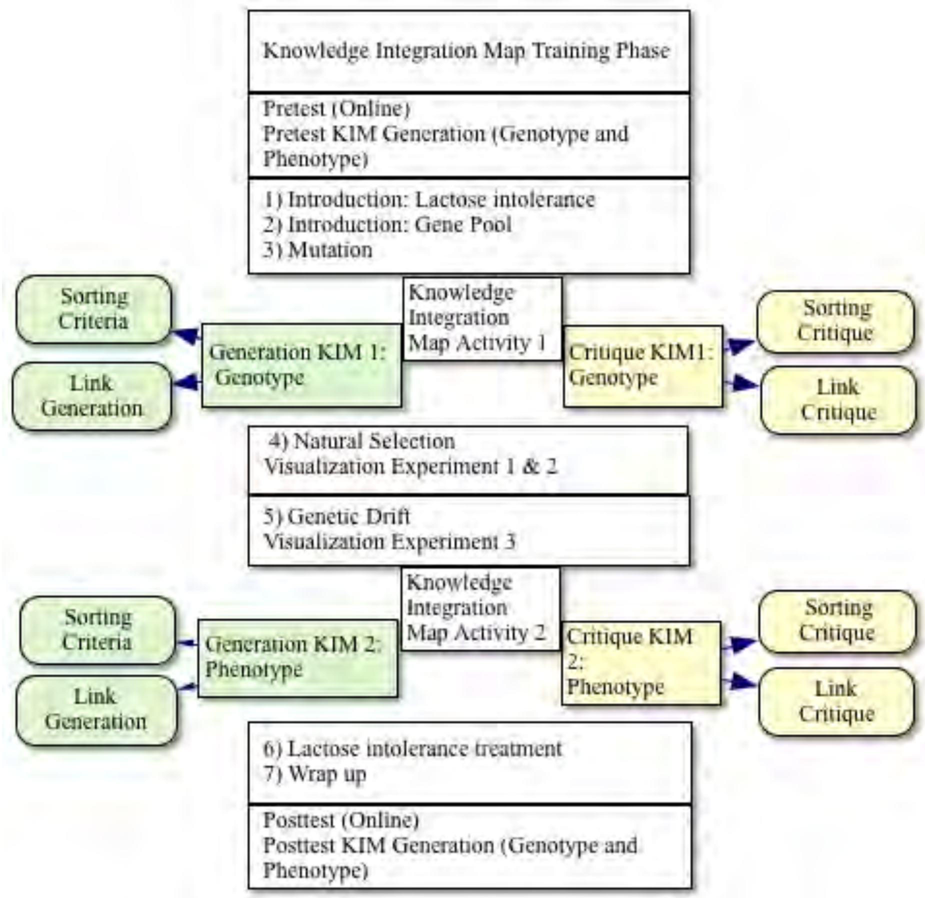


Figure 43: WISE module "Gene Pool Explorer" structure.

D. Design-Based Research

Study 3 uses a design-based research approach [See chapter 2: Design-Based Research] that aims to gain a deeper understanding of biology learning through the iterative implementation and revision of the WISE evolution module in high school science classrooms. This study compares experimental conditions within a designed learning environment.

E. Iterative Changes from Study 2

According to the iterative design process of this dissertation research, the following revisions have been implemented in the design of study 3 and the WISE evolution module [See table 36]:

Table 36: Overview of changes in study 3.

Revised Element	Description
Guiding story	The WISE *Gene Pool Explorer* module uses a revised guided story. The guiding story in study 2's WISE module *Space Colony* explored the colonization attempts of a group of human settlers in a futuristic space ship. While this guiding story was of interest to a number of students, it provides an abstract setting that has few connections to

	the students' everyday life experiences. Study 3 continues to use a case study of human evolution to illustrate evolutionary change but uses the genetic basis of lactose intolerance as a guiding story instead [See study 3: Case Study of Human Evolution Development].
Knowledge Integration Maps (KIM)	Study 2 used KIMs with three levels (DNA; cell; organism/population). Results indicate that these three levels allowed for different placements for certain ideas. Study 3 uses KIMs with only 2 levels (genotype; phenotype) (see Lewis (2004)). These two levels are distinct from one another and are central to biology [See chapter 2: Entities: Genotype and Phenotype]. Study 2 asked students to revise only a single element; study 3 allows students to revise any number of elements in their critique KIMs. Instead of the paper-based KIMs from study 2, study 3 used an electronic concept mapping tool, Cmap, to deliver the KIMs [See study 3: Criteria for Selecting Concept Mapping Tool]. Study 2 used peer-generated KIMs for the critique activities that led to a wide variety of maps. To provide all students in the critique group with the same critique challenge, study 3 provides students with the same faux-student critique KIM. Study 3 divides the two levels with a dashed line (instead of the solid line in study 2) to show that the line could (and should) be crossed by cross-links.
Treatment groups	Results from study 2 indicate that critiquing peer-generated KIMs can support using specific criteria better than critiquing expert-generated KIMs. Study 3 extends these findings by using two embedded KIMs [See study 3: Treatment Groups]. Findings from study 2 suggest that generating and critiquing KIMs can effectively support knowledge integration of evolution ideas. However, the combination of these two activities can be time-consuming. Study 3 explores the learning effects of either generating or critiquing embedded KIMs. To further reduce time requirements, limit complexity, and avoid redundancy of having students generate the same map multiple times, study 3 splits the embedded KIM activities into a "genotype ideas only" (KIM activity 1) and a "phenotype ideas only" (KIM activity 2) activities. In study 2, students either critiqued a peer's map (peer map group) or critiqued their own map using an expert-generated map for comparison (expert map group), but both groups revised their own maps. To create equal conditions for all students in the critique group in study 3, students receive the same faux-student KIM to critique. Different than in study 2, students revise the faux-student KIM and not their own map. In study 2, whole classes were randomly assigned one of two treatments. To improve randomization, study 3 randomly assigns student dyads in each class to one of the two treatments.

Pretest/posttest	In addition to a KIM generation activity, study 3 includes a KIM critique activity in the pretest/posttest. These two activities are designed to reveal differences between the generation and critique treatment groups [See study 3: Pre- and Posttest design].
Dynamic visualization	Study 3 replaces the dynamic visualizations Evolution Lab and BioLogica with a simpler population genetics visualization Allele A1 that has a simpler interface and allows exploring all variables of the Hardy-Weinberg principle (mutation, natural selection, genetic drift, and migration) [See study 3: Dynamic Visualization].

F. Human Evolution Case Study Development

1) Human Lactose Intolerance Case Study

In collaboration with biology teachers and evolution researchers, human lactose intolerance was identified to meet the specified criteria [See table 37].

Lactose intolerance (adult lactase non-persistence) is a common worldwide phenomenon. 99% of Native Americans, Native Australians, and Asian Americans, 75% of African Americans, and 55% of Hispanics cannot digest large amounts of milk after infancy. Exceptions are the northern European and western African groups: Only 4-10% of adults show lactose intolerance in these groups. Recent research findings described that the ability to digest lactose beyond infancy (adult lactase persistence) was caused by a mutation around 5000 BC – independently from each other in northern Europe and Western Africa. Dairy farming in these areas acted as a strong natural selection factor to favor the new mutation. Until the age of 4, most infants produce the enzyme lactase that breaks down the milk sugar lactose in the mother milk into glucose and galactose. After infancy, 75% of adults worldwide no longer produce the enzyme lactase. The undigested disaccharide lactose cannot pass through the walls of the small intestine and passes into the colon (large intestine). Colon enteral bacteria switch to lactose metabolism, an in vivo fermentation that produces copious amounts of gas (hydrogen, carbon dioxide, and methane). This results in different degrees of stomach cramps, bloating and flatulence. People with lactose intolerance should avoid consuming large quantities of milk products while looking for alternative sources for protein and calcium.

Table 37: Study 3 criteria for human lactose intolerance case study.

Criteria	**Rationale**
Human evolution	Lactase persistence after infancy is a phenomenon specific to humans and represents a recent evolutionary change (about 5000 years ago). This recent evolutionary change illustrates the ongoing evolution process (Bloom & Sherman, 2005; Gerbault et al., 2011; Swallow, 2003; Tishkoff et al., 2007).
Directly observable phenotype in everyday life	Adult lactose tolerance is a real-life phenomenon that directly affects many students and their families. Between 30 and 50 million US-Americans are to some degree lactose intolerant

	(about 25% of the total US population). The effects of lactose intolerance can be directly observed in varying forms and degrees of stomach cramps, bloating, diarrhea, and flatulence about thirty minutes to two hours after consuming milk products. However, lactose intolerance is often only a mild inconvenience that can be countered with a lactose-reduced diet or lactase enzyme pills. The WISE module includes information about how to deal with lactose intolerance by showing lactose-free alternative food options.
Simple underlying genetic cause	Research indicates that adult lactase persistence was caused by a single mutation that changed the production of the enzyme lactase (Bloom & Sherman, 2005; Gerbault et al., 2011; Swallow, 2003; Tishkoff et al., 2007).
Connection between genetic, protein, and phenotype level	Lactose intolerance allows illustrating the effects of a single mutation, enzyme production, and phenotypic symptoms. Lactose intolerance allows illustrating the connection between genotype and phenotype through a discussion of the role of the enzyme lactase.
Builds on current research findings	Understanding the genetic basis for human lactose intolerance is based on recent research findings, for example see (Bloom & Sherman, 2005; Gerbault et al., 2011; Hollox, 2004; Swallow, 2003; Tishkoff et al., 2007).
Allows to illustrate the effects of all Hardy-Weinberg model variables: Mutation, natural selection, genetic drift, and migration	Lactose intolerance allows illustrating the Hardy-Weinberg model. The mutation that caused adult lactase persistence coincided with positive selection pressures in early dairy farming cultures. Migration of northern European settlers (for example to north America) influenced the frequency of the mutation. Genetic drift can be demonstrated by exploring who randomly selected small groups of settlers colonize different environments. Using a population genetics approach aims to challenge the existing alternative idea of essentialism [See chapter 2: Individual variation vs. Essentialism]. Evolution does not happen to individuals but populations. Using a dynamic population genetics simulation, students can observe evolution as a change in allele frequencies over many generations instead of changes in an individual over it's lifetime.
Novel example	Many biology textbooks use animals as examples for evolution, for example the peppered moth or Darwin finches. For human examples, sickle cell anemia case studies are often used. Lactose intolerance can be used as a case study that is novel to most students.
Ability to simulate using a dynamic visualization	Several general population genetics simulations (based on the Hardy-Weinberg model) have been developed that allow learning about the processes that affect genetic diversity in the gene pool through inquiry [See study 3: Dynamic Visualization].
Example of a positive	Adult lactase persistence is an example for a positive mutation

mutation	that challenges the common alternative idea that mutations are inherently negative. Students often describe all mutations as being detrimental to organisms (Cho et al., 1985; Nehm & Schonfeld, 2007). The lactose tolerance example addresses this alternative idea by showing a positive mutation. Students learn that the environment determines if a mutation is neutral, negative, or positive. For example, if a mutation for adult lactose tolerance occurs in a population that does not have access to milk, the mutation would be considered neutral. If the mutation occurs in a cow farming population and people now have to ability to consume milk beyond infancy, the mutation would be considered positive. Students often describe mutations as occurring in response to environmental changes (Jensen & Finley, 1995). The lactose tolerance example addresses this by discussing that the environment (for example the presence of cow milk) did not cause the mutation. Rather, the mutation was found to be beneficial in this environment while being neutral in areas without cow farming.
Interesting to an ethnically diverse group of students	Lactose intolerance should be interesting and relevant to an ethnically diverse group of students as the effects can be experienced in real-life.

G. Dynamic visualization

Carefully constructed inquiry activities using dynamic visualizations have been found to support students' knowledge integration (Linn et al., 2006). Study 2 used two different dynamic visualizations, Evolution Lab and BioLogica [See study 2: Dynamic visualization]. Using two different visualizations required students to learn two different interfaces and graphical representations, which is time-consuming. Because of the limitations of Evolution Lab and BioLogica [See study 2: Implications and Outlook], study 3 uses a single population genetics visualization in a series of guided inquiry activities [See study 3: Criteria for Population Genetics Visualizations Selection].

1) Criteria for Population Genetics Visualization Selection

To identify a scientifically and educationally sound population genetics visualization suitable for high school learners, a set of selection criteria has been developed:

- The visualization should be freeware or open-source.
- The visualization should be available for different operating systems (Win, OSX, Linux).
- The visualization should have a simple and well-designed user interface that allows changing the Hardy-Weinberg formula variables (natural selection, population size, mutation, and migration).
- The visualization should allow direct comparison of multiple experimental conditions.

- The visualization should allow the user to change the time scale (for example the number of generations) shown in the graph. This allows observing short and long term changes in allele frequencies.

Several population genetics simulation programs were evaluated: PopG (Felsenstein et al., 2008), Evolve (Prince & Vaughan, 2006), and Allele A1 (Herron, 2003) [See table 38].

Table 38: Population genetics visualizations comparison.

Criterion	PopG	Evolve	Allele A1
Open Source or Freeware	Freeware	Freeware	Freeware
Cross-Platform	Win, OSX, Linux	OSX	Win, OSX
Well-designed interface	Simple interface, but the settings menu needs to be opened in separate window each time.	Complex interface with numerous advanced setting options.	Simple interface with basic options.
Comparison of multiple experiments	No	Yes	Yes
Change time scale	Yes	Yes	Yes

Only Allele A1 (by Jon C. Herron, University of Washington) met all the criteria. Allele A1 offers a well-designed user-interface, allows seeing several frequency curves at the same time, and distinguishes each curve by color [See figure 44]. Allele A1 is a population genetics visualization consisting of only two alleles, A1 and A2. However, the graph only shows the frequency of allele A1 (as the frequency of allele A2 is known through subtracting the frequency of allele A1 from the total 100%).

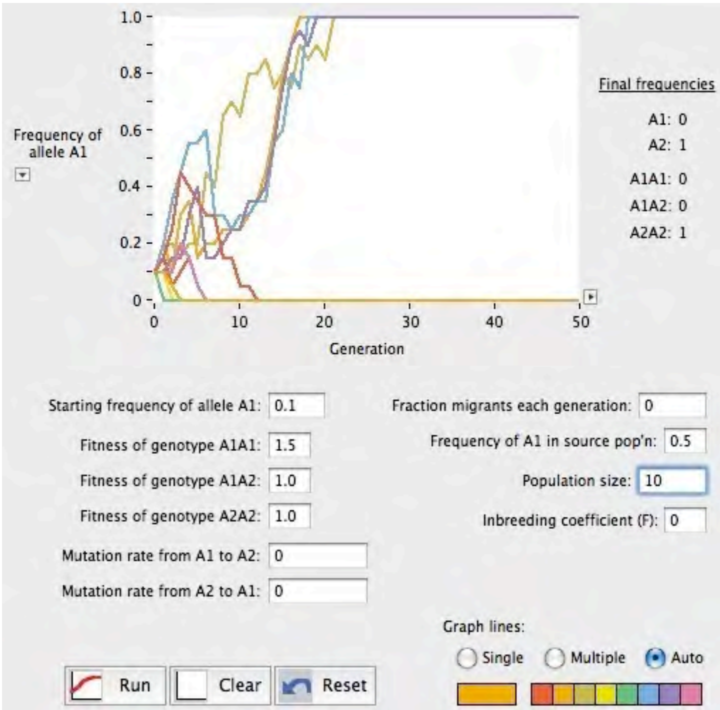


Figure 44: Dynamic population genetics visualization Allele A1.

Students can directly compare the frequency changes of allele A1 over many generations under different environmental conditions. The WISE module *Gene Pool Explorer* uses Allele A1 for three consecutive experiments:

- Experiment 1: A large non-dairy farming population with 10% allele A1 (that causes adult lactase persistence) in the gene pool illustrates neutral selection without genetic drift. Because the lactose tolerant phenotype is neutral in a non-dairy farming population, the frequency of allele A1 will not change over time.
- Experiment 2: A large dairy farming population with 10% allele A1 in the gene pool illustrates positive natural selection without genetic drift. Because the lactose tolerant phenotype has a higher fitness in a dairy farming population, the frequency of allele A1 will increase over time.
- Experiment 3: Several small randomly selected groups of dairy-farming settlers colonize different islands without contact to the main population. This experiment illustrates the effects of genetic drift. By repeating the experiment for each group of colonists, students can explore the unpredictable effects of genetic drift on the gene pool. Genetic drift causes either a loss (0%) or a fixation (100%) of allele A1.

The inquiry activities were designed following the Knowledge Integration design pattern of 1) Predict (to elicit existing alternative ideas), 2) observe (to gather data from the visualization): "What does the curve look like?", "Do you get the same result in repeated experiments?", 3) explain your observation and if your prediction came true or not (to connect ideas, sort out ideas, and revisit ideas), and 4) identify general connections between genotype and phenotype ideas.

H. Study 3 Knowledge Integration Map

1) KIM Training Phase

An initial Knowledge Integration Map training phase is important to familiarize learners with a) the concept mapping generation principles, and b) criteria for concept map evaluation (Novak & Gowin, 1984; Reader & Hammond, 1994; Shavelson et al., 1994) [See chapter 2: Concept Map Training]. However, existing concept map training approaches are often not time efficient or quite laborious to employ (Hilbert & Renkl, 2009).

Based on the findings from study 1 and 2, an efficient Knowledge Integration Map training sequence was developed for study 3.The KIM training sequence consists of increasingly more challenging tasks that alternate between individual practice and classroom discussions. The goal of the training sequence is to familiarize students with the KIM technique and collaboratively develop criteria for KIM critique and revision.

1) KIM technique demonstration: The teacher demonstrated the concept map technique on the whiteboard using a familiar and simple example ("rock-paper-scissors"). First, the teacher demonstrated the concept mapping heuristic on the whiteboard. Students were then asked to generate further propositions. The teacher introduced concept maps as a semantic networks consisting of noun-verb-noun sentences that can be read in the direction of the arrow. Propositions are "simplified sentences". The teacher stressed the point that there is no single solution for concept maps and made the possible benefits for learners explicit, for example to keep track of your own learning progress, to revise your understanding towards a deeper understanding, to communicate what would otherwise be incommunicable, or to make connections between ideas visible that would otherwise be invisible (see (Kinchin, 2000b; Lehrer et al., 2000)). Duration: About 5 minutes.

2) Individual KIM generation practice: Students individually generated a paper-based Knowledge Integration Map on a familiar science topic (genetics). The training KIM was divided into the levels "DNA" and "Cell". Students received detailed scaffolds on how to generate their KIM from a given list of ideas, for example "Sort out ideas into the corresponding level", "connect related ideas with arrows", and "label each arrow to describe the nature of the relationship" [See appendix chapter 5: study 2]. Duration: About 10-15 minutes.

3) Individual KIM critique practice: The teacher used a projector to showed a KIM based on the same ideas students used in the generation practice, but with deliberate errors in it [See appendix chapter 6: study 3]. Based on the findings from study 2, students need to be in an equal (or higher) position of power to feel empowered to critique others' work. The critique activity KIM was introduced as having been generated by another student. This "faux student" KIM was generated by the researcher to include common alternative evolution ideas [See chapter 2: Students' alternative ideas of evolution] and different types of errors: Missing link, missing label, misplaced ideas, and mismatch between arrow direction and label. Critiquing and revising another student's map can add a social element of helping a fellow peer [See chapter 2: Critique]. Following a think-pair-share heuristic (Lyman, 1987), students first individually tried to identify possible errors by comparing the flawed map to their own map (similar to study 2), then students partner with a peer to discuss their observations and possible improvements.

Finally, the student dyads share their critique with whole class (see next step). Duration: About 5 minutes.

4) Classroom discussion of KIM critique: The teacher asked student dyads to share their critical observations with the class and invited other students to comment on suggestions. The class collaboratively identified errors and alternative revisions. The teacher prompted students to create categories of different forms of KIM critique, for example "Are important connections missing?", "Which links labels do you agree with?", "Are ideas placed in the correct level?", "Are all arrows labeled?", and "Are the arrows going in the right direction?". This criteria rubric is based on the findings from study 2 [See study 2: Quantitative Results]: Superficial criteria (label all links, make arrows instead of just lines) and specific criteria (sorting of ideas, does the arrow direction make sense, do labels make sense). Research suggests that students will internalize the role of the critic and improve their self-reflections about their own work, similar to the reciprocal teaching approach (Brown & Palincsar, 1989). Duration: About 10 minutes.

5) Pretest KIM critique activity and KIM generation activity: As part of the pretest and posttest, students individually work on a KIM generation activity and a KIM critique activity. The KIM worksheet is divided into "genotype" and "phenotype" levels and provides ideas from genetics and evolution. Each KIM worksheet includes a scaffolded focus question (Derbentseva et al., 2007) ("What role does genetic variability play in the survival of a species?"), a forced choice list of ideas, and detailed instructions.

2) KIM ideas

Many students have difficulty distinguishing important ideas in a text, lecture, or other form of presentation. Part of the reason is that many students learn only to memorize but not distinguish and sort out ideas. They fail to construct propositional frameworks and see learning as "blur of myriad facts, dates, names, equations, or procedural rules to be memorized, especially in science, mathematics and history" (Novak & Canas, 2006). Knowledge Integration Maps can help students eliciting relationships between ideas, distinguish central ideas, and making sense of complex science topic such as evolution.

Concept mapping tasks are found in many different forms and provide different amounts of constraints. The task range from low directed maps where students can freely choose their ideas and labels to highly directed tasks where students fill in ideas out of a given list into blanks in a given skeletal network structure (Novak & Canas, 2006). Highly constrained maps can be beneficial for low performing and younger students, but they provide less insight into students' partial knowledge. Free drawing concept maps provide the most insight, but do not allow for standardized comparisons between students. Constraining students by providing them with a set of ideas or link labels allows for standardized or even automated comparison across students on the exact same content, but appears to be more challenging for many students than working from memory. They must discipline themselves to use the given ideas rather than to freely follow their thought patterns (Fisher, 2000). Study 3 seeks a to develop a balanced form of Knowledge Integration Map by providing students with a small set of ideas but allowing them to generate their own connections and labels [See task type #2; 2 DoF in table 5]. This design allows comparing maps of different students with each other.

Study 3 models what experts consider important ideas by providing students with a list of ideas for their KIMs. Kinchin noted that the number of given ideas should be kept small (around 10-20) to reduce complexity and time-consumption (Kinchin, 2000a). Based on an evaluation of major biology textbooks, state standards, interviews with experts, and the two previous studies 1 and 2, 11 ideas have been selected for the Knowledge Integration Map [See table 39]. Study 3 uses KIMs with a forced-choice design by providing students with a list of 11 ideas. The number of ideas was kept low in order to keep to size and complexity of the KIM reasonable for the given time constraints for its creation. A total of 55 connections are possible between the given 11 ideas, but not all propositions are of equal importance. (Considering each direction individually and allowing for circular links to same idea, 11x11=121 connections are possible). Students need to decide which connections are essential to represent their understanding. Additionally, each connection can go in either direction and be described with many different labels. Students need to match the directionality of the connection with the label and construct a label that accurately describes the nature of relation [task type #2; 2 DoF. See table 5 in chapter 2: Types of Concept Map Tasks]. As the map constrains students to only one connection for each relation, the students needs to develop decision-making criteria. To model expert understanding, the given list of ideas includes only expert ideas, but no alternative ideas such as “need”, “intentionality”, or “want”. Alternative ideas can be expressed through idea placement and link labels. Following the findings from study 2, all students in the same treatment group receive the same list of ideas (generation group) or KIMs with errors (critique group). This provides each student dyad with equivalent opportunities.

Six genotype level ideas and five phenotype level ideas were chosen [See table 39]:

Table 39: Ideas used in study 3 KIMs

Idea	Level
Gene	Genotype
Allele	Genotype
Genetic Drift	Genotype
Gene Pool	Genotype
Adaptation	Phenotype
Fitness	Phenotype
Population Size	Phenotype
Natural Selection	Phenotype
Environment	Phenotype

3) KIM Activity Design

(i) Novel Concept Map Type

Integrating biology ideas requires connecting ideas from different fields (such as genetics and evolution). Markham (1992) found that the major differences in content knowledge of novices and experts are a lack of integration, lack of cross-links between ideas, and a limited number of hierarchical levels. Research indicates that re-representing text in a concept mapping format can be done in a fairly automated way without requiring construction of new or revision of existing connections between ideas (Holley, Dansereau, & Harold, 1984; Karpicke & Blunt, 2011). Greater benefit may arise if the concept map activity constrains ideas and relationships to a novel format, for example by providing biology-specific scaffolding to distinguish "genotype ideas" and "phenotype ideas".

This dissertation research proposes two new approaches to use concept maps to integrate evolution ideas:

A) A novel form of non-hierarchical biology-specific concept map, called Knowledge Integration Map (KIM), elicits and scaffolds cross-field connections through the spatial arrangement of ideas in specified levels. Knowledge needs to be structured to be meaningful (Bransford, 2000a). Ausubel (1963; 1978) discussed the importance of the hierarchical arrangement of information within organizational tools. Evolution ideas, however, are not necessarily hierarchically organized but consist of ideas from different levels. The novel Knowledge Integration Map divides the drawing area into evolution-specific levels.

B) The novel concept mapping form developed for this dissertation research can be used in a wide variety of concept mapping tasks [See chapter 2: Types of Concept Map Tasks], for example for concept map generation or critique activities. The novel concept mapping form aims to apply knowledge integration principles to concept mapping [See chapter 2: Concept Maps and Knowledge Integration]: Eliciting ideas, adding ideas and connections, distinguish ideas, sort out ideas, revise and refine ideas. Generating concept maps can be time-consuming and effort intensive [See chapter 2: Limitations of Concept Maps]. To foster the distinction of alternative ideas, support knowledge integration, and be more efficient, critiquing concept maps with deliberate errors, based on known alternative ideas, can be used as an alternative learning and assessment tool.

Table 40: The novel concept mapping form can be described by the following characteristics:

Table 40: Study 3 KIM characteristics.

Biology-specific levels	This characteristic combines aspects of concept mapping with aspects of Venn diagrams. The concept map drawing area is divided into several biology-specific vertical levels, for example genotype and phenotype. This arrangement requires learners to a) generate criteria and categorize ideas, b) sort out ideas into according levels (clustering), and c) generate connections between ideas within and across levels. Sorting out out and grouping ideas spatially according to semantic similarity requires learners to generate criteria and make decisions about information structure that is latent in texts (Nesbit & Adesope, 2006). This is expected to support knowledge integration by showing ideas in contexts to other ideas and eliciting existing (and missing) connections within and across levels. Cross-links are especially desirable as they can be interpreted as "creative leaps on the part of the knowledge producer" (Novak & Canas, 2006) and support reasoning across ontologically different levels (Duncan & Reiser, 2007).
Given list of ideas, but free labels and	Ruiz-Primo et al. (2000) compared concept mapping tasks with varying constraints and found that constructing a map using a given list of ideas

links	(forced choice design) [See table 5 in chapter 2: Types of concept map tasks: Task #2] reflected individual student differences in connected understanding better than more constrained fill-the-map forms. Evolution consists of a large number of ideas that often make it challenging for novices to identify key ideas [See chapter 2: Difficult Use of Terminology]. Providing students with a list of expert-selected key ideas can serve as signposts and model expert understanding. Concept maps generated from the same set of ideas allow for better scoring and comparison. Students' alternatives ideas are captured in the idea placement, link labels, and link direction.
Concept map training activity	Students need initial training activities to learn the concept mapping method and generate criteria for concept map critique [See chapter 2: Concept Map Training]
Starter Map (Optional)	Building a concept map from scratch can be challenging. Providing a starter map as a partially worked example could reduce anxiety (Czerniak & Haney, 1998; Jegede, Alaiyemola, & Okebukola, 1990). Critiquing and revising concept maps with starter maps requires a completion strategy (Chang et al., 2000; Sweller et al., 1998; Van Merriënboer, 1990).
Faux-peer map	Students get few opportunities for critique or revision [See chapter 2: Critique]. Providing students with concept maps made by a peer (or a faux-peer) allow students to revisit their ideas by adding to, critiquing, or revising an existing concept map.
Collaborative concept map activity	Concept maps are generated collaboratively in dyads. As each proposition is constrained to only one link, students are required to negotiate which connection to revise or generate. Students are required to generate criteria [See chapter 2: Concept Maps as Metacognitive Tools] and negotiate with their partner [See chapter 2: Concept Maps as Collaborative Tools].
Focus question	The biology-specific focus question guides the construction of the concept map as learners select ideas and generate links to answer the focus question (Derbentseva et al., 2007).
Feedback and Revision	Feedback and revision supports students' knowledge integration through revisiting, reflecting, and revising existing and new ideas. Concept maps often need several revisions to adequately answer the focus question [See study 1A].

Bruner stated that "virtually all cognitive activity involves and is dependent on the process of categorizing." (Bruner, Goodnow, & Austin, 1986) (p. 246). Study 2 used a KIM with three levels: DNA, cell, and organism/population level. Providing such scaffolding for sorting out and grouping related ideas into categories can support knowledge integration of evolution ideas [See study 2 discussion]. However, results indicate that categorizing ideas into three levels can be challenging - maybe because the distinction between the three levels was not always clear enough. To address this issue, study 3 uses a revised KIM with two distinctly separate levels: Genotype and phenotype [See chapter 2: Evolution Ideas on Different Levels]. The distinction between phenotype and genotype is fundamental to the understanding of heredity and development of organisms (Mayr, 1988b).

- The **genotype** is the genetic information that codes for the creation of an individual. Genotype level ideas describe the genetic material and its changes over time.

- The **phenotype** is the expressed form that results from the developmental rules, the genotype and environmental influences [See chapter 2: Entities: Genotype and Phenotype]. Phenotype level ideas describe phenotypic traits and its interactions with the environment.

Kinchin (2005) suggested that generating several new concept maps could support revisiting ideas better than continuously revising one concept map. Starting new maps allows reviewing of superordinate structures that otherwise persist without revision. In the WISE *Gene Pool Explorer* project, student dyads work on two embedded KIMs. After completing the genotype section (activities 1-3), student dyads in the critique group [See Critique group] revise a faux-student KIM that contains genotype level ideas; students in the generation group create a KIM from a starter map using the same genotype levels as the critique KIM. After completing the phenotype section (activities 4-5), student dyads either critique or generate a phenotype level KIM. Students in both treatment groups connect genotype and phenotype level ideas in the pretest and posttest KIM generation activity [See figure 45].

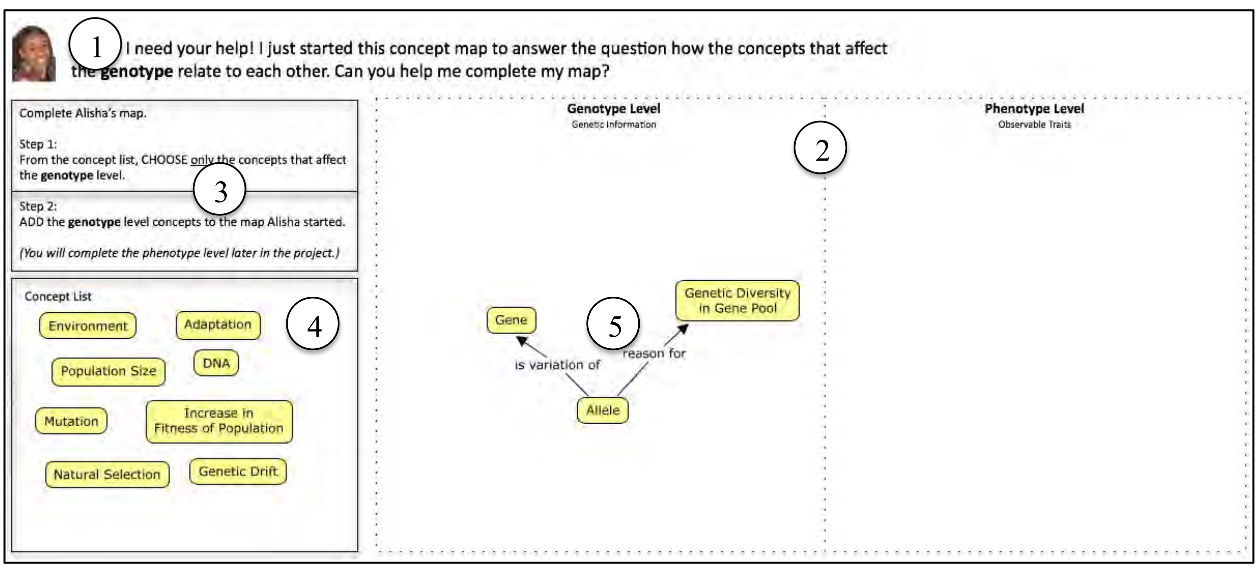


Figure 45: Study 3 KIM worksheet (generation treatment group): 1) Focus question, 2) Evolution-specific levels (genotype and phenotype), 3) Instructions, 4) Given list of ideas, 5) Starter map.

How to create a KIM activity (for researchers or teachers) [See table 41]:

Table 41: KIM activity construction.

1) Generate focus question
2) Based on field-experts and textbooks, identify key ideas for the map that allow answering the

focus question adequately. 3) Structure concept map into field-specific levels, for example in biology: genotype/phenotype, or individual/population; in chemistry: micro/macro/symbolic. 4) Create a starter map. 5) Create a concept map training activity.

Students' concept map activities [See table 42]:

Table 42: KIM generation or critique activities.

Critique Map	Generation Map
1) Generate criteria to analyze concept map, for example link direction, link label, idea placement, missing connections 2) Revise concept map	1) Distinguish and sort out given ideas into evolution-specific levels 2) Generate labeled links within and across evolution-specific levels from the starter map 3) Review and revise map

(ii) Treatment Groups

Study 2 suggests that a combination of generating KIMs followed by a critique and revision activity can support integrating evolution ideas across levels. However, generating and critiquing KIMs can be time-consuming. As time in science classrooms is very limited, study 3 aims to distinguish the learning effects from either **generating** or **critiquing** embedded KIM activities. During the WISE *Gene Pool Explorer* module, student dyads either generate or critique KIMs using the Cmap concept mapping software [See study 3: Concept Mapping Tool Cmap]. To further reduce time requirements, limit complexity, and avoid redundancy of having students generate the same map multiple times, study 3 splits the embedded KIM activities into "genotype ideas only" (KIM activity 1) and "phenotype ideas only" (KIM activity 2) activities [See table 43]. Both treatment groups (generation and critique group) received the same initial training [See study 3: KIM training phase] and were given the same list of evolution ideas [See study 3: KIM ideas].

Table 43: Study 3 treatment groups.

Treatment group	Training (individual and in dyads)	Pretest/ Posttest (individual)	Embedded KIM 1: Genotype level (in dyads)	Embedded KIM 2: Phenotype level (in dyads)
Generation group	KIM generation and critique activity	Genotype & Phenotype KIM generation and critique activity	KIM generation map 1	KIM generation map 2
Critique group	KIM generation and critique activity	Genotype & Phenotype KIM generation and critique activity	KIM critique map 1	KIM critique map 2

(a) Generation Group

Student dyads in the generation group created their own KIM connections from a given list of expert-chosen ideas. Generating their own connections allows students to elicit their existing and missing relationships between ideas within and across levels (genotype and phenotype). Each KIM contains a guiding question and a starter map. The guiding question poses a question that the students should answer in their KIM. The starter map serves as a model for the generation of further propositions. Students in the "generation" treatment have to develop their own criteria how to identify important connections between ideas. Student dyads need to negotiate where to place ideas, which connections to create, arrow directions, and link labels. Representing their ideas in visual form might help them to identify gaps in their understanding that require revisiting the curriculum material [See chapter 2: Generation]. On the other hand, they might miss identifying important connections. After individually generating the initial KIM as part of the pretest, student dyads revisit and revise their ideas in two embedded KIMs. Student dyads in the generation treatment group first create an embedded KIM using only genotype level ideas (KIM generation activity 1) after completing activity 3, and a second embedded KIM using only phenotype level ideas (KIM generation activity 2) after activity 5.

1) Embedded KIM generation activity 1 [See figure 46]

After the activity on mutations, student dyads received a mixed list of eight genotype and phenotype ideas to be sorted out. Students were instructed to select and connect only genotype level ideas to the started map. Students created only intra-level connections between genotype ideas.

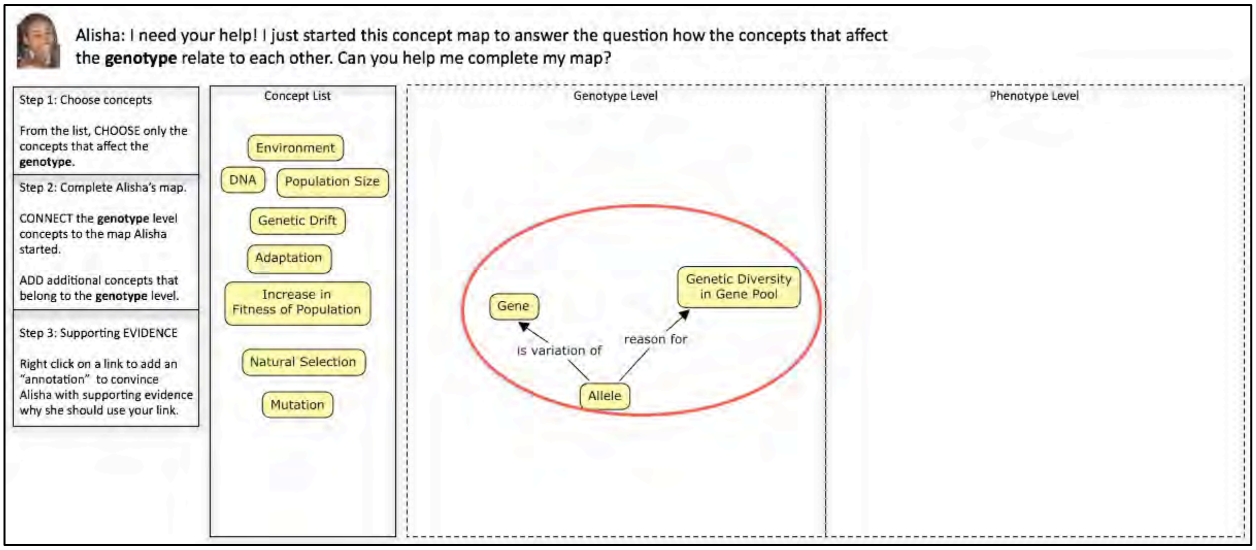


Figure 46: KIM generation activity 1 (genotype level ideas) (Highlighted: The starter map is identical to the correct connections in KIM critique activity 1).

2) Embedded KIM generation activity 2 [See figure 47]

After the curriculum section on selection processes (selection of phenotypes), student dyads generated a second KIM by adding phenotype related ideas to a starter map. Students created both intra-level phenotype and cross-level connections.

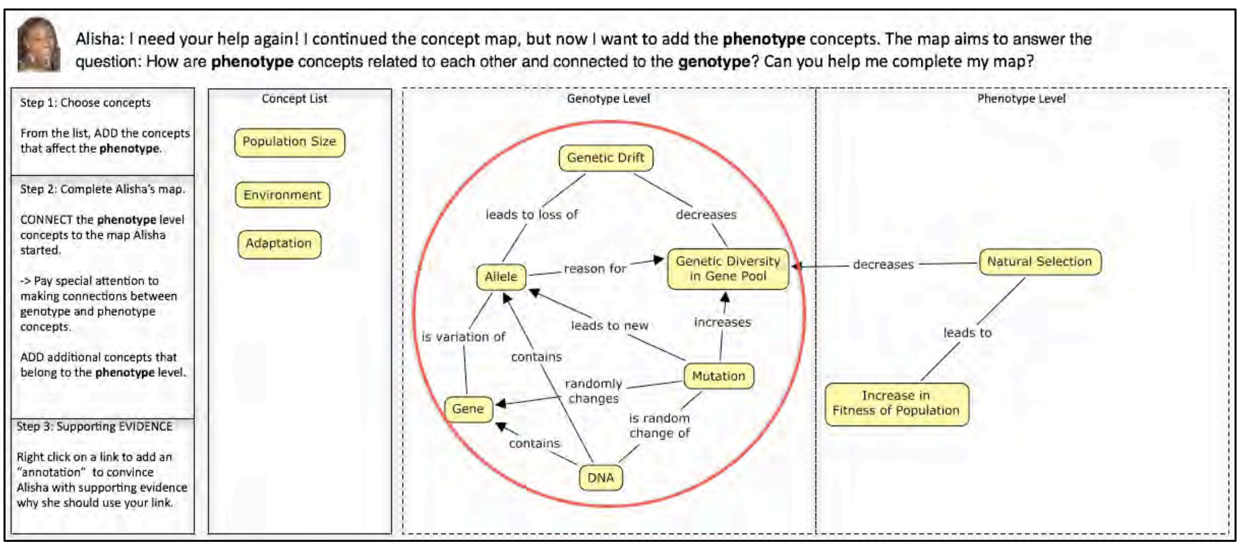


Figure 47: KIM generation activity 2 (phenotype level ideas) (Highlighted: The starter map is identical to the correct connections in KIM critique activity 2).

(b) Critique Group

Based on findings from study 2, critiquing a peer-generated KIM empowers students more to be critical than comparing their work to an expert-generated KIM. However, using peer generated KIMs for critique activities provide students with work of varying quality and might cause bias toward certain students' work (despite anonymization). Study 3 aims to alleviate these issues by providing students with "faux-peer" KIMs to critique. Critique KIMs are introduced as being the work of another student (the virtual student that guides through the WISE module *Gene Pool Explorer*). Faux-peer KIMs promise several advantages: First, to equilibrate treatment conditions, all students receive the same KIM to critique; second, students might hesitate to critique a classmate's KIM, but critiquing a virtual peer might avoid peer discrimination issues; third, helping a (virtual) peer improve a KIM has a social aspect; and fourth, critiquing peer generated work generates a genuine opportunity for students to apply critique [See chapter 2: Concept Maps as Critique Tools]. The given critique maps require students to critically reflect on the presented ideas as well as their own. Building on the knowledge integration tenet of "learning from others" [See chapter 3: Scaffolded Knowledge Integration], students learn by negotiating with their partner which propositions need revision. Student dyads need to study each proposition, build criteria to distinguish connections, and generate improvements [See chapter 2: Critique]. These criteria are expected to improve students self-monitoring and can be applied to the posttest KIM tasks.

The KIM critique activities contain deliberately flawed connections (placement errors, link errors, and missing links), derived from study 1, study 2, and the misconception literature (for example (Bishop & Anderson, 1990)) [See figure 48]. This design allows directly addressing common alternative ideas and monitoring changes during and after the intervention. Students needed to generate criteria to review and revise the presented connections. These criteria are expected to improve students self-monitoring and can be applied to the posttest-mapping task. Being able to compare and contrast one's own ideas against another person's ideas might scaffold more complex connections than the generation activity. Study 2 suggests that critiquing KIMs is more effective than receiving feedback. Students in the study 3 critique group only give critique but do not receive feedback. This can reduce the time requirements and workload for the teacher. To save time and reduce complexity, each of the embedded KIM critique activities focuses only on either on genotype or phenotype level connections, just like in the generation group.

1) Embedded KIM critique activity 1 [See figure 48]

After the mutation activity (sources of genotype variety), student dyads are asked to critique and revise a faux-peer genotype level ideas KIM containing deliberate errors by rearranging ideas, changing arrow directions, or change the link labels. KIM critique activity 1 contains the same correct links as the starter map of KIM generation activity 1.

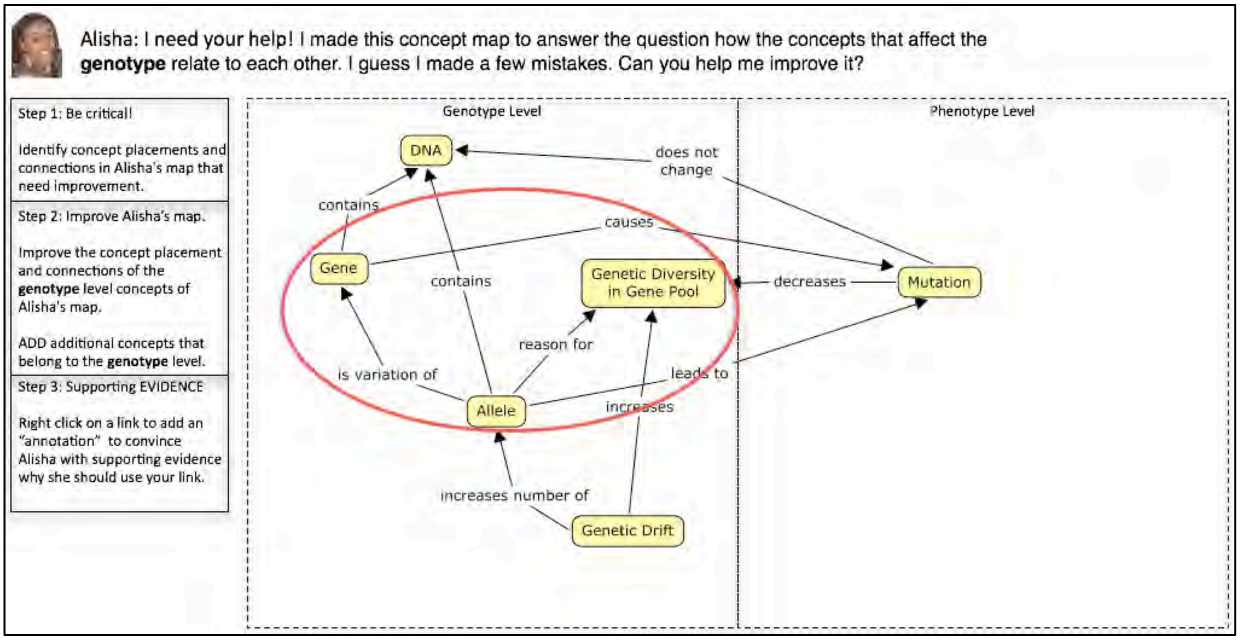


Figure 48: KIM critique activity 1 (genotype level ideas) (Highlighted: Correct connections that are identical to the starter map in KIM generation activity 1).

1) Embedded KIM critique map 2 [See figure 49]

After the curriculum section on selection processes (selection of phenotypes), student dyads are asked to critique and revise a faux-peer phenotype level ideas KIM containing deliberate errors by rearranging ideas, changing arrow directions, or change the link labels. To provide students in the critique group with the same correct starter propositions, the KIM critique map 2 contains the same correct genotype level propositions as KIM generation map 2. Students are instructed to revise only phenotype level ideas and cross-connections.

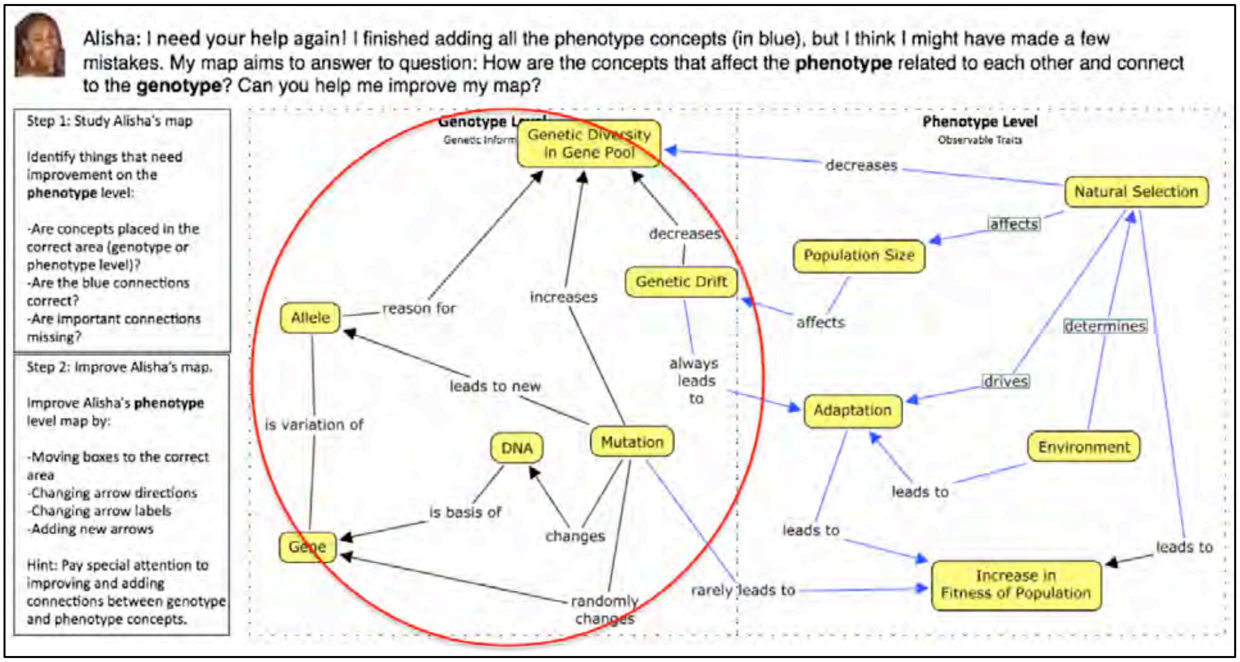


Figure 49: KIM critique activity 2 (phenotype level ideas) (Highlighted: Correct connections that are identical to the starter map in KIM generation activity 2). Students are instructed to focus their critical evaluation and revision on the blue marked connections in the phenotype level.

(iii) Concept Mapping Tool Cmap

Observations in study 2 suggest that revising paper-based KIMs can be cumbersome for students. A number of students did not add labels to their connections or used lines instead of arrows. Royer (2004) found that electronic mapping tools facilitate construction and revision of concept maps better than paper-and-pencil tasks.

Over two dozen concept mapping tools were evaluated using these criteria [See appendix chapter 3 appendix: table 65 and chapter 2: Concept Mapping Software]. The evaluation identified the freeware java-based tools "Cmap" by IHM (Canas, 2004) as the best freeware concept mapping tool. Cmap has a well-designed graphic interface that make adding ideas, generating links, and rearranging easy. Cmap prompts learners to add link labels and automatically generates arrows. Cmap allows saving concept maps either locally, on a Cmap server, or on one's own server. Cmap allows users to collaboratively work on concept maps, and receive comments from teachers and peers. Cmap is available for multiple platforms and multiple languages. Cmap allows setting up custom tasks, for example an idea bank, focus question, or specific levels. A research collaboration with IHMC allowed setting up a WISE Cmap server to store all data for this study.

I. Study 3 Participants

The WISE module *Gene Pool Explorer* was implemented by one teacher in four classes in a high school with an ethnically and socio-economically diverse student population of 9th and 10th grade science students [See table 44] (n=115). The high school had an enrollment of around 2000 students and was located in the urban fringe of a large city. School-wide, 12% of students received free or reduced price meals. Four percent of students were classified as English Learners; 67% were White, 16% were Hispanic or Latino, 10% were Asian, and 3% were Black.

The teacher randomly grouped students into dyads. A roughly equal number of student dyads in each class was randomly assigned to one of two experimental conditions: One treatment group generated KIMs from a given list of ideas (generation group; n=41) [See study 3: Treatment Groups], and the other treatment group critiqued faux-student KIMs with deliberate errors (that are based on commonly found alternative ideas) (critique group; n=52). Only students who completed pretest, posttest, and both embedded KIMs were included in the analysis (n=93).

The participating teacher was an experienced master teacher with nine years of teaching experience in high schools and community colleges and experience in using WISE modules. The teacher implemented the WISE module *Gene Pool Explorer* as an introduction to the subsequent topic of evolution after completing several weeks of introduction to genetics.

Table 44: Study 3 participants.

Class	Number of Students	Details
Class 3	28 (21 9th graders; 7 10th graders)	7 students enrolled in program for gifted and talented students; 2 students with disabilities. 6 English learning students.
Class 4	28 (22 9th graders; 5 10th graders; 1 11th grader)	11 students enrolled in program for gifted and talented students. 8 English learning students.
Class 5	30 (19 9th graders; 11 10th graders)	8 students enrolled in program for gifted and talented students. 5 English learning students.
Class 6	29 (21 9th graders; 8 10th graders)	8 students enrolled in program for gifted and talented students. 1 student with disabilities. 8 English learning students

J. Study 3 Data Sources and Analysis

1) Study 3 Data Sources

Like studies 1 and 2, study 3 used a pretest-posttest design to measure students' knowledge integration of evolution ideas. The assessment items were designed and scored using the Knowledge Integration framework (Linn et al., 2006) to measure students' abilities to connect genotype and phenotype level ideas. To achieve a rich description of classroom learning, study 3 used a mixed methods approach including quantitative and qualitative data sources [See table 45]. The pretest-posttest items represent revised versions of previously tested items from study 1 and 2 (Schwendimann, 2007; 2008) and several new items. Students individually filled out the pretest on the first day of the project and the posttest immediately after finishing the project. WISE was used to deliver the pretest-posttest items and collect embedded items. All assessment items were reviewed by biology experts, education researchers, and science teachers.

Table 45: Study 3 data sources.

Pretest/Posttest	Eight two-tiered assessment items that consisted of multiple-choice items followed by short essay items that asked students to explain their choice. The alternative options of the multiple choice items were based on known alternative ideas, for example: The idea of "need" to explain evolutionary change; Mutations occur to help an individual organism adapt to new situation; Evolution happens to individuals; and Acquired adaptations are inheritable. The items used real-life examples and a variety of contexts, for example human, animal, or plant evolution. Several items were based on biology content inventories (See (Anderson et al., 2002; Bishop et al., 1986; Nehm & Reilly, 2007). Three short essay items: The essay items focused on the connections between multiple ideas (especially between genotype and phenotype ideas). Two KIM critique tasks: Students had to identify deliberate errors on a KIM and suggest revisions. One KIM generation task (delivered using the electronic concept mapping tool Cmap). Links in the KIM generation activity were aligned with connections between ideas in the pretest/posttest and embedded items.
Embedded Items	Embedded multiple choice items and short essay items were collected. The electronic concept mapping tool Cmap was used for the two embedded KIM activities (generation or critique treatment).
Qualitative field notes	Detailed qualitative field notes were generated by the researcher to describe the teacher's behavior, behavior of the whole class, behavior of student dyads, and descriptions of the general course of events.

2) Study 3 Analysis Methods

Study 3 used a pretest-posttest design to investigate overall learning gains. Paired t-tests, chi-square tests and effect sizes were calculated. To investigate whether the two treatment groups (critique and generation) differed from each other in learning gains and changes in ideas, multiple regression analysis and ANOVA was used to determine the explanatory value of the variables treatment, pretest score, and KIM variables. Analysis of the propositional and network KIM variables were used to track changes in students' alternative ideas about evolution in each treatment group. A better integration of genotype and phenotype ideas would be expected to lead to a more frequent use of the idea "mutation" instead of the alternative idea "need" (teleological/ functional ideas).

(i) Pretest/Posttest Analysis

Pretest and posttest items were scored using a five-level knowledge integration (KI) rubric (Linn et al., 2006). The knowledge integration framework has been found to effectively measure the quality of students' connections among ideas. Explanations were coded for conceptual connections between ideas on a score ranging from 0 to 5, a higher score indicating a more complex connection [See table 46] [See detailed KI rubrics for each item in appendix chapter 6: study 3]. All items were weighted equally. KI rubrics were created based on theoretical expectations and then iteratively refined using student data. Higher knowledge integration scores indicate more complex normative links among different ideas relevant to the population genetic view of evolution.

Table 46: Study 3 Knowledge Integration rubric. Sample item: "What changes occur gradually over time in groups of finches that live in different environments?"

	KI Score	Sample Answers
No Answer (blank)	0	None
Offtask	1	I don't know.
Irrelevant/Incorrect	2	Finches develop new beaks to adapt to a new environment
Partial	3	Finches inherit traits from their parents.
Basic	4	Finches have differently shaped beaks that give them different chances to survive natural selection.
Complex	5	Natural selection causes those finches with helpful mutations to their beaks to be more genetically fit and adapt to the environment better. Therefore, the finches with the beaks adapted to their environment are more likely to reproduce and the trait gradually becomes dominant in the group.

(ii) KIM Analysis

The Knowledge Integration Maps generation and critique activities were used as complementary assessment items in the pretest and posttest (Rice et al., 1998). KIMs are rich sources of information about students' understanding. Many existing analysis methods often do not capture the manifold alternative ideas students represent in a concept map and tend to lose information by representing concept map scores as a single number [See chapter 2: Forms of Concept Map Analysis], for example by scoring components of the concept map either quantitatively by counting the number of ideas, links, hierarchy levels, and examples (Novak & Gowin, 1984), by qualitatively evaluating propositions (McClure, Sonak, & Suen, 1999b), or by comparing the students' concept map with a benchmark map (for an overview of concept mapping analysis methods see (Cathcart, Laura et al., 2010)). This study posits that no single scoring method can accurately describe all the different kinds of information in concept maps. Study 3 addresses the need for a more comprehensive multi-level analysis method for concept maps. Multiple forms of rubrics provide complimentary insights about students' connections between ideas. This study aims to identify variables that allow one to describe and track changes in the quality of multiple KIMs.

Knowledge Integration Maps can serve as sources for several different forms of information: Presence or absence of connections, quality of connections, different types of link labels, different types of networks, and spatial placement of ideas. To account for these different aspects of KIMs, several different analysis strategies were applied, both on a propositional [See study 3: Propositional Analysis] and on a network level [See study 3: Network Analysis]. Network analysis complements propositional analysis of isolated connections by using the maps' own characteristics to describe the overall geometrical structure of the network. The goal of the KIM analysis was to identify effective methods to track changes in students' ideas about evolution throughout the embedded KIM activities.

(a) KIM Generation Analysis

(1) Benchmark KIM

A benchmark KIM was developed in collaboration with biology experts and science teachers. As found in study 1, experts can create a wide variety of KIMs. Therefore, a benchmark map should not be used as the single correct solution but as an expert suggestion [See study 1A: Concept Map Analysis and Benchmark Maps]. Study 3 uses the benchmark KIM to identify central ideas and connections for detailed analysis [See figure 50].

A benchmark KIM can be used to standardize variables to compare different student-generated KIMs against one another. The benchmark KIM indicates how many and which connections experts generate. To calculate standardized KIM variables, student-generated KIM variables are divided by the benchmark KIM variables.

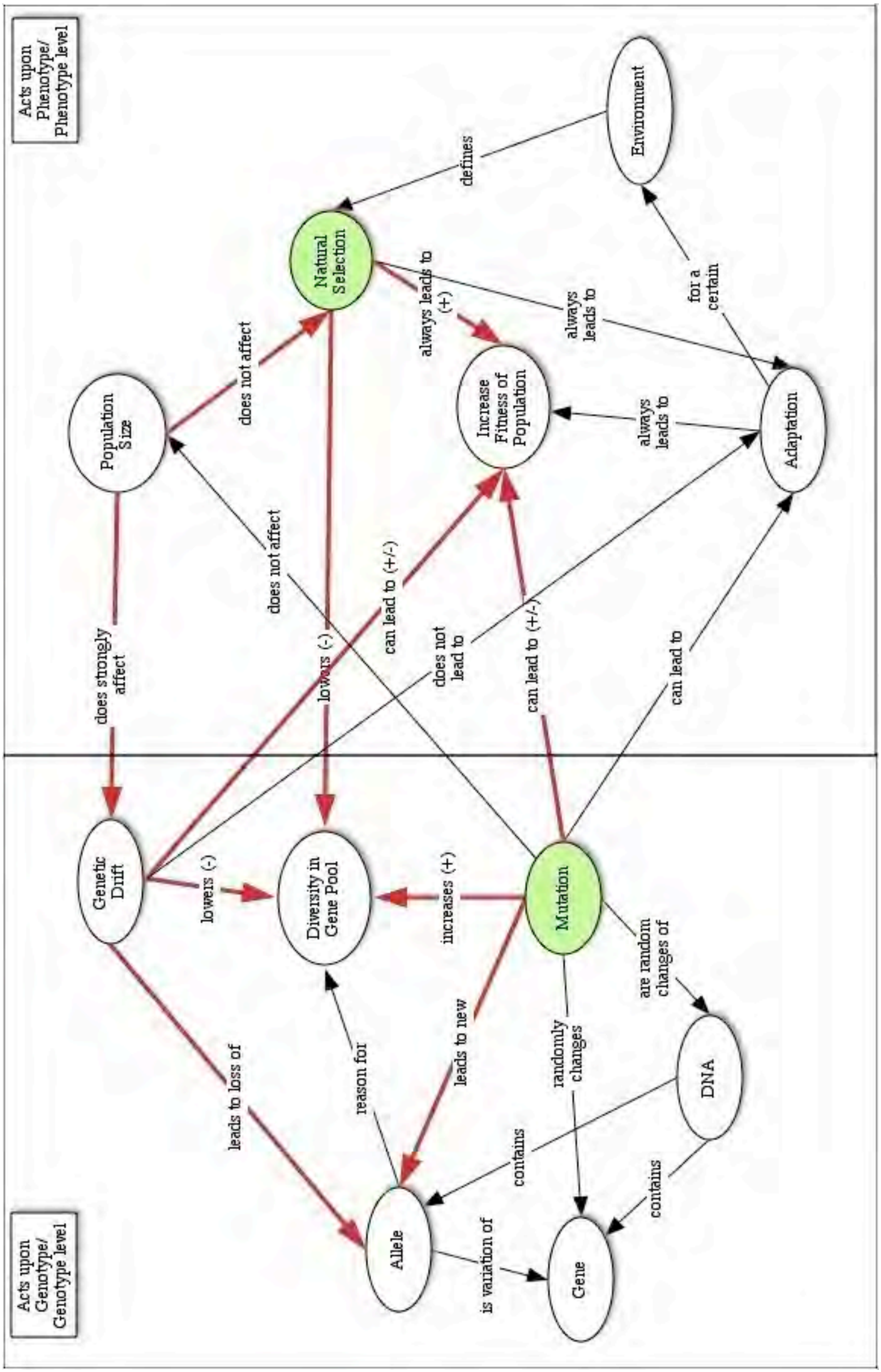


Figure 50: Study 3 benchmark KIM. Indicator ideas (green), essential connections (red).

(2) Indicator Ideas

For the KIM network analysis, one idea from each level (genotype/phenotype) was selected as the "indicator idea." The analysis of each indicator idea shows how often and through what kind of relationships students connected this idea to others. The criteria for selecting the indicator idea were: 1) Centrality in the expert benchmark KIM, and 2) Importance according to evolutionary theory literature [See figure 50].

- For the genotype level, "mutation" has been identified as the indicator idea.
- For the phenotype level, "natural selection" has been identified as the indicator idea.

(3) Essential Connections

Ruiz-Primo (1997) suggested that knowledge within a content field is organized around central ideas, and to be knowledgeable in the field implies a highly integrated conceptual structure.

Graphic organizers can enhance student learning by representing complex ideas in an organized structure reflecting the importance of each idea (Plotnick, 1997; Romance & Vitale, 1999). To reverse this finding, learners' understanding of the importance of ideas can be identified by analyzing how connected selected ideas are in a KIM.

Study 2 and Ruiz-Primo (2009) found that a KIM analysis that focuses on pre-selected "essential links" instead of all links can capture a great variety of ideas while being more efficient. Study 3 identified ten essential connections [See figure 50] [See table 47]. The criteria for selecting the essential connections were: 1) Connections between the indicator ideas and the newly introduced idea "gene pool" and "genetic drift", and 2) Cross-connections between genotype and phenotype levels. An increased number of cross-connections can be interpreted as a more connected understanding of genotype and phenotype ideas.

Table 47: Study 3 essential connections in KIM benchmark.

Genotype level	Mutation leads to new alleles. Mutation increases the diversity in the gene pool. Genetic drift decreases the diversity in the gene pool. Genetic drift leads to the loss of alleles.
Phenotype level	Natural selection always leads to an increase in the fitness of a population. Natural selection affects the population size.
Cross-Connections	Natural selection lowers the diversity in the gene pool. Mutations can lead to an increase in the fitness of a population. Genetic drift can lead to an increase in the fitness of a population. Population size does strongly affect genetic drift.

(b) Propositional Analysis

(1) Primary KIM Analysis Variables

(I) KI Rubric for Concept Maps

To quantitatively describe changes in KIMs from pretest to posttest, primary and secondary analysis variables were used. Primary variables are based directly on the KIMs, while secondary variables are calculated from primary variables. Primary propositional scoring included 1) scoring of all propositions, and 2) scoring of only essential propositions.

1) Score all propositions

KIM propositions consist of two ideas and their relationship (indicated by a labeled line with an arrowhead). Propositions are elementary units of Knowledge Integration Maps. Individual propositions were analyzed using a five-level Knowledge Integration rubric [See study 2] [See table 46]. All propositions were weighted equally.

Table 48: Study 3 KIM Knowledge Integration rubric.

KI Score	Link label quality	Link Arrow	Sample Propositions
0	None (No connection)	None (No connection)	
1	Wrong label	Wrong arrow direction	Genetic variability includes mutation
2	a) No label	a) Only line	a) Mutation -- genetic variability
	b) Correct label	b) Wrong arrow direction	b) Genetic variability – contributes to > mutation
	c) Incorrect label	c) Correct arrow direction	c) Mutation – includes > genetic variability
3	No label	Correct arrow direction	Mutation --> Genetic Variability
4	Partially correct label	Correct arrow direction	Mutation – increases -> Genetic Variability
5	Fully correct label	Correct arrow direction	Mutation – causes random changes in the genetic material which in turn increases -> Genetic Variability

2) Score only essential propositions [See study 3: Benchmark KIM]

Using the same five-level knowledge integration rubric [See table 48], only essential propositions were scored. Scoring only essential propositions is more efficient than scoring all propositions.

(A) Idea Placement Analysis

Knowledge Integration Maps ask students to sort out ideas into genotype and phenotype levels. Idea placement is an additional level of information that indicates how students categorize ideas. Connecting ideas within a level indicates students' understanding of the relationships between closely related ideas. Connecting ideas across levels (cross-links) indicates students' understanding across ontologies and levels of space and time. Cross-links are of particular interest as they can indicate "creative leaps on the part of the knowledge producer" (Novak & Canas, 2006) and reasoning across ontologically different levels (Duncan & Reiser, 2007). Cross-connections are of particular interest as they indicate if students see connections between genotype and phenotype level ideas. As ideas might be wrongly placed by students, an observed cross-connection might actually be a connection between two ideas of the same level ("uncorrected cross-link). To account for such cases, a "corrected cross-link" variable indicates intra-domain connections even if the ideas were wrongly placed [See study 3: Primary Analysis Variables]. Study 3 identifies such cross-links as important indicators of students' emerging systemic understanding.

(B) Primary Analysis Variables

Two different sets of primary variables were created: Number of links [See table 49] and knowledge integration (KI) scores [See table 50].

1) Primary variables: Number of links [See table 47].

Table 49: KIM primary variables: Number of links.

Variable	**Comment**
Total number of links	
Total number of essential links	
Total number of uncorrected cross-links	**Uncorrected** cross-links are connections that cross the line between the genotype and phenotype level. Because of falsely placed ideas, some connections might not be a true cross-connection between a genotype and phenotype level idea. However, the uncorrected cross-link can be seen as an indicator of students' intention to connect ideas across levels.
Total number of corrected cross-links	**Corrected** cross-links count connections between genotype and phenotype level ideas, even if the ideas were wrongly placed.

Knowledge integration rubrics were created for each proposition [See appendix chapter 6: study 3 and table 49].

2) Primary Variables: Knowledge Integration (KI) scores [See table 50].

Table 50: KIM primary variables: KI scores.

Total KI score of all links (Total Accuracy Score)
KI score essential links
KI score genotype level only
KI score phenotype level only
KI score uncorrected cross-connections
KI score corrected cross-connections

(2) Secondary KIM Analysis Variables

(I) Secondary Network Analysis Variables

Other ways to describe KIMs are density variables and ratios (calculated from primary analysis variables):

- Relative density: Total number of student-generated connections divided by total number of possible connections (=55).
- Standardized density: Total number of student-generated connections divided by total number of links in benchmark map (=23)
- Relative essential link ratio: Total number of essential student-generated connections divided by total number of student-generated connections.
- Standardized essential link ratio: Total number of essential student-created connections divided by total number of essential connections in benchmark map (=10).
- Corrected cross-connections ratio: Total number of student-generated cross-connections (corrected) divided by total number of cross-connections in benchmark map
- KI score ratio: Total KI score in student-generated map divided by total KI score in benchmark map (=126)
- Standardized KI score ratio: Total KI score of essential connections in student-generated map divided by total KI score of essential connections in benchmark map (=50)

(c) KIM Qualitative Link Analysis

(1) Qualitative Proposition Analysis

Learning about relationships between ideas is challenging for all learners. When learning a language, students learn nouns before verbs (Gentner, 1978). Typically, KIM ideas are nouns while link labels are verbs. Learning about the relationships between ideas can be more challenging than understanding individual ideas. However, understanding the relationships between ideas is essential to an integrated understanding of biology.

Most existing concept map analysis methods focus mostly on quantitative variables [See chapter 2: Forms of Concept Map Analysis]. To describe semantic changes in the relationships between ideas, qualitative variables are needed. To track changes in relationship types, a link label taxonomy has been developed for study 3 [See appendix chapter 6: study 3 table 98: Categories of different types of KIM relationships].

The concept mapping literature suggests a number of different link types. For example, Kathleen Fisher distinguished three main types of propositional relationships in biology that are used in 50% of all instances: *Whole/part*, *set/member*, and *characteristic* (Mintzes et al., 2000a) (p. 204). O'Donnell distinguished between three types of relationships in knowledge maps: Dynamic, static, and elaboration (O'Donnell et al., 2002). Lambiotte (1989) suggested dynamic, static, and instructional relationship types for concept maps. Derbentseva distinguished between static and dynamic relationships in concept maps (Derbentseva et al., 2007; Safayeni, Derbentseva, & Canas, 2005).

To create a taxonomy of link types, higher order variables are needed. Study 3 used the structure-behavior-function (SBF) framework to create the super-categories of the taxonomy.

The SBF framework was originally developed by Goel (1989; 2008) to describe complex systems in computer science, and then applied to complex biological systems by Hmelo-Silver and colleagues (2004; 2007) and Liu (2009). The taxonomy is both theory-driven and informed by empirical data from previous studies.

- Structure: What is the structure (in relation to other parts)? These variables describe static relationships between ideas. Static relationships between ideas include hierarchies, belongingness, composition, and categorization.
- Behavior: What action does it do? How does it work/influences others? These variables describe the dynamic relationships between ideas. Dynamic relationships between ideas indicate how one idea changes the quantity, quality, or state of another idea.
- Function: Why is it needed? These variables describe functional relationships between ideas, for example "want" (intentionality) or "need" (teleological).
- The sub-categories for the taxonomy emerged from KIM analysis from study 1 and 2. Categorizing link labels will allow tracking and describing how connections changed ontologically.

(2) Network Analysis

An analysis method that focuses only on isolated propositions does not account for the network character of a whole map. Study 3 uses two strategies to capture the network characteristics of KIMs: 1) Network analysis focuses on the connectedness of select indicator ideas, and 2) Topological analysis describes the overall geometrical structure of the KIM.

The network analysis strategy uses the frequency of usage of essential ideas as indicators for a more integrated understanding. As students develop a more complex understanding, they might also identify certain ideas as more important and connect them more often. Study 3 uses the indicator ideas "mutation" (genotype level) and "natural selection" [See study 3: Benchmark KIM: Indicator Ideas]. Two measurements were used to capture changes in connection frequencies to the indicator ideas.

The network analysis method developed for study 3 is based on social network analysis (Wasserman & Faust, 1994) (Chapter 5). Network analysis method can identify changes in "centrality" (outgoing connections) and "prestige" (incoming connections) of expert-selected indicator ideas (mutation for genotype level; and natural selection for phenotype level).

- **Centrality**: Outgoing connections from the indicator idea. This variable describes how many relationships lead away from the indicator idea.

- **Prestige**: Incoming connections to the indicator idea. This variable describes how many relationships from other ideas lead to the indicator idea.

The two network variables centrality and prestige can be combined to a total "prominence score" (Importance Indicator) for each indicator idea. Multiplied with the KI score for each connection, a "weighted prominence score" for each of the two indicator ideas can be calculated.

An adjacency matrix was used to establish centrality and prestige of each indicator idea. The adjacency matrix, sometimes also called the connection matrix, is a matrix with rows and columns labeled by graph vertices, with a 1 or 0 in position according to whether two ideas are adjacent or not (Chartrand & Zhang, 2004; Pemmaraju & Skiena, 2003). The expert-generated KIM benchmark was used to determine benchmark values of centrality and prestige.

(3) Topological Analysis of Network Geometry

Kinchin (2000b; 2001) suggested a framework of four classes (simple, chain/linear, spoke/hub, net) to describe the major geometrical structures of a concept map. A "network" structure indicates a more integrated understanding than a "fragmented" concept map structure. However, a ranking of these categories is only possible at the extreme ends, with "fragmented" at one end and "networks" at the other. All other classes fall in between. Yin (2005) extended Kinchin's framework by two additional classes (tree and circle):

(0) Simple: Mostly isolated propositions.
(1) Chain: Propositions are in a linear chain.
(2) Tree: Linear chain but with branches.
(3) Hub: Connections emanate from a center idea.
(4) Circular propositions: Propositions are daisy-chained, forming a circle.
(5) Network: Complex set of interconnected propositions.

Study 3 further extends Yin's framework. As Knowledge Integration Maps are divided into genotype and phenotype levels, the geometrical structure of each level needs to be described. Study 3 distinguishes 28 different topological categories [See appendix chapter 6: study 3: table 99: Topological categories to describe the geometrical structure of KIMs]. Changes in the topology of KIMs from pretest to posttest can indicate changes in students' knowledge integration.

(d) KIM Critique Analysis

The study 3 pretest and posttest contained a Knowledge Integration Map critique activity [See appendix chapter 6: study 3]. The KIM included several deliberate errors: I) Proposition errors: Label error (for example, "Natural selection increases diversity in the gene pool") and direction errors (for example, "Increase in fitness of population always leads to natural selection"); and II) Placement error (Idea "Natural Selection" should be in phenotype level"). Students were asked to identify (A: Error detection) and correct errors (B: Error correction).

A) Error Detection: The error detection rubric [See table 51] distinguishes between type I and II errors: Type I error refers to false detection of a correct element as an error (false positive); Type II error refers to failing to detect a deliberate error (false negative).

Table 51: KIM error detection rubric.

Level	**Score**
No answer	0
Irrelevant answer (e.g. replaced a correct answer with another correct answer)	1
One or multiple false positives (Type I error)	2
<u>One</u> mistake correctly identified, <u>but</u> also one or more false positives (Type I + Type II error)	3

One mistake correctly identified, and no false positives (Type II, but no Type I error)	4
Two mistakes correctly identified, but also one or more false positives (Type I error + Type II error)	5
Two mistakes correctly identified, and no false positives (Type II error, but no Type I error)	6
All three mistakes correctly identified, but also one or more false positives (Only Type I error)	7
All three mistakes correctly identified, and no false positives (no errors Type I or II)	8

B) Error Correction: For each of the three deliberate errors, an error correction rubric was created [See appendix chapter 6: study 3] and [See table 52]. The error correction rubric distinguishes between false, weak correct, and strong correct corrections.

Table 52: KIM error correction rubric.

Level	**Score**	**Sample answer**
No Correction	0	
False Correction	1	
Weak correct Correction	2	Leads to; affects
Strong correct Correction	3	Decrease

VI. Study 3 Results

A. Study 3 Quantitative Results

1) Study 3 Pretest/Posttest Results

(i) Study 3 Research Question 1: Pretest-Posttest Overall Analysis

Research question 1: How does the WISE module *Gene Pool Explorer* change students' integration of evolution ideas?

Findings indicate that students overall made significant learning gains [Paired $t(93) = 6.08$, $p<0.0001$ (two-tailed)]; Effect size (Cohen's d)=0.63 (SD pretest=2.24, SD posttest=2.41)]. Figure 51 shows overall changes in knowledge integration scores [See study 3: Pre- and Posttest Analysis] from pretest to posttest. Results indicate a shift towards higher knowledge integration scores (KI scores 3-5).

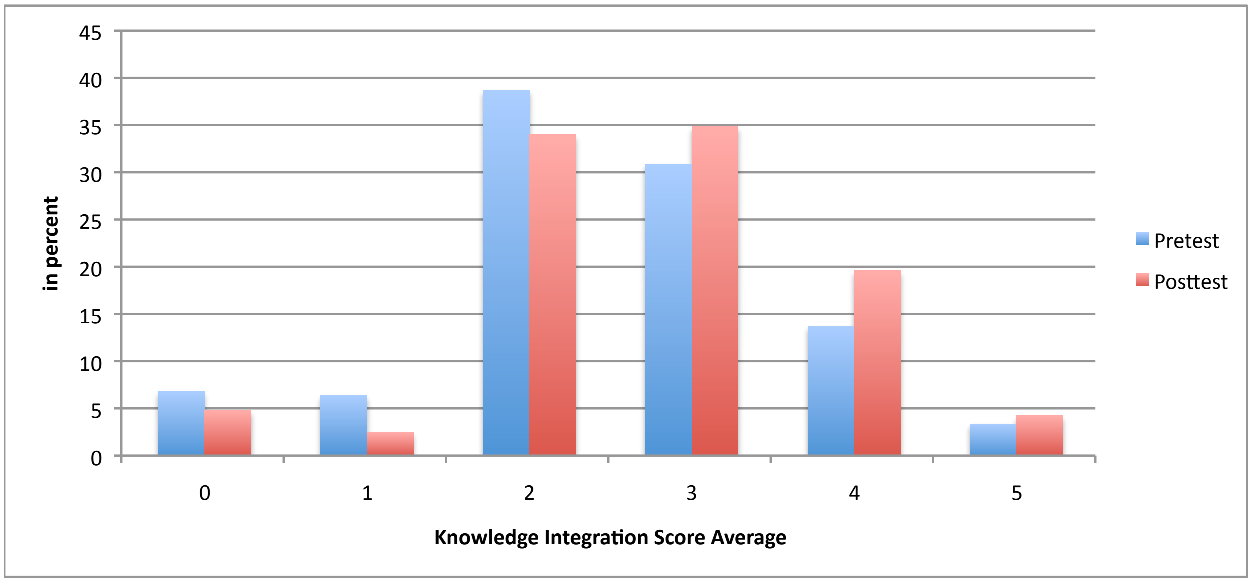


Figure 51: Overall changes in average KI score for explanation items.

Scores for each multiple choice item indicate gains only for some items [See figure 52]. However, the explanations items [See figure 53], in which students had to elaborate their multiple choice decisions, show gains for each item. These findings can be interpreted as explanation items being better indicators of knowledge integration gains than multiple choice items.

For example, a student answered the pretest item 9 about why some ivy plants produce poison "*Ivy plants were decreasing in population and in order to survive they needed to produce poison so other organisms wouldn't decrease their life span"*. The same student answered in the posttest "*A mutation in ivy plants caused them to produce poison. These plants were better protected and able to survive more than those that didn't produce poison. The ivy plants with poison produced more offspring that were able to survive to a reproductive age*." The pretest explanation indicates the alternative idea that currently living plants started the production of poison because had a need for it. The posttest explanation uses the normative genotype level idea "mutation" to explain differences in phenotypic traits. Instead of focusing on individual plants, the student showed statistic reasoning in the posttest "…able to survive more than those that didn't produce poison."

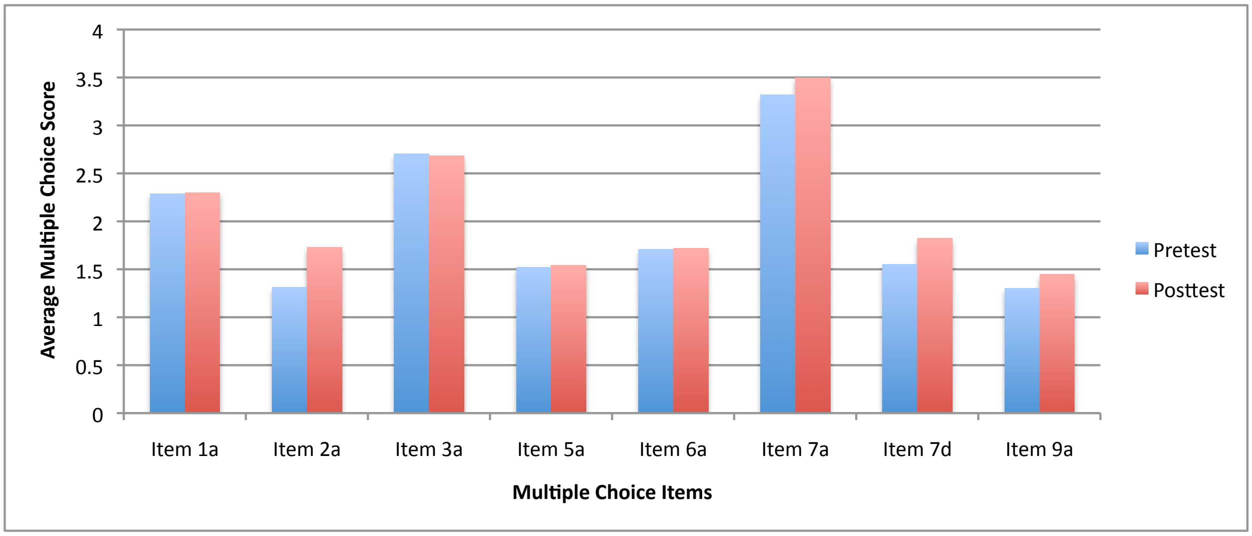


Figure 52: Overall changes in multiple choice items.

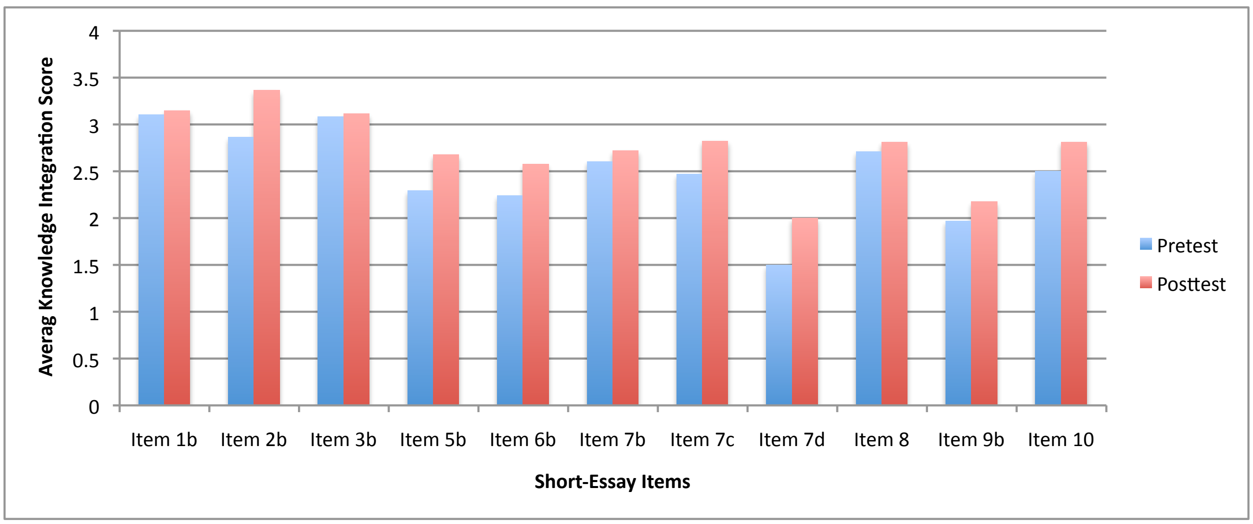


Figure 53: Overall changes in average KI score by item.

Students were stratified into three performance groups according to their pretest score (low, medium, and high pretest performance) [See figure 54]. Results indicate that students in all three strata and both treatment groups gained from pretest to posttest. Findings suggest that especially lower performing students gained significantly after using the WISE module *Gene Pool Explorer*.

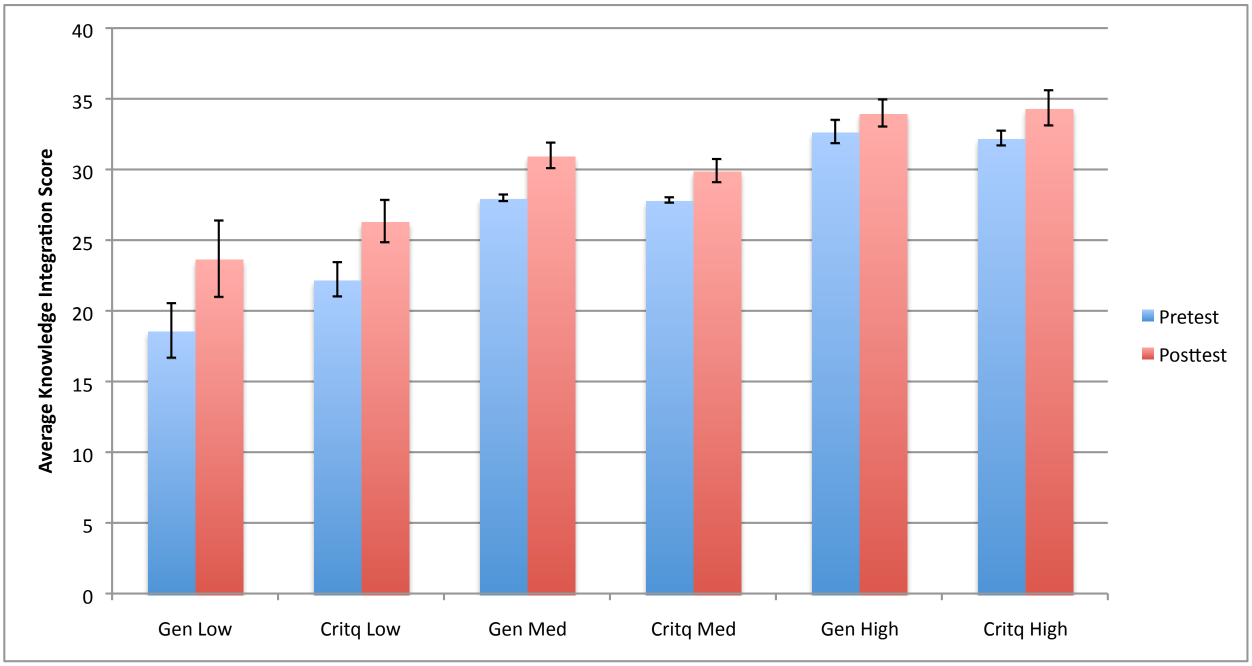


Figure 54: Overall change in average KI score by pretest performance and treatment. [Error bars in study 3 use standard error of mean (SEM)].

(ii) Study 3 Research Question 2: Contextualization

Research Question 2: How does the WISE module *Gene Pool Explorer* help students to integrate evolution ideas across contexts (plants and humans)?

Knowledge Integration aims to support students to add normative ideas to their repertoire and elicit and sort out alternative ideas. Applying normative ideas in different contexts can be seen as indication for more integrated knowledge. The pretest and posttest presented students with the same alternative ideas in the context of human lactose tolerance (item 6) and poison production in plants (item 9). The multiple choice items were coded incorrect = 0 and correct = 1; the explanation items were coded 0, 1, or 2 = 0 and 3, 4, or 5 = 1. Results indicate that students gained in both contexts (humans and plants) significantly in their knowledge integration score: Humans ($t(95)=2.94$, $p=0.0041$); Plants ($t(95)=2.19$, $p=0.03$). Of students answering item 6 correctly, 1/3 also answered item 9 correctly, 1/3 were mixed on that item, and 1/3 answered it incorrectly [See figure 55]. Findings suggest that students used their ideas consistently in both contexts.

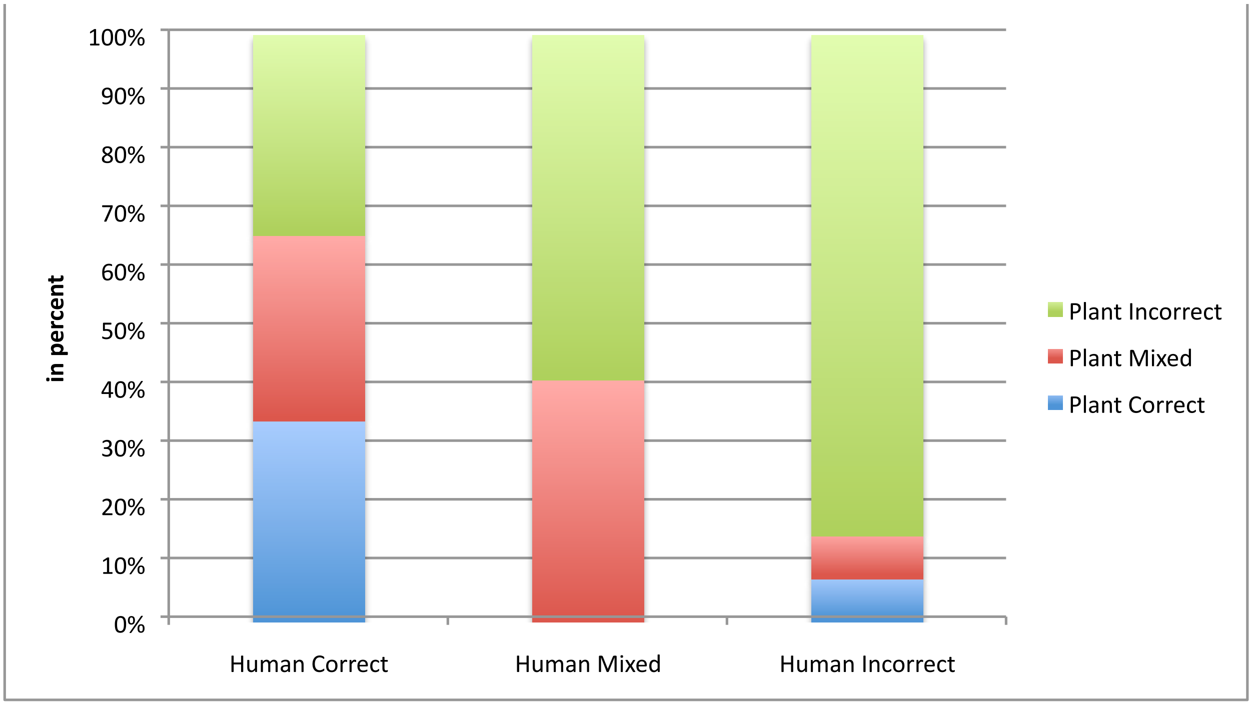


Figure 55: Combined multiple choice and explanation scores for posttest human evolution item (item 6) and plant evolution (item 9).

2) Study 3 KIM Results

(i) Study 3 KIM Generation Results

(a) Study 3 KIM Propositional Results

(1) Study 3 Primary KIM Analysis Results

(I) Study 3 Research Question 3: KIM Generation Results

Research Question 3: How do treatment groups (critique and generation) differ in generating Knowledge Integration Maps after the WISE module *Gene Pool Explorer*?

Multiple regression analysis indicates that both groups gained significantly in their average KIM knowledge integration scores, R^2=2.013, F(2, 88)= 11.09, p=0.000. The critique group showed equal KIM posttest performance [See figure 56], but was significantly more time efficient in the embedded KIM activities [See KIM Time Results].

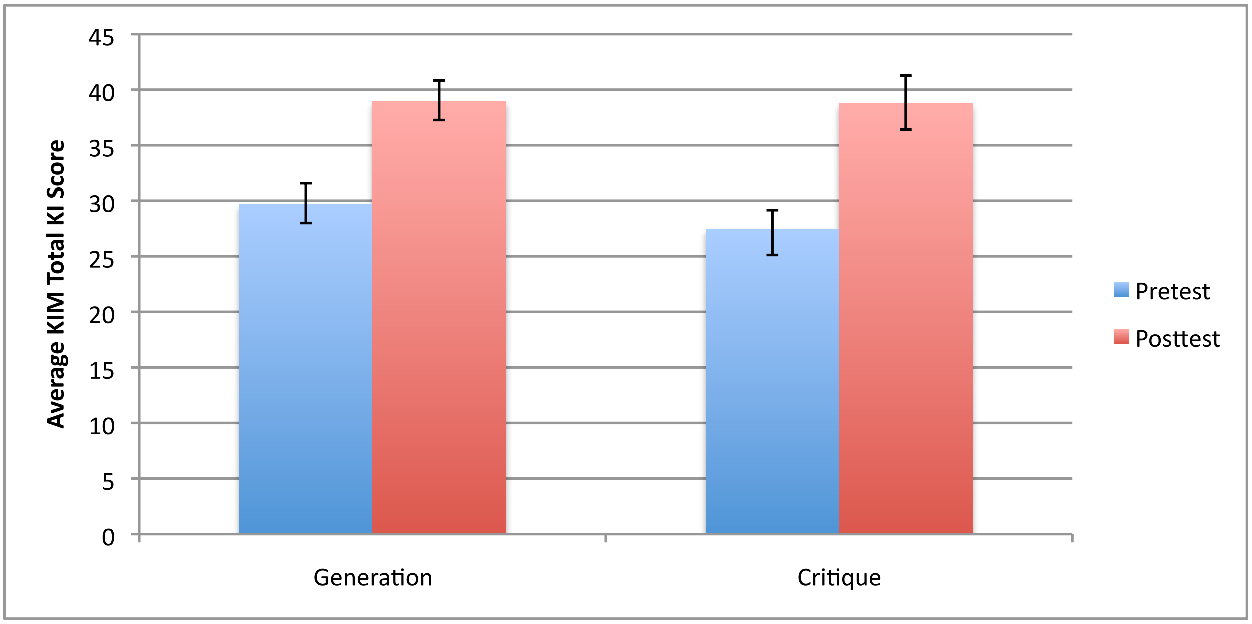


Figure 56: Change in average KIM Knowledge Integration score by treatment.

(II) Study 3 Research Question 4: Cross-Links Results

Research Question 4: How do treatment groups (critique and generation) differ in cross-links between genotype and phenotype level ideas in their Knowledge Integration Maps after the WISE module *Gene Pool Explorer*?

Both treatment groups significantly increased the number of cross-links between genotype and phenotype ideas from pretest to posttest, (N=94): Pretest Mean=2.52 (SD=1.66), Posttest Mean=1.03 (SD=1.15). t(93) = 7.49, p< .001; Effect size (Cohen's d) = 1.04. This indicates that students integrated genotype and phenotype ideas after the WISE module *Gene Pool Explorer* [See figure 57]. Students in both groups saw worked examples of KIMs with cross-links in the training map, pretest critique map, and the second embedded KIM.

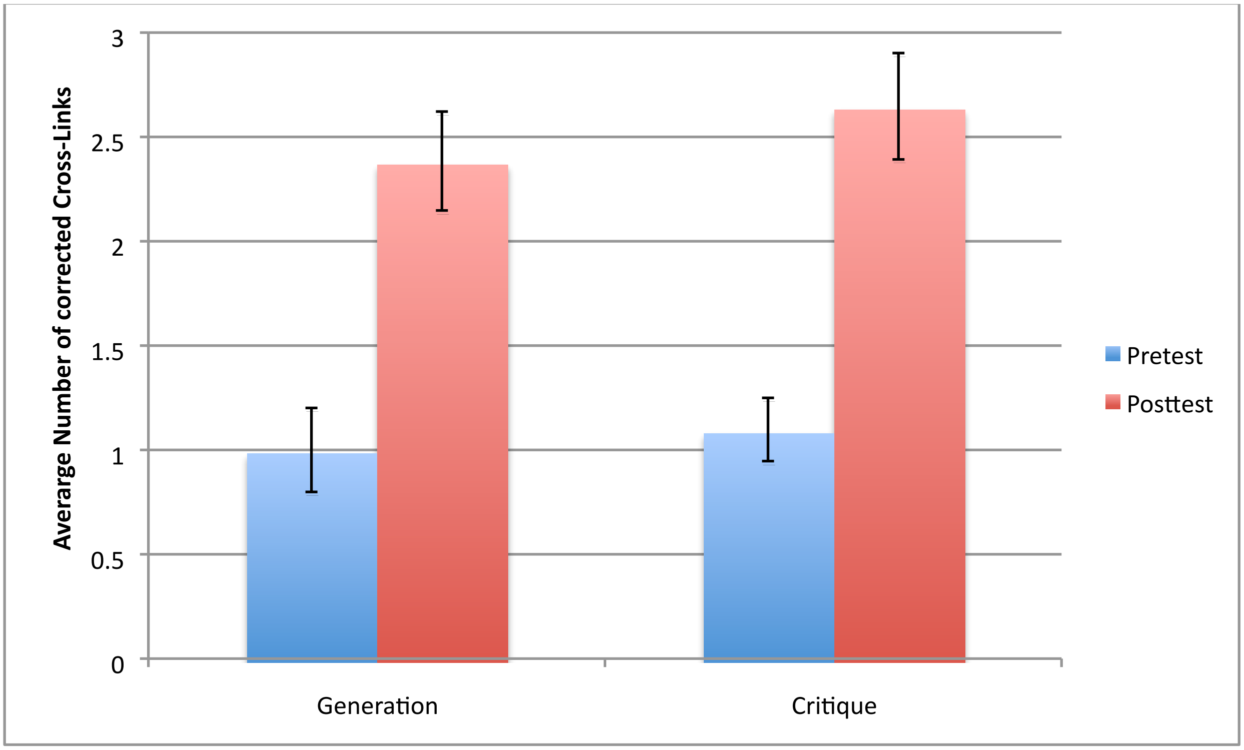


Figure 57: Average number of KIM corrected genotype-phenotype level cross-links.

(III) Study 3 Research Question 5: KIM Qualitative Link Results

Research Question 5: How do treatment groups (critique and generation) differ in qualitative changes of connecting ideas in their KIMs after the WISE module *Gene Pool Explorer*?

Students can improve their KIM performance not only quantitatively (the number of links and knowledge integration score of KIM connections) but also qualitatively change the types of relationships [See figure 58]. Using the structure-behavior-function (SBF) framework [See study 3: Qualitative proposition analysis] to categorize different types of relationships, students most frequently generated relationships in the "behavior" category. Neither in the pretest or the posttest KIM did any students generate functional relationships using teleological ideas of "need" or "want". However, the multiple choice and explanation items in the pretest and posttest indicated that students use teleological ideas to explain evolutionary processes. This observation supports the importance of using multiple assessment tools to measure and triangulate different forms of knowledge [See chapter 2: Concept Maps as Assessment Tools].

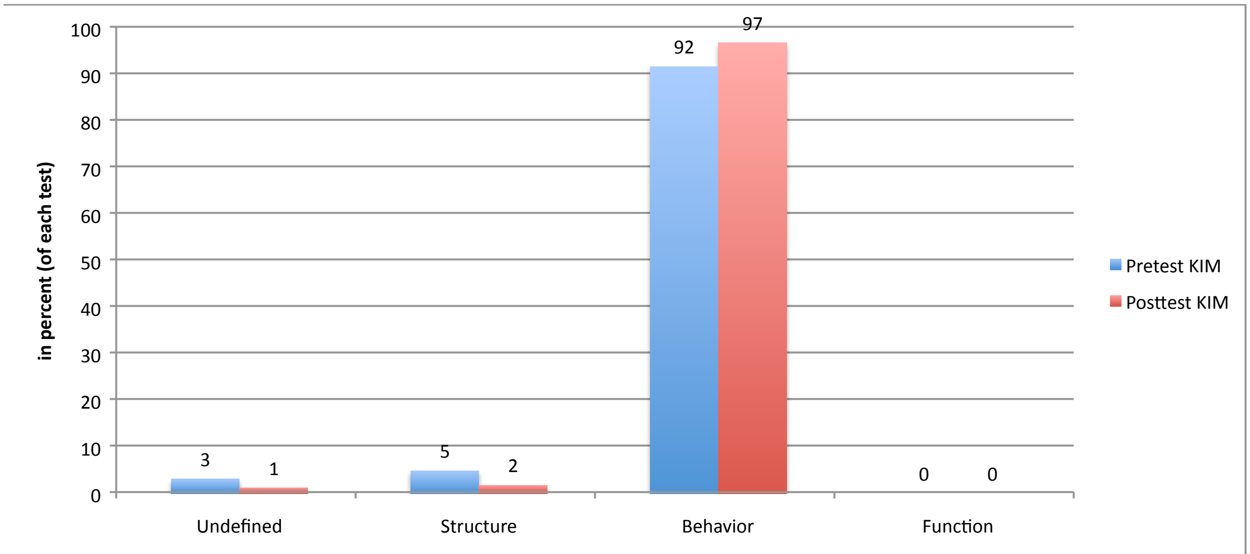


Figure 58: Changes in KIM relationship super-categories from pretest to posttest.

A more detailed analysis of the relationship types in each super-category revealed that students generated fewer causal-deterministic (-7%) and more causal-probabilistic (+4%) (for example "could lead to") and quantified (+11%) (for example "increases") KIM relationships in the posttest [See figure 59]. The increase in causal probabilistic relationships can be seen as shift towards more statistical thinking on a gene pool level [See chapter 2: Nature of Evolution Phenomena]. The increase of quantified relationships could indicate a shift towards thinking more in dynamic relationships that reflects the functional interdependency of evolution ideas (See (Derbentseva et al., 2007)).

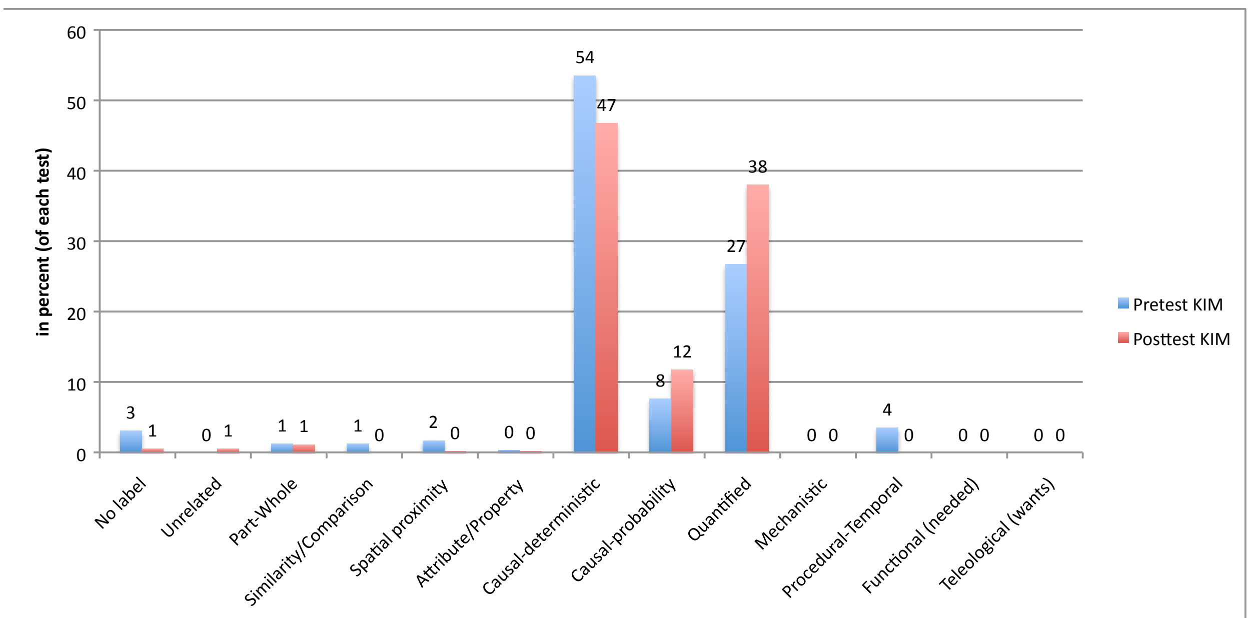


Figure 59: Changes in KIM relationship sub-categories from pretest to posttest.

(2) Study 3 Secondary KIM Analysis

(I) Study 3 Research Question 6: KIM Secondary Variables Results

Research Question 6: What variables can track changes in students' evolution ideas in KIMs?

In addition to primary KIM analysis variables, several secondary variables show moderate to strong correlations with the KI posttest score for explanation items [See table 53]. These secondary variables can be used as alternatives to describe quantitative changes in KIMs.

Table 53: Secondary KIM variable correlations.

Secondary KIM variable	Correlation to KI posttest score
Total number of links in post KIM	0.5314
Total KI of all links in post KIM	0.5958
KI of only the essential links	5.000
Relative Density	0.5314
Standardized Density	0.5314
Standardized all KI	0.5958
Standardized Essential KI	0.5000

Results suggest that coding only essential links using a KI rubric could be a more efficient way to track students' learning gains in posttests. The two KIM variables "Total KI score of al links" (Total Accuracy Score) and "KI score essential links" are strongly correlated, $r(94) = 0.84$, $p<0.001$. This strong correlation suggests that coding only essential KIM connections can be used as a more efficient method to describe changes in Knowledge Integration Maps. Additionally, these findings indicate that network KIM variables, for example relative and standardized density, can be used to describe changes in Knowledge Integration Maps [also see study 3 KIM Network Analysis Results].

(3) Study 3 KIM Network Analysis Results

(I) Study 3 Research Question 7: KIM Network Results

Research Question 7: How do treatment groups (critique and generation) differ in integrating core evolution ideas in their KIMs after the WISE module *Gene Pool Explorer*?

Changes in weighted prominence scores for the indicator ideas "mutation" and "natural selection" suggest that students in both treatment groups made significant gains in integrating these central evolution ideas [See figure 60 and 61; and table 55 and 56]. The KIM variables "weighted prominence score" for indicator idea "mutation" and "natural selection" are strongly correlated with the overall KIM KI score: Mutation $r(94) = 0.75$, $p<0.001$, and Natural Selection $r(94) = 0.70$, $p<0.001$. The "weighted prominence score" was calculated by multiplying each connection leading to or from an indicator idea with the KI score. These correlations suggest that coding only the links to and from the indicator ideas can be a more efficient way to score KIMs than coding all connections.

The indicator idea variables show strong correlations with the overall posttest KI score [See table 54]. These results indicate that evaluating the KI score of connections to and from indicator ideas can be a more efficient alternative to tracking learning gains than posttests or scoring all KIM propositions.

Table 54: Correlations between indicator idea variables and posttest KI score for explanation items.

KIM variable	Correlation to posttest KI score for explanation items
Number of links to/from indicator idea "mutation"	0.6832
KI score of links to/from indicator idea "mutation"	0.7462
Number of links to/from indicator idea "natural selection"	0.5920
KI score of links to/from indicator idea "natural selection"	0.6995

Results suggest that the weighted prominence score for the KIM genotype level indicator idea "mutation" increased significantly in both treatment groups from pretest to posttest [See figures 60 - 62]. ($t(93) = 5.39$, p=0.00). There was no significant difference between the treatment groups.

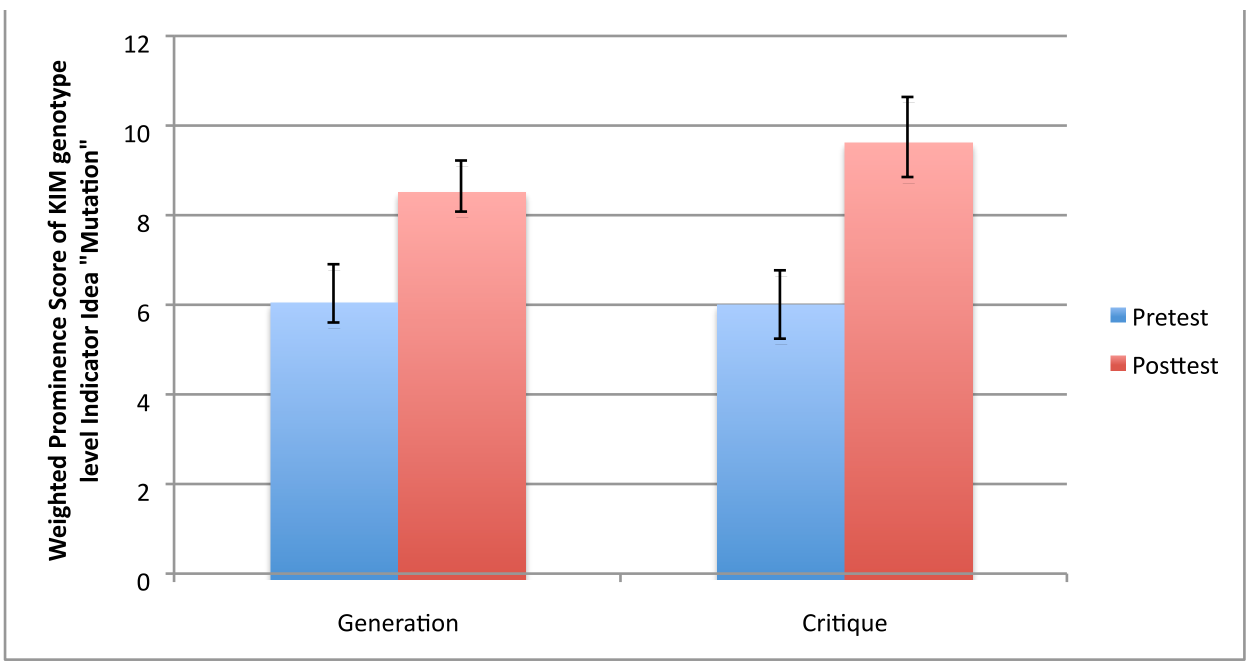


Figure 60: Weighted prominence score of the KIM genotype level indicator idea "mutation".

Posttest results suggest that students placed the idea "mutation" more correctly, generated more connections to/from the idea "mutation", and that these connections were of higher knowledge integration scores [See table 55]. These observations indicate that the idea "mutation" gained in explanatory strength in students' repertoire of ideas. The treatment groups did not significantly differ in each of the three indicator idea "mutation" variables.

Table 55: Indicator idea "mutation".

	M (SD)			
	Pretest	**Posttest**	**t**	**Significance Level: p**
Mutation Placement	0.61 (0.49)	0.83 (0.37)	4.07	0.001 (*)
Mutation Number of Links	1.73 (1.17)	2.49 (1.26)	5.16	0.000 (*)
Mutation KI score	6.10 (4.52)	9.18 (5.24)	5.39	0.000 (*)

The increase in normative evolution ideas was also found for the KIM phenotype level indicator idea "natural selection". Results suggest that both treatment groups gained significantly in the weighted prominence score for the KIM phenotype level indicator idea "natural selection" from pretest to posttest [See figures 61 - 63]. ($t(93) = 5.83$, p=0.00). There was no significant difference between the treatment groups.

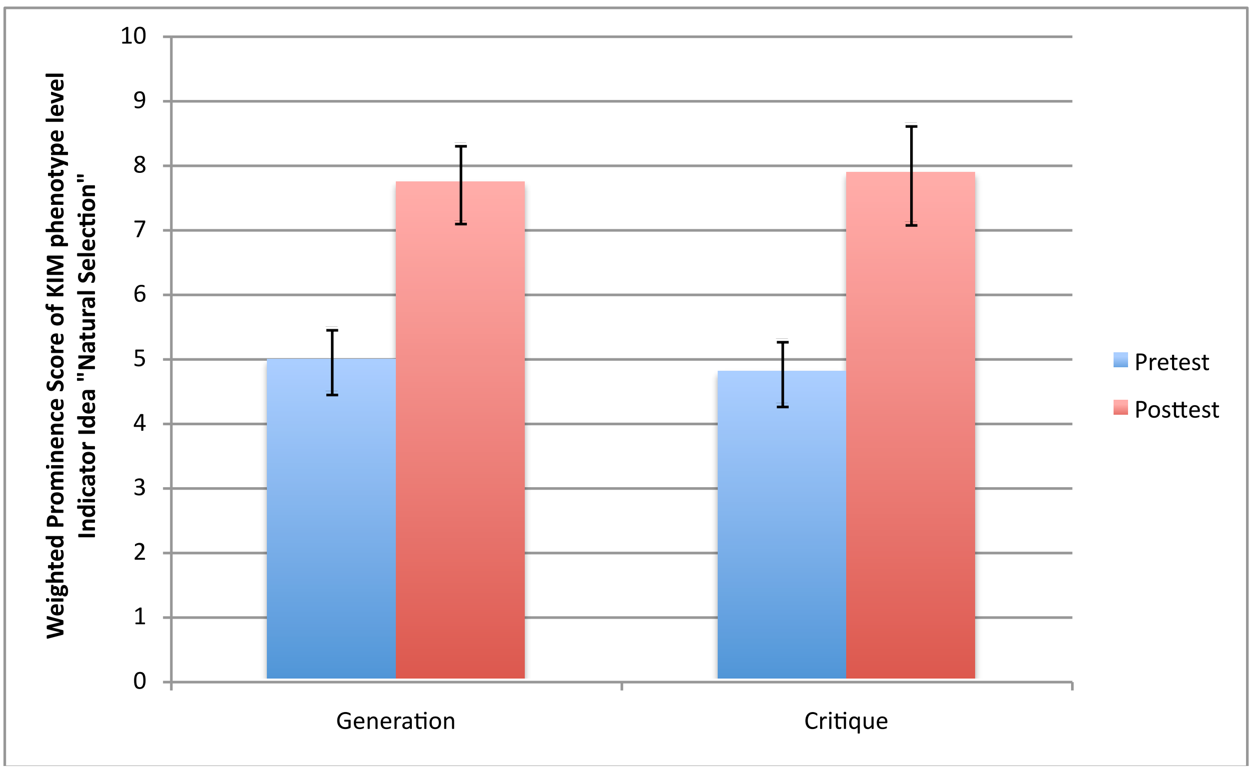


Figure 61: Weighted prominence score of the KIM phenotype level indicator idea "natural selection".

Similar to the indicator idea "mutation", posttest results suggest that students placed the idea "natural selection" more correctly, generated more connections to/from the idea "natural selection", and that these connections were of higher knowledge integration score [See table 56]. These observations indicate that the idea "natural selection" gained in explanatory strength in students' repertoire of ideas. The treatments groups did not significantly differ in each of the three indicator idea "natural selection" variables.

Table 56: Indicator idea "natural selection"

	M (SD)			
	Pretest	**Posttest**	**t**	**Significance Level: p**
NatSel Placement	0.76 (0.43)	0.79 (0.41)	0.66	0.52
NatSel Number of Links	1.5 (0.97)	2.26 (1.22)	5.39	0.000 (*)
NatSel KI Score	4.82 (3.43)	7.68 (4.77)	5.83	0.000 (*)

Students' posttest KIMs showed significantly higher overall scores and cross-links between genotype and phenotype level ideas [See study 3 KIM Results] [See sample KIM of the same student in figures 63 and 64]. The KIM indicator ideas "mutation" and "natural selection" gained in prominence by being more connected to other ideas.

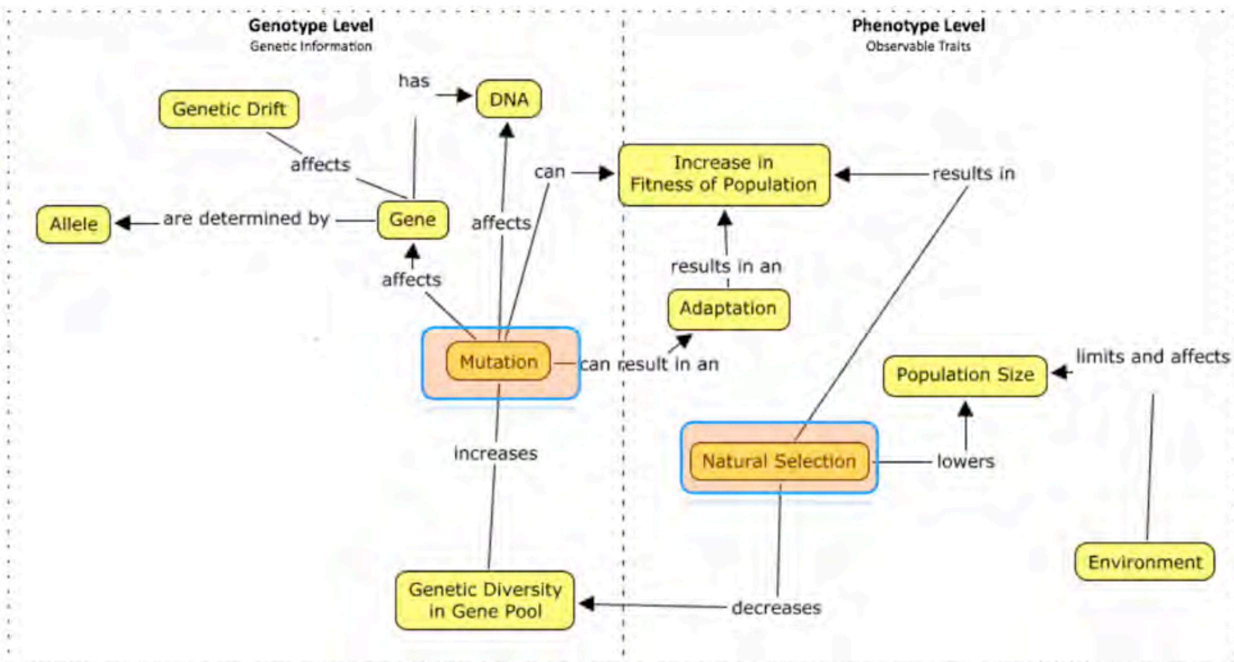


Figure 62: Pretest KIM student example. KIM indicator ideas "mutation" and "natural selection" are marked in orange.

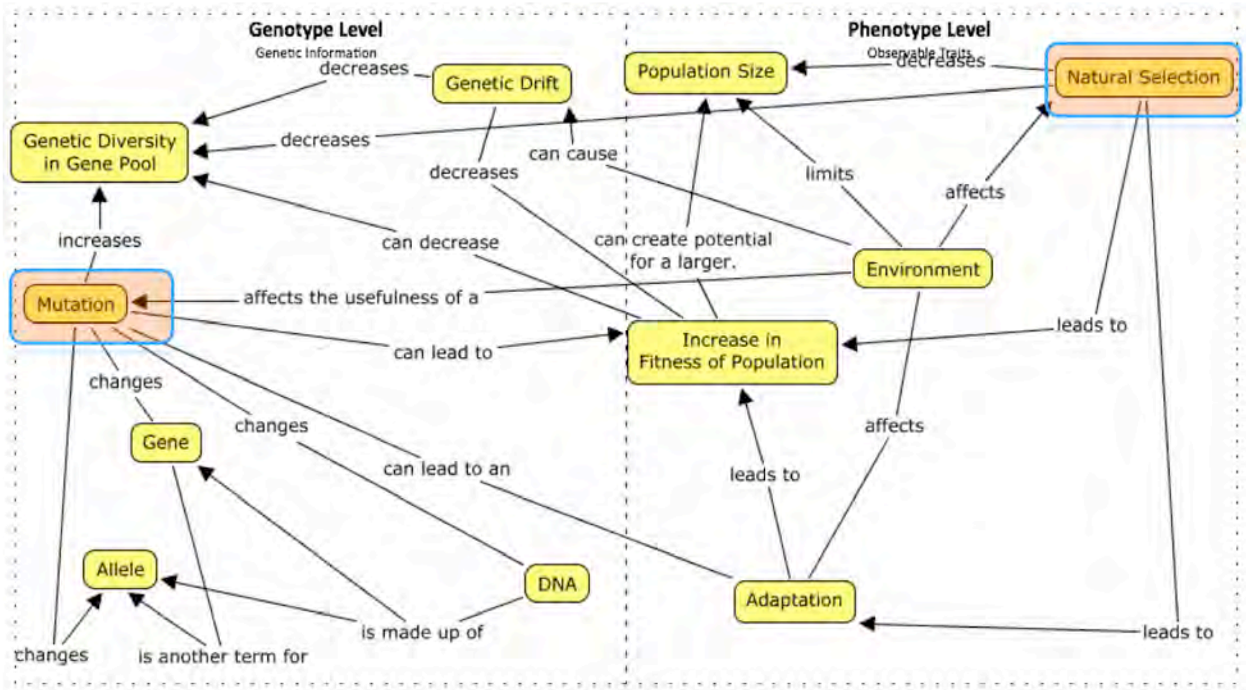


Figure 63: Posttest KIM student example. KIM indicator ideas “mutation” and “natural selection” are marked in orange.

In accordance with gains in prominence of the indicator ideas “mutation” and “natural selection” in KIMs, multiple regression analysis suggests that students overall used normative evolution ideas more often than non-normative teleological ideas (such as “need”) in the posttest than in the pretest ($R2$ =0.18, $F(1,94) = 20.18$, $p < .001$. There was no significant difference between the treatment groups [See figure 64]. The score for normative evolution ideas is a composite of the explanation items 1, 5, 6, and 9 [See appendix chapter 6: study 3]: KI 0, 1, or 2 = used all non-normative ideas; KI 3 = mixed; KI 4 or 5 = used all normative evolution ideas.

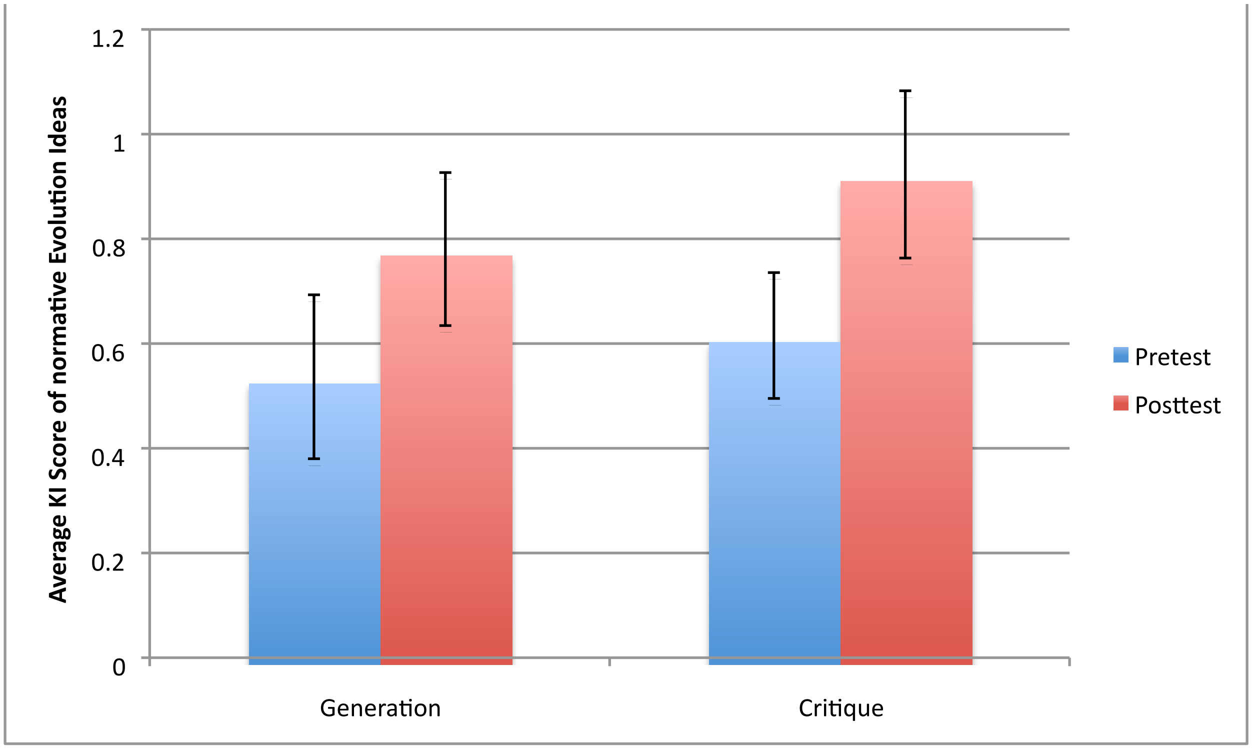


Figure 64: Changes in usage of normative Darwinian evolution ideas from pretest to posttest.

A student example from item 6 illustrates gains in multiple choice and explanation tasks [See table 57]. In the pretest, the student chose three non-normative options in the multiple choice item. In the posttest, the student chose the normative option. The pretest explanation suggests that some people were able to adapt to digesting cow milk. All ideas are on a phenotype level. In the posttest explanation, the student uses the genotype level "mutation" to explain the differences in people's ability to digest milk. The mutation for lactase persistence is only beneficial in a dairy farming culture. The student revised the initial idea of fitness equals survival to fitness means the production of more offspring that survive to reproductive age.

Table 57: Item 6 student sample answer.

	Multiple Choice Selection (Multiple options could be selected)	**Explanation**
Pretest	People needed to digest cow milk to survive. The availability of cow milk caused some people to become able to digest milk. People wanted to digest cow milk.	People started drinking cow milk because of its nutrients and those that were able to adapt and digest it survived more than those that couldn't.
Posttest	Random genetic changes created the ability to digest cow milk in some people.	A mutation caused some people to be able to digest cow milk. The people that lived in a dairy milk culture found this mutation useful so their fitness increased and they were able to produce more offspring that survived to reproduction age.

(II) Study 3 Research Question 8: KIM Topology Results

Research Question 8: How do treatment groups (critique and generation) differ in changes of the topology of their Knowledge Integration Maps after the WISE module *Gene Pool Explorer*?

Network topologies describe the main geometrical structure of Knowledge Integration Maps. Results indicate a trend towards more "network-type" KIMs in both treatment groups [See figure 65 and 66]. In the pretest, 41% of critique group student dyads and 53% of generation group student dyads generated "network-type" KIMs (No 28) [See appendix chapter 6: study 3: table 99: Topological Categories to Describe the Geometrical Structure of KIMs]. In the posttest, student dyads in the critique group increased "network-type" KIMs by 51% and the generation group by 39%. The "network-type" topology refers to KIMs that are networks on both genotype and phenotype level and have (at least one) cross-connection. "Network-type" KIMs can be interpreted as indicators for gains in integrating genotype and phenotype level ideas within and across levels.

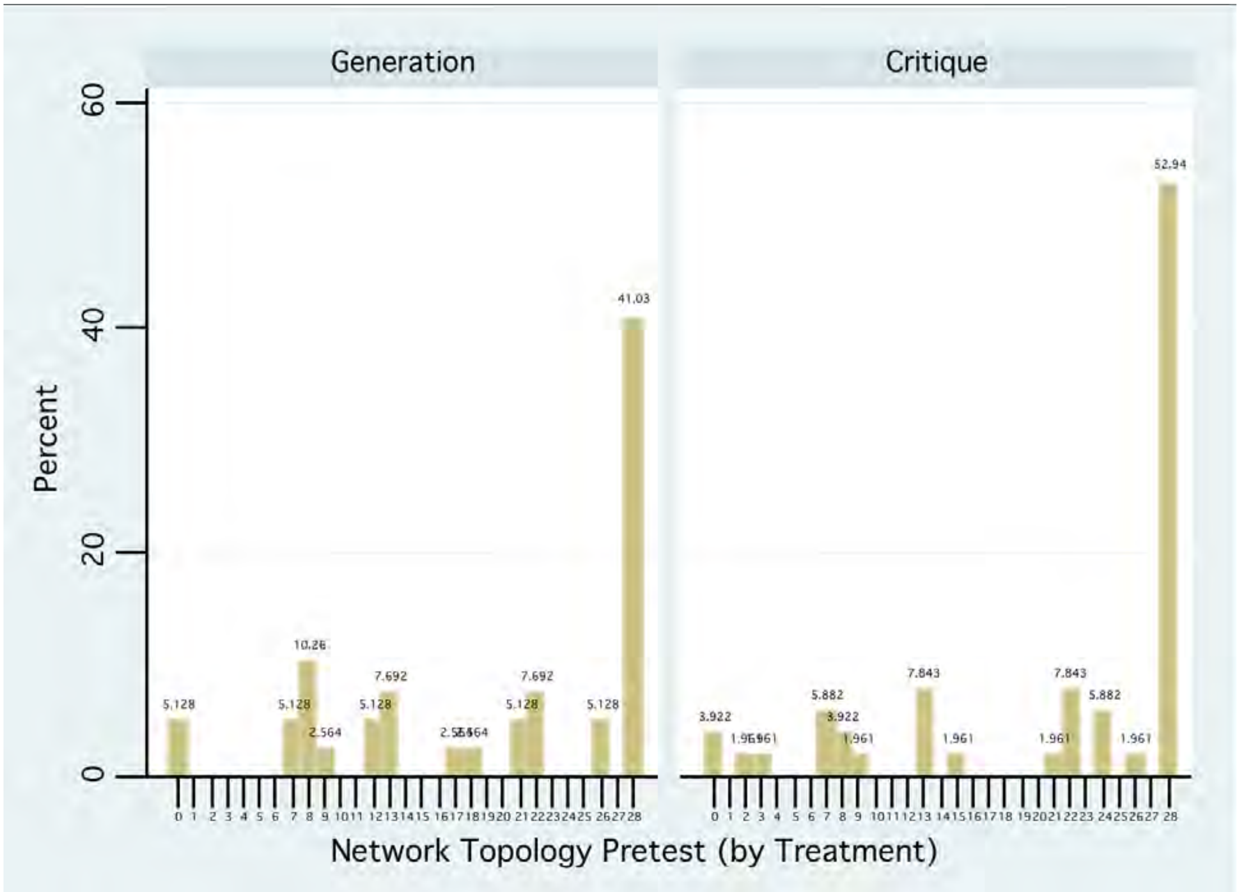


Figure 65: Pretest KIM topologies by treatment.

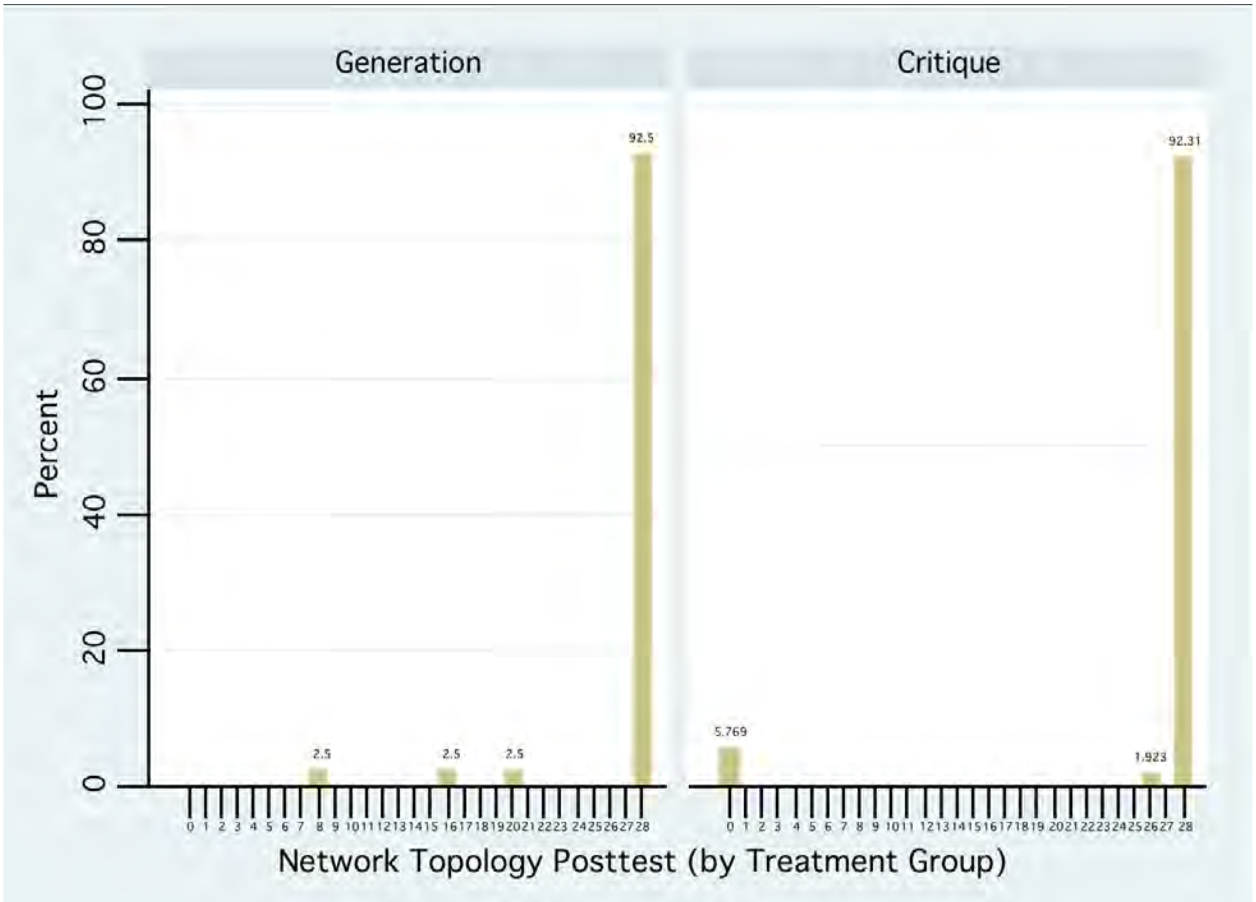


Figure 66: Posttest KIM topologies by treatment.

(4) Study 3 KIM Critique Results

(I) Study 3 Research Question 9: KIM critique results

Research Question 9: How do treatment groups (critique and generation) differ in critiquing Knowledge Integration Map after the WISE module *Gene Pool Explore*r?

Posttest item 4 asked students to critique and correct a KIM with different types of errors: I) Proposition errors: Label error and direction error; II) Placement error [See figures 67-69 and table 58]. The differences between treatment groups did not reach statistical significance. These results indicate that the embedded KIM activities helped both treatment groups to critically reflect on KIMs, revisit, and revise connections between ideas: $R^2 = 0.27$, $F(1, 94) = 36.25$, $p < 0.001$.

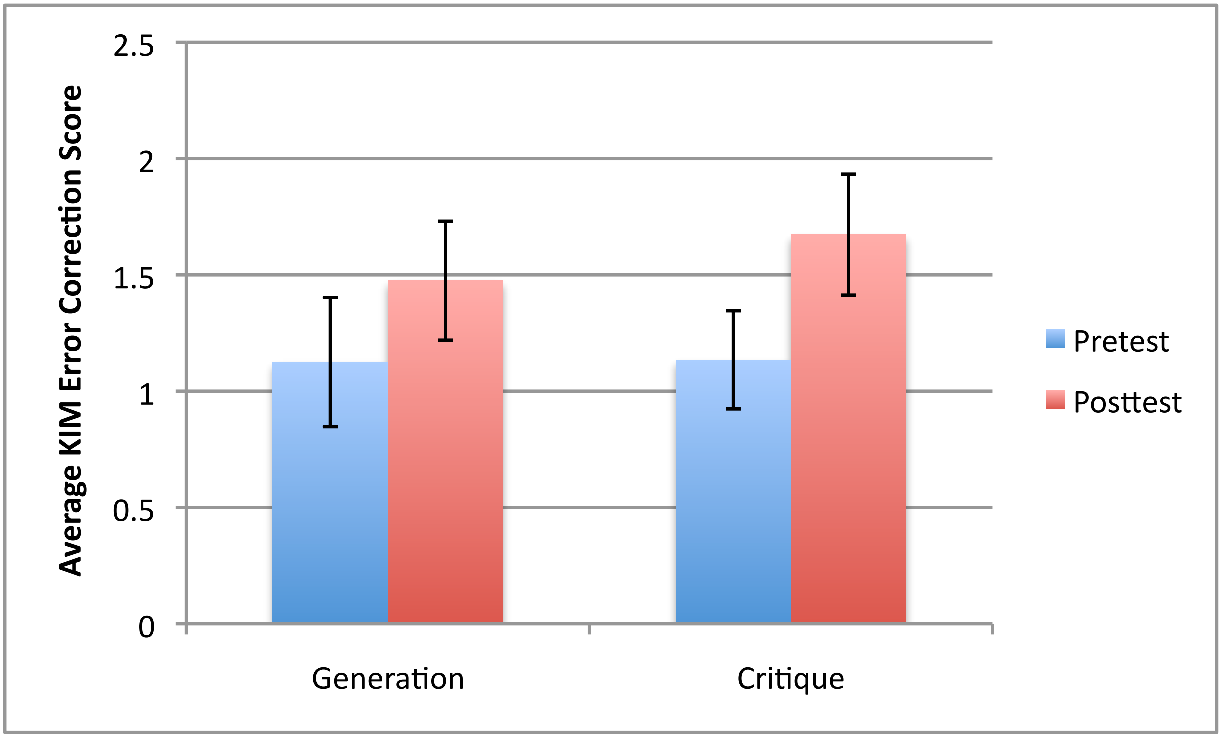


Figure 67: Overall KIM proposition errors correction scores.

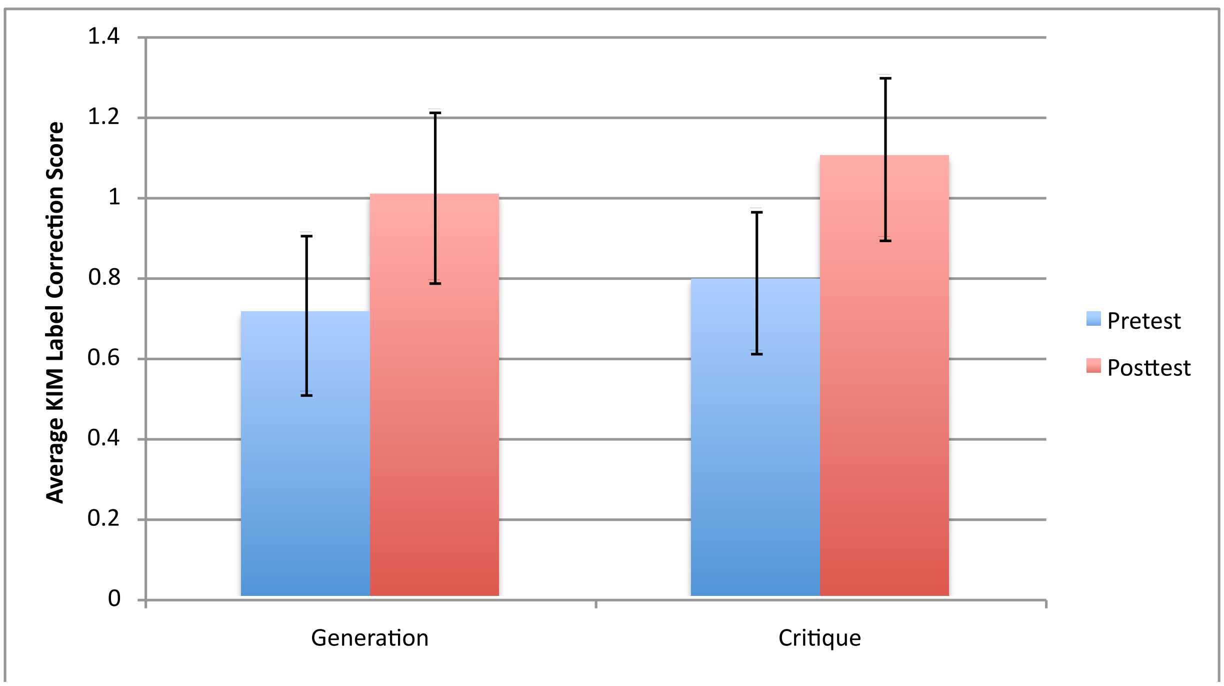


Figure 68: KIM label error correction scores.

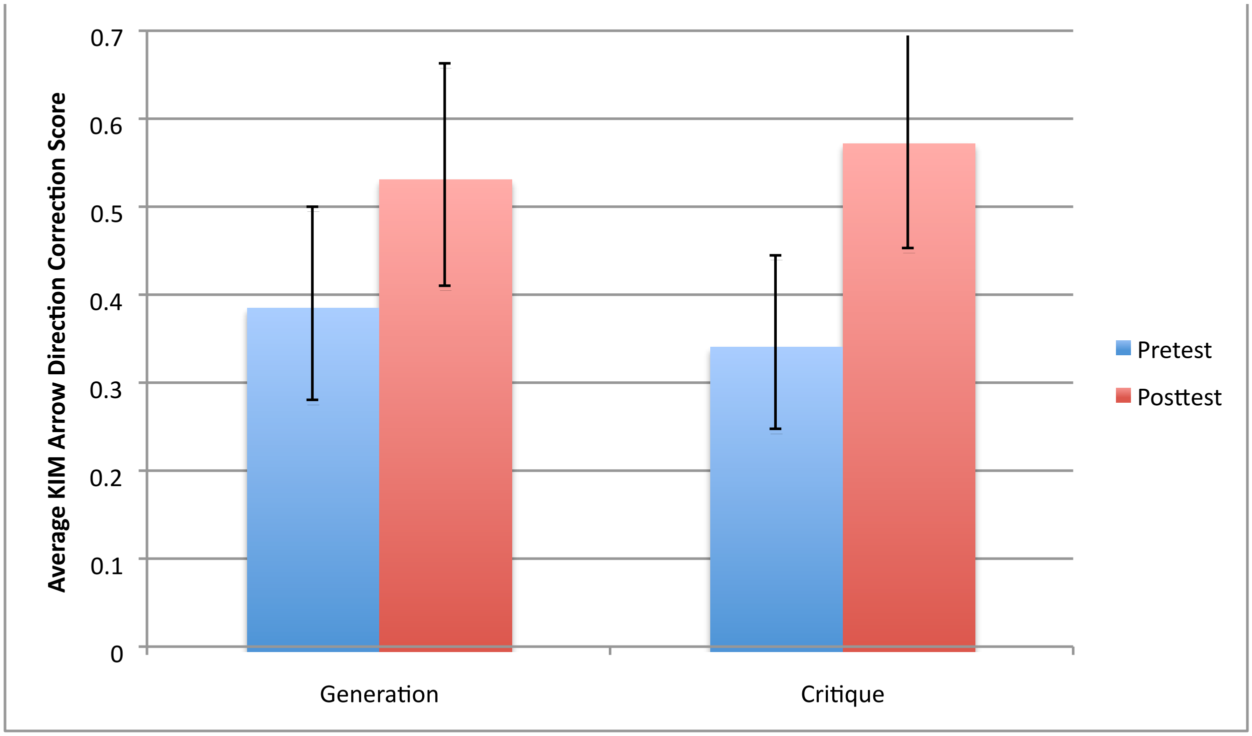


Figure 69: KIM direction error correction scores

Only few students in either treatment group detected and corrected the wrongly placed idea in item 4 (The idea "natural selection" should be placed in the phenotype level instead of the genotype level). No students made a false correction [See table 58].

Table 58: KIM idea placement error correction scores. 0=no correction; 1=false correction; 2=correct correction.

	Pretest	**Posttest**
Generation	No correction (0): 32 students; Correct correction (2): 9 students	No correction (0): 38 students; Correct correction (2): 3 students
Critique	No correction (0): 49; Correct correction (2): 3 students	No correction (0): 48 students; Correct correction (2): 4 students

(5) Study 3 KIM Time Results

(I) Study 3 Research Question 10: KIM Time Results

Research Question 10: Is generating or critiquing Knowledge Integration Maps a more time efficient knowledge integration activity to learn about evolution ideas?

Students dyads either critiqued or generated two embedded KIMs delivered through the electronic concept mapping tool Cmap. Additionally, students created individual KIMs in the pretest and posttest. Students did not have time-limits for KIM activities [See table 59: Data could only be collected from students who completed their KIM activities within the same period.].

On average, students in both groups spent 9 minutes on KIM 1 and 6.5 minutes on KIM 2. However, student dyads in the critique group were significantly faster on the embedded KIM activities than the generation group, $p<0.05$. ($t(27)=2.72$, $p=0.01$. These results indicate that the KIM critique activities were more time efficient than the KIM generation activity while leading to the same posttest performance.

Students in both treatment groups spent about the same average amount of time on the pretest KIM (14 minutes) and posttest KIM (13 minutes).

Based on quantitative results and qualitative classroom observations, the critique group might be faster because generating new relationships from scratch can be more challenging than revising existing connections. Critiquing KIMs might be faster than generating KIMs as it requires in-depth reflection only of a selection of connections: First, student dyads studied each connection and decided if they agreed or disagreed. Second, students negotiated how to revise only the connections they disagreed with.

Table 59: Time spent on KIM activities.

In Minutes	**Generation Group Mean**	**Critique Group Mean**	**Total Mean (Median)**
KIM 1 (Genotype)	11.94	6.55	9.03 (8)
KIM 2 (Phenotype)	8.62	5.39	6.54 (4)
Pretest	14.95	13.39	14.12 (16)
Posttest	13.65	13.06	13.35 (12.5)

(b) Study 3 Qualitative Results

These qualitative observations are based on fieldnotes. The WISE module *Gene Pool Explorer* was implemented in the first week after spring break. The students finished genetics before spring break but had not yet started with evolution. The teacher used the WISE *Gene Pool Explorer* module as an introduction to evolution. The students had already learned the ideas genotype, phenotype, and gene pool, but not genetic drift. Each class had one 60 minute and two 120 minute biology lessons per week. The teacher assigned short readings about evolution in the textbook as homework and assessed students' understanding in short quizzes at the beginning of each lesson.

Day 1 (60 minutes)

KIM training phase [See study 3: Methods: KIM Training Phase]: The teacher introduced the project (five minutes) and demonstrated the concept mapping method on the whiteboard using the "rock-paper-scissors" example (5 minutes). Students worked individually or collaboratively on the concept map training activity (10-15 minutes), followed by the classroom discussion of the KIM error map (5-10 minutes). The teacher prompted students to identify different types of errors and suggest improvements. Students individually completed the pretest and KIM pretest activity (25-30 minutes). Because of large class sizes and time constraints, some students received paper-based KIM pretest worksheets and others used the electronic concept mapping tool Cmap. Students were very focused and on task. Students were allowed to use the vocabulary section of their textbooks to look up definitions of unfamiliar terms.

Day 2 (120 minutes)

The teacher started with a short quiz: Define "fitness" (Answer provided: Ability to survive and reproduce); What is Darwin's great contribution to science? (Theory of Evolution by means of Natural Selection (not the process of evolution); Explain the idea of "survival of the fittest" (Best suited to survive and reproduce in a certain environment); Give an example for a vestigial organ. (Human appendix); What do "homologous structures" suggest? (Common ancestors). The teacher discussed the questions with the class, wrote the answers on the whiteboard, and asked students to self-evaluate their answers. The teacher reminded students of their upcoming California Standardized Testing and Reporting (STAR) exam the next week. Afterwards, student dyads started working on the WISE module *Gene Pool Explorer* at their own pace. Once student dyads reached the first embedded KIM activity, the teacher demonstrated how to open and save the KIM template. Student dyads were randomly assigned to treatment groups (generation or critique) once they arrived at the first embedded KIM activity. Several students who previously used the paper-based pretest KIM commented that they prefer generating KIMs using Cmap to the paper-based version. Several students in the generation treatment group considered the activity repetitive as they had just completed a similar activity in the pretest. None of the critique treatment group students expressed such concerns. Student dyads had no time-limits working on their KIM activities. In the KIM critique map activity, some students reasoned that the idea "mutation" was correctly placed in the phenotype level as it alters an organism's traits. Some students groups also hesitated to move the idea "mutation" because it would involve major rearrangement of other ideas and links to maintain an aesthetic map. Embedded interviews were valuable to learn about students' reasoning that might not be expressed in the final product. Some students expressed that KIM activities are "hard work", which indicates that students realized that actively reflecting on one's own understanding is cognitively more demanding than listening to a lecture or reading a text.

Qualitative observations suggest several possibilities for why students did not generate certain important connections in their KIMs:

- The students did not know that a connection between two ideas exists.
- Student forgot to make the link.
- Student might have had vague understanding of a link, but felt unsure about generating it.
- Student knew about the link but felt that they already created enough links.
- Student knew about the link but decided not to generate it for aesthetic reasons. This motivation for aesthetics may be a limiting factor when creating KIMs.

Technical issues: The WISE Cmap server caused some initial delays. The Internet connection was slow at times. One class experienced a black out as a tree fell on the power line serving the entire school. As an alternative, the teacher ran the project "Punch Bug Lab" about natural selection. Student dyads received containers of differently colored confetti and multi-colored cloth. Students had 30 seconds to pick as many confetti as possible (using only one hand and by picking up only one confetti at a time). After each round, the surviving confetti "reproduced". Students counted the confetti of each color after each round in a table and generated a histogram (after a template the teacher drew on the board). After the activity, the teacher discussed general principles of natural selection, adaptation, and fitness. This class received additional time to complete the WISE module. Overall posttest results indicate that this class' means are not significantly different from others.

Day 3 (120 minutes)

The teacher started with a short quiz: What is an allele? What is lactose intolerance? Name two organisms that Darwin studied while in the Galapagos; True/false: Acquired traits can be inherited? List three factors that limit the size of human populations. Students were allowed to use their biology textbooks as a reference. After discussing the answers, the teacher demonstrated the population genetics visualization Allele A1 on the projector. The teacher led a classroom discussion on how to interpret the line graph in the visualization: What does the line represent? What does it mean for genetic diversity if the line reaches extreme values (100% or 0%)? Students were able to set up the experiments following the embedded instructions in the WISE module on their own. Despite the previous training, interpreting the resulting line graph was challenging for many students.

-The line graph showed only one out of two alleles in the population. This caused some confusion for students who expected to see separate lines for each allele.

-Many students interpreted the line as "number of individuals having a certain phenotype" instead of "frequency of an allele in the gene pool of a population".

-If the line reached either 0% or 100%, one allele got fixed and the other got lost from the gene pool. In either case, the genetic diversity in the gene pool decreased. However, many students interpreted an increase in the line graph as an increase in genetic diversity, and vice versa.

-The line graph of the population genetics visualization Allele A1 shows only changes on the genotype level. It might be difficult for some students to imagine related phenotype changes.

The teacher and the present researcher mentored individual student groups to support their interpretation of the population genetics visualization. Students continued working on the WISE module *Gene Pool Explorer* at their own pace. Many students used their textbook vocabulary section to look up term definitions during the project. The researcher provided students with online feedback for the first embedded KIM activity. Students were instructed to revisit and revise their KIMs. At the end of day 3, most student dyads finished the project.

Day 4 (50 minutes) and Day 5 (120 minutes)

Students completed the WISE module *Gene Pool Explorer* and took the posttest. While one half of the students worked on the online posttest, the other half completed the KIM posttest generation activity. Several students had to wait their turn until a computer became available. The teacher always had follow-up activities available to keep faster students engaged, for example students who finished both the project and all posttest assignments read a textbook chapter on evolution (in preparation for the upcoming STAR test).

After all students completed the posttest, the teacher conducted an inquiry lesson based on the Hardy-Weinberg equilibrium (building on the ideas introduced in the WISE module). Students used a container with brown and white beans as the gene pool and calculated phenotype and genotype frequencies.

VII. Study 3 Discussion and Implications

A. Significance

Study 3 aimed to achieve a better understanding of how different forms of Knowledge Integration Map (KIM) activities can be used to foster integrating genotype and phenotype level evolution ideas. Eliciting the connections between phenotype and genotype ideas is important to develop a coherent understanding of the core principles of biology.

Study 3 developed and identified scaffolds for effective activities to support all kinds of learners. The WISE module *Gene Pool Explorer* used human lactose intolerance to connect evolution ideas to students' real-life experiences. Using human evolution helped students address existing alternative ideas of evolution. Results suggest that students in both treatment groups significantly improved at integrating evolution ideas after using the WISE module *Gene Pool Explorer*. Gains in knowledge integration are indicated by more normative evolution ideas being used in a variety of contexts (for example plants and humans) in the posttest.

B. KIM Activity Design

Findings from study 2 suggest that generating and critiquing Knowledge Integration Maps can support students' knowledge integration of evolution ideas. However, the combination of both activities can be time-consuming. Study 3 developed and investigated A) more efficient KIM activity designs, and B) more efficient KIM analysis methods.

A) The novel concept mapping form Knowledge Integration Maps asked students to sort out, connect, and contrast genotype and phenotype level ideas. Sorting ideas into biology-specific levels can provide scaffolds for students to think about why ideas belong into a specific category. This aligns with Marzano's findings that the identification of similarities and differences is one of the most effective learning strategies (Marzano, Pickering, & Pollock, 2001). Students collaboratively used their existing knowledge to compare categories, generate criteria for each category, and negotiate where to place ideas. The initial KIM training activity was effective at introducing students to the methods of KIM generation and critique. Presenting KIMs as faux-student work for critique allowed conditions to be equivalent and provided students with a genuine opportunity to develop criteria and apply critique. A forced choice design for KIM ideas but free choice for idea placement, connections, and labels seemed to be an effective and balanced form of concept mapping. Using an electronic concept mapping tool made it easier to add and rearrange ideas. The Cmap tool prompted students to add labels to each connection and automatically generated arrows. From a research perspective, electronic KIMs increased the readability of KIMs and allowed saving all student data on a secure backup server.

Results from study 3 suggest that either generating or critiquing KIMs can effectively support knowledge integration of evolution ideas. Students in both treatment groups improved in the number of cross-links between genotype and phenotype level ideas, use of normative evolution ideas, and connections to/from indicator ideas. These findings support the hypothesis that strengthening the connections between genotype and phenotype level ideas can reduce the use of non-normative evolution ideas, for example teleological ideas. Students not only generated more connections in the KIM posttest, but they generated more quantified relationships, which can be seen as an indicator for deeper understanding (Derbentseva et al., 2007). Working on KIMs collaboratively in pairs required students to negotiate and make their criteria explicit. The visual knowledge representation of KIMs can support collaborative work by enabling efficient information retrieval and exchange. Multiple embedded KIMs can allow students to self-monitor their learning progress by making existing and absent connections explicit. Findings indicate that critiquing KIMs can be a more time efficient knowledge integration activity than generating KIMs. Critiquing and sorting out of alternative ideas is a central process of knowledge integration. Critical evaluation of alternative ideas is an important skill for lifelong learning.

B) Study 3 explored several complementary KIM analysis methods. Results suggest that analyzing KIM cross-links, indicator idea prominence, essential links, and network topologies can serve as more efficient ways to track changes in students' understanding than scoring each proposition.

C. KIM Treatment Groups

Results indicate that the WISE module *Gene Pool Explorer* helped students in both treatment groups to add normative ideas to their repertoire and sort out existing alternative ideas. This shift is indicated in the increase of prominence of indicator ideas "mutation" and "natural selection" and a decrease of teleological ideas "need" or " want". Students in the two treatment groups showed similar learning gains from pretest to posttest. Both the generation and critique activities were designed according to knowledge integration principles: To elicit ideas, add ideas, distinguish ideas, reflect and sort out ideas. Both treatments encouraged reflection, negotiation, decision-making, and revision of existing ideas. Either generating or critiquing Knowledge Integration Maps can be beneficial to support learning about evolution.

Student dyads in the **generation** treatment group had to negotiate and generate important connections between evolution ideas. Being able to represent your own ideas with few constraints seems to be beneficial for learning (Davis, 2003). Representing your own ideas in visual form can help self-monitoring by identifying gaps in one's understanding that require revisiting the curriculum material. On the other hand, generating your own KIMs can be cognitively challenging, especially for students with limited prior knowledge and fragmented understanding.

The **critique** treatment group focused specifically on building criteria. The critique process worked in two phases: First, the student dyads had to decide if they agreed or disagreed with the given propositions. Based on their prior ideas, students needed to apply criteria to distinguish the presented propositions, for example "Do we agree or disagree with direction of the connection, the nature of the connection, the placement of the idea, or the absence of a connection?". Second, the students needed to decide how to revise only the connections they disagreed with. The KIM critique activity can constrain reasoning and serve as a starting point for reflections. The pre-made KIM is expected to reduce the demanding decision-making process as students only revise connections they disagree with. Students in the generation group needed to make more decisions: Which two ideas should be connected? How should they be connected? Where should they be placed? Even with a limited number of given ideas, students had to generate their own connections which required them to choose from a large number of possible options. This might explain why student dyads were significantly faster in the KIM critique activity than in the KIM generation activity.

D. Implications

- Findings of study 3 suggest that human evolution can be used to connect evolution ideas to real-life experiences. Many existing evolution curricula compare and contrast Lamarck to Darwin's theory of evolution. Study 3 only presents the target-view (synthetic view of evolution). Lactose tolerance can serve as a pivotal case study by bridging genotype and phenotype ideas through the notion of the protein level.
- Knowledge Integration Maps can elicit cross-connections between genotype and phenotype ideas.
- Students might try to find the one "correct answer" for a KIM. Teachers need to stress the point that each KIM is unique, and that there are many different possible solutions for a good KIM. Even experts in the same field generate KIMs that are different from one another (See study 1). Expert-generated KIM benchmark maps can be used to identify central ideas and establish comparison variables, but should not be seen as the only correct solution for direct comparison.
- Results from study 3 support the importance of using multiple assessment tools to measure and triangulate different forms of knowledge, for example KIMs, explanation, and multiple choice activities.
- KIMs can be rich sources for students' alternative ideas. KIMs can contain different forms of information: Presence or absence of connections, quality of connections, different types of link labels, different types of networks, and spatial placement of ideas. To account for these different aspects of KIMs, several different analysis strategies need to be applied to triangulate ideas. Study 3 identified several efficient ways to analyze KIMs: A) Focus on essential connections (identified from expert-generated benchmark maps); B) Network analysis focusing on indicator ideas; C) Topological analysis; and D) Cross-link analysis.
- For Knowledge Integration Maps, both critique and generation activities support students' knowledge integration. Critiquing Knowledge Integration Maps can be used as a more efficient alternative to generating KIMs.

CHAPTER 7: OVERALL CONCLUSIONS AND DISCUSSION

I. Summary of Findings

This dissertation research investigated the overarching question of how Knowledge Integration Map activities embedded in a technology-enhanced curriculum building on knowledge integration principles can contribute to improve learning of evolution ideas. Students hold a rich repertoire of alternative ideas of evolutionary change [See chapter 2: Students' Alternative Ideas of Evolution], particularly of human evolution. Using human evolution as an example helped students to address their existing alternative ideas of evolution, for example human exceptionalism [See chapter 2: Contextualization and Human Exceptionalism]. The theory of evolution is challenging to understand because evolution ideas need to be connected across different levels [See chapter 2: Evolution Ideas on Different Levels]. Knowledge Integration Map activities can support students connecting ideas across levels, identify central ideas, and distinguish alternative ideas. This dissertation research explored how Knowledge Integration Map activities can effectively support the knowledge integration processes of human evolution ideas.

This dissertation research combines findings from three iterative studies:

Study 1: Concept maps as generative assessment tools

Study 1 consisted of two connected studies (study 1A and 1B). Study 1A investigated the reasoning of experts and novices while creating a specific form of inscription, concept maps, in the field of biology, in particular cell biology, evolution, and genetics. While study 1B used concept maps as a summative form of assessment, study 1A explored the generation process of concept maps on a more detailed level. The study compared the concept mapping generation process of novices (high school students) and biology experts. The study investigated if domain-knowledge influences the reasoning type (constraint-based or model-based) when creating the same kind of external representation (concept maps). The same summative concept mapping task as in study 1B was used. Results suggest that concept maps are a sensitive assessment tool to reveal alternative evolution ideas. The talk-aloud protocol uncovered differences between the concept map generation process of experts and novices that could not be found in the final concept mapping product. Results suggest that experts used more complex reasoning processes during their concept map generation than novices. Additionally, each expert created a different concept map, which suggests that no single concept map should be used as a best-solution-benchmark for direct comparison.

Study 1B described the design and implementation of the WISE evolution module *Meiosis - the next generation* in high school biology classrooms. Study 1B explored students' integration of evolution ideas from the WISE module *Meiosis - the next generation* through concept maps and essays as summative generative assessment tools. Building on knowledge integration design principles, the WISE evolution module supported students to elicit their existing evolution ideas, add new normative evolution ideas, sort out and distinguish alternative ideas based on evidence. The WISE module incorporated a scaffolded dynamic visualization to facilitate students to make connections among evolution ideas across different levels (genetics, cell biology, and evolution). Study 1B compared two generative assessment activities, concept maps and essays. Both treatment groups received the same list of ideas. Generation activities can promote learning (van Amelsvoort et al., 2005). By generating, students articulate and represent their knowledge, apply their representations to solve scientific problems, realize gaps in their knowledge, reorganize ideas, and strengthen connections among ideas. The generation effect of giving explanations (to oneself or others) has been found more beneficial for learning than receiving explanations (Chi et al., 1994). Study 1B explored how generative assessment methods (concept mapping and essay writing) can reveal students' knowledge integration of evolution ideas. The rich, authentic data gathered from thirteen classes indicated that students showed more integrated knowledge of evolution ideas after using the WISE module *Meiosis – the next generation.* Building connections between ideas from different levels (genetics, cell biology, and evolution) is essential to understand evolution phenomena. Using humans as a pivotal case for genetic diversity and evolution allowed connecting scientific ideas to real-life phenomena. Based on the Knowledge Integration framework, a new concept map analysis rubric was developed that focuses on core evolution ideas. This novel concept map rubric was used in study 2 and 3. The new rubric was found to be a more economical and efficient scoring method than previously proposed methods while having a similar diagnostic power. Focusing on core evolution ideas, instead of scoring all connections, allowed for a much more sensitive measurement of change over time, rather than a total score that may include a large number of correct but non-essential connections. Concept maps scores were strongly correlated with essay scores, which support the use of concept maps as a valid alternative generative assessment method to measure students' understanding. Different than essays, concept maps were found to show clusters of related ideas, and reveal both existing and missing links. Using a single one-shot generation activity is common usage in classrooms. Study 1 found that concept maps often need several revisions to reflect one's understanding more accurately. The implication for curriculum design from these findings is to extend concept mapping activities with a revision step. This implication was explored in study 2.

Study 2: Knowledge Integration Maps as learning tools: Generation and Critique

Study 2 extended the concept map generation with a subsequent revision and critique step to foster students' reflection and revision of their concept maps. Asking students to critique has been found to support the development of more coherent and generative criteria (Lehrer & Schauble, 2004) [See chapter 2: Critique]. Critique activities require students to use or develop criteria to reflect, elaborate their ideas, revise their ideas, and self-monitor their learning progress, which supports the development of skills for lifelong autonomous learning (Chi, 2000b). In traditional classrooms, students are often given very limited opportunity to apply critique as scientific knowledge is frequently taught as given facts and delivered by textbooks or teachers who represent authority (Shen & Confrey, 2010). Generation and critique activities can encourage students to actively use dynamic visualizations and facilitate integration of ideas from the visualizations (Buckley, 2000). To make cross-connections between DNA, cell, and organism/population levels explicit, the novel form of concept maps, called Knowledge Integration Maps (KIM), was developed for study 2.

Study 1 suggested that concept maps need additional critique and revision after the initial generation step. Study 2 compared two different critique treatment groups: One group compared their KIM against an expert-made KIM while the other group conducted a KIM peer-review. Students were required to develop their own criteria for their critique. Analysis of the KIMS indicated that both treatment groups significantly improved their understanding of the connections between DNA, cell, and organism/population levels. However, evaluating other people's ideas was perceived as being more engaging than being critical about one's own ideas (also found by (Hoadley & Kirby, 2004; Sandoval & Reiser, 2004)). Additionally, the two groups developed different criteria: The expert map comparison group focused mostly on superficial criteria (such as "Was the idea placed in the same level in the expert KIM?"), while the peer-review group used more specific criteria (like "Is an important connection missing?" or "Does an existing link description need revision?"). These findings suggested that a combination of embedded KIM generation and critique activities could support students' knowledge integration of evolution ideas. Two shortcomings of this instructional design were identified: First, the completion of both activities required a large time investment. Second, students in the peer review group received work of varying quality, providing them with unequal opportunities for critique.

Study 3: Knowledge Integration Maps as learning tools: Generation or Critique

Following the iterative process of design studies, study 3 built on and extended the findings of study 1 and 2. Study 2 found that a combination of generating and critiquing KIMs can supported students' knowledge integration of evolution ideas but was time consuming. As time in classrooms is very limited, study 3 aimed to distinguish the learning effects from either generating or critiquing KIMs. Findings from study 3 aimed to inform the design of more time efficient KIM activities. The WISE module was revised to use a case study of human evolution that connects to everyday life experiences. An inquiry-based curriculum was developed using human lactose intolerance as a case study. The revised KIM activity distinguished between genotype and phenotype level ideas. Study 3 aimed to achieve a better understanding of how different forms of KIM activities can be used to foster integrating genotype and phenotype level evolution ideas. Eliciting the connections between phenotype and genotype ideas is important to develop a coherent understanding of the core principles of biology. Study 2 suggested KIM peer-review as an effective and engaging alternative to using expert generating KIMs for comparison. However, using peer generated KIMs created unequal conditions as KIMs varied in quality. In study 3, students in the critique group received the same faux-student KIM with deliberate errors to critique to create equal conditions for all students in the treatment group and provide students with a genuine opportunity to develop criteria and apply critique. Study 3 used an electronic concept mapping tool to make KIM generation and critique activities easier. Results suggested that students in both treatment groups significantly improved in integrating evolution ideas after using the WISE module *Gene Pool Explorer*. Students in both treatment groups showed a positive shift in the prominence of normative evolution ideas "mutation" and "natural selection" and a decrease of teleological ideas "need" or " want" - which might evince an increase in understanding evolution ideas. Findings indicated that either generating or critiquing KIMs can effectively support knowledge integration of evolution ideas. Students in both treatment groups improved in the number of cross-links between genotype and phenotype level ideas, use of normative evolution ideas, and connections to/from indicator ideas. Students did not only generate more connections in the KIM posttest, but they generated more quantified relationships, which can be seen as an indicator for deeper understanding (Derbentseva et al., 2007). Working on KIMs collaboratively in pairs required students to negotiate and make their criteria explicit.

The visual knowledge representation of KIMs can support collaborative work by enabling efficient information retrieval and exchange. Multiple embedded KIMs can allow students to self-monitor their learning progress by making existing and absent connections explicit. Findings indicate that critiquing KIMs can be a more time efficient knowledge integration activity than generating KIMs. Critiquing and sorting out of alternative ideas is a central process of knowledge integration. Critical evaluation of alternative ideas is an important skill for lifelong learning.

Overall, this dissertation research found that Knowledge Integration Map activities embedded in a technology-enhanced curriculum can effectively and efficiently foster knowledge integration of evolution ideas. KIMs can be used both as learning and assessment tools to elicit and track changes in students' alternative ideas of evolution. Collaboratively critiquing KIMs can serve as an alternative to generating KIMs. Additionally, critiquing alternative ideas is central to the knowledge integration process. KIMs can help distinguishing and connecting evolution ideas among different levels (for example genotype and phenotype). This dissertation suggests novel efficient KIM analysis methods using network analysis and weighted scoring. Students' more frequent use of normative evolution ideas over alternative non-normative ideas after the WISE evolution modules developed for this dissertation can be interpreted as an increase in understanding human evolution ideas.

II. WISE Module Refinement

This dissertation research iteratively refined the WISE module to teach evolution more effectively [See table 60].

Case study: All three WISE evolution modules used a case study of human evolution to relate evolution ideas to students' real-life experiences. The case study from study 1 was modified for study 2 to illustrate the effects of natural selection in different environments. Study 3 refined the case study to illustrate variations in the gene pool through a real-life example.

Data collected from the studies of this dissertation research helped to identify frequently found alternative ideas about evolution. Embedded activities were developed to address these alternative ideas and help students distinguish them. For example,

- Sources of variation: Mutation and recombination. Distinguish from non-normative ideas "use or disuse" [See chapter 2: Use or disuse], "need" [See chapter 2: Need], and "intentionality" [See chapter 2: Intentionality].
- Selection: Distinction of non-random natural selection and random genetic drift [See chapter 2: Natural Selection]
- Focus on gene pool view [See chapter 2: Confusion of Individual and Population].

Concept map activities were revised to provide better scaffolding for KIM generation and revision. Findings suggest that the KIM training phase and worksheets instructions can effectively support KIM activities.

Evolution ideas at different levels [See chapter 2: Evolution ideas on different levels]: The curriculum structure was revised to better illustrate connections between evolution ideas across different levels. Study 2 distinguished three different levels (DNA/ Cell/ Organism). Based on the literature [See chapter 2: Entities: Genotype and Phenotype] and observations from study 2, study 3 simplified the distinction to two levels (genotype/ phenotype). To illustrate the connection between genotype and phenotype level ideas, study 3 focused on genetic causes for the production of the enzyme lactase in the human population [See Chapter 2: Entities: Genotype and Phenotype]. KIM activities were designed to illustrate cross-connections between genotype and phenotype level ideas [See study 3: KIM activity design].

Table 60: WISE module refinement.

	Study 1	**Study 2**	**Study 3**
Concept map activity	Concept map generation	Concept maps generation + critique	Concept maps: Critique or Generation
Structure of concept map activity	Forced choice; No given levels	Forced choice; Three levels (DNA/ Cell/ Organism)	Forced choice; Two levels (genotype/phenotype)
Purpose of concept map	Concept map as posttest assessment tool	Concept map as embedded learning tool: Generation and critique; Concept maps as pre/post-assessment tool	Concept map as embedded learning tool: Generation or critique; Concept maps as pre/post-assessment tool
Case Study of Human Evolution	Human parents expect a baby and wonder which of their traits might get inherited	Human settlers need to decide if high or low genetic diversity is better for survival	Human lactose intolerance
Guiding Question	Can phenotypic traits of a baby be predicted? Why are no two babies alike (except identical twins)?	What are the sources of genetic diversity? Under which circumstances is genetic diversity beneficial?	Why can some adults digest milk while others cannot?
Dynamic Visualization	BioLogica Dragon Genetics	BioLogica Dragon Genetics + Biology in Motion: Evolution Lab	Allele A1
Assessment	Multiple choice items; explanation items; essay or concept map generation	Multiple choice items; explanation items; concept map generation.	Multiple choice items; explanation items; concept map generation; concept map critique.
Experimental groups	Students (novices) and experts	Students: Peer KIM critique or expert-KIM comparison	Students: KIM critique or generation

A. Dynamic Visualization Design Principles

This dissertation research used several dynamic visualizations embedded in the WISE evolution module [See study 1B, 2, and 3]: BioLogica, Evolution Lab, and Allele A1. Using two different visualizations required students to learn two different interfaces and graphical representations, which is time-consuming. Study 3 identified a single visualization, Allele A1, which allowed exploring all variables of the Hardy-Weinberg principle (mutation, natural selection, genetic drift, and migration) [See study 3: Criteria for Population Genetics Visualizations Selection]. Study 3 used the Allele A1 visualization to illustrate changes over time in the frequency of an enzyme (lactase) expressed by a certain allele in the gene pool.

This work led to a set of selection criteria to identify scientifically and educationally sound population genetics visualizations suitable for high school learners [See table 61]:

- The visualization should have a simple and well-designed user interface that allows changing the Hardy-Weinberg formula variables (natural selection, population size, mutation, and migration).
- The visualization should allow direct comparison of multiple experimental conditions.
- The visualization should allow the user to change the time-scale (for example the number of generations) shown in the graph. This allows learners to observe short and long term changes in allele frequencies.
- The visualization should be freeware or open-source.
- The visualization should be available for different operating systems (Win, OSX, Linux).

Table 61: Dynamic visualization comparison.

	BioLogica	Evolution Lab	Allele A1
Easy to use interface	Yes	No	Yes
Direct comparison of multiple experimental conditions	No	No	Yes
Allows to manipulate Hardy-Weinberg principle variables	No	No	Yes
Allows changes in time-scale	No	Yes	Yes
Freeware or open-source	Yes	Yes	Yes
Cross-Platform	Java-based	Flash	Win, OS X

The dynamic visualizations Evolution Lab and BioLogica used in study 1B and 2 had several limitations [See study 2: Implications and Outlook]. For example, the complex interface of Evolution Lab required time-intensive demonstrations and support by the teacher. Students struggled to make sense out of the multiple connected graphs of the simulation. The BioLogica visualization did not include the intermediary steps that show how alleles lead to phenotypic traits, for example by producing certain proteins. This might reinforce the alternative idea that genes are “trait-bearing particles” (Lewis & Kattmann, 2004) that directly control or contain phenotypic traits. The version of BioLogica used in study 1B and 2 did not offer a population view that would allow students to explore the effects of genetic diversity in the context of natural selection.

III. Curriculum Design Principles

This dissertation research has implications for designing evolution instruction. The design principles emerged from iterative classroom trials and application of the Knowledge Integration framework.

These studies contribute to both theory and practice of biology education by identifying design principles that were found effective in classrooms. All three studies support the notion that students enter the biology classroom with a rich repertoire of alternative ideas of evolutionary change [See chapter 2: Students' Alternative Ideas of Evolution]. Evidence from this dissertation suggests that students' evolution ideas are often disconnected and contextualized. To integrate evolution ideas, students need to connect ideas from different levels (for example genotype and phenotype) and scientific fields (for example molecular genetics, cell biology, population genetics, ecology, and physiology). The theory of evolution permeates and connects all fields and levels of biology. Findings from this dissertation suggest that evolution can and should be used as a unifying principle for the design of biology curricula. To gain a deep understanding of evolution, evolution instruction should address the questions "TO WHOM does evolution happen" [See chapter 2: TO WHOM does evolution happen?] and "HOW does evolution work?" [See chapter 2: HOW does evolution work?].

Human evolution can serve as a pivotal case for evolution education by illustrating that humans are animals and subject to evolution, and that human evolution is not over [See chapter 2 and 7: Human Evolution as a Pivotal Case]. Human evolution allows connecting evolution ideas to students' everyday life experiences. Applying scientific ideas in everyday contexts can strengthen the explanatory power of scientific ideas over alternative non-normative ideas (Linn, 2008). Additionally, scientific ideas should be made accessible by using everyday language. The amount of text in the curriculum should be reduced as much as possible.

Biology presents students with a large number of new ideas and novices often struggle to identify central ideas. This dissertation suggests that students can be helped to identify central ideas through modeling expert questions and providing ideas for KIM activities. Expert-generated KIMs can be used to identify essential propositions for curriculum design. Formative and summative assessments should be aligned with curriculum design to focus on essential propositions and address commonly found alternative ideas.

All three studies were developed using knowledge integration design principles:

1) Eliciting students existing alternative evolution ideas through pretest and embedded assessment items.

2) Adding new normative evolution ideas through multiple sources (for example text, pictures, animations, dynamic visualizations, and KIMs). Providing learners with a variety of different sources allows learners to choose and presents the same ideas in multiple contexts.

3) Connecting and grouping ideas across different levels (for example genotype and phenotype level).

4) Distinguishing and sorting out of alternative ideas by connecting them to evidence (for example through KIM or inquiry activities).
5) Encourage students to revisit and revise their initial ideas.

Using a combination of scaffolded inquiry activities using dynamic visualizations, Knowledge Integration Map activities, and explanation generation activities helped students learn evolution ideas. Inquiry activities allowed students to explore the nature of connections between ideas and provided evidence to distinguish alternative ideas, KIMs supported eliciting connections semantically to get a big-picture view, and generating explanations adds details and linking ideas to evidence. Scaffolded inquiry activities for this dissertation used the Knowledge Integration design pattern:

1) Make a prediction based on your existing ideas.
2) Run the dynamic visualization to observe changes under different conditions.
3) Distinguish your observations from the predictions.
4) Sort out alternative ideas and form a coherent argument based on the found evidence.

Findings from the three studies suggest that dynamic visualizations can support knowledge integration of evolution ideas through inquiry activities. However, findings from this dissertation research suggest that it can be difficult for novices to make-sense out of dynamic visualizations of genetics and evolution processes. Qualitative observations indicate that even seemingly simple visualizations, such as the line graph diagrams in study 3, need carefully designed scaffolds to support students' sense-making processes.

A. Human Evolution Pivotal Case Design Principles

This research developed a case study of human evolution as a pivotal case. Linn identified four characteristics of pivotal cases (Linn, 2002):

First, *create compelling comparisons.* Scaffolded inquiry activities help students to compare situations that differ in one dimension. Pivotal cases offer compelling comparisons that reveal the power of scientific inquiry, connect to the prior ideas of learners, and encourage learners to deliberately seek more cohesive accounts of scientific phenomena.

Second, *place inquiry in accessible, culturally relevant contexts.* Pivotal cases place science in real-life contexts familiar to students. By engaging in inquiry around an accessible case, students learn inquiry processes they can reuse to revise their understanding in the future.

Third*, provide feedback to support pre-normative self-monitoring*. Students are asked to make predictions or create artifacts. Teachers, peers, or computer programs then provide feedback on these productions. Student can learn to self-monitor their learning progress (Chi, 1996), which is an important skill for continuous lifelong learning.

Fourth*, enable narrative* accounts *of science.* Narratives that connect multiple examples into a coherent story with the mechanism of the pivotal case as the focal point can pull together different forms of representations. This builds on the success of curriculum materials featuring case studies that used a narrative format to present a complex case (Kolodner, 1993; Linn & Clancy, 1992b).

1) Criteria for Case Study of Human Evolution

A set of criteria has been developed to select and develop a case study into a pivotal case for evolution [See table 62]:

Table 62: Criteria for design of a case study of human evolution.

Criteria	Rationale
Human evolution	Studies (for example see Evans (Evans, 2008)) have found that many people consider humans an exception that follows different rules for its development than other organisms (contextualization) [See chapter 2: Human Exceptionalism] and [See chapter 2: Human Evolution as a Pivotal Case]. To address these commonly found alternative ideas, the case study should use human evolution to illustrate evolutionary changes, the nature of ongoing evolution, and that humans are subject to evolutionary mechanisms like all other organisms.
Directly observable phenotype in everyday life	The case study should have a directly observable phenotype that allows students to connect the new ideas to their prior experiences. The phenotypic traits should be of interest to an ethnically diverse group of students. Knowledge Integration aims to connect new ideas to existing ideas to explain everyday life phenomena. Integrating new scientific ideas allows applying them in a variety of contexts and seeing their relevance as they allow explaining real-life phenomena better than alternative ideas. Besterman (2007) found that many students have difficulties recognizing individual phenotypic differences in non-human organism. Consequentially, novices tend to think of non-human organisms as entire homogenous species [See chapter 2: Essentialism]. Evolutionary change affects therefore the essence of a whole species and not individuals. However, humans are good at identifying differences among other humans. Using a human example can make the idea of individual genetic variation more accessible.
Simple underlying genetic cause	The genotypic explanation of the trait should be based on a relatively simple mechanism that is accessible for novices, for example a single mutation.
Connection between genetic, protein, and phenotype level	Many students find it difficult to understand how the genotype influences the phenotype (Lewis & Kattmann, 2004). Shea (2010) suggested that students need to learn about the role of proteins as the connecting element between genes and phenotypic traits. Duncan and Reiser (2007) suggested focusing on proteins as the connecting element between genes and expression of traits. For example, enzymes could be used to

	bridge between mutations and observable phenotypic traits. Connections between levels can be elicited through Knowledge Integration Maps (KIMs) [See study 2 and 3: Knowledge Integration Maps]
Builds on current research findings	The case study should illustrate recent research findings to illustrate the ongoing efforts of evolution research and the dynamic process of science.
Allows to illustrate the effects of all Hardy-Weinberg model variables: Mutation, natural selection, genetic drift, and migration	The case study should allow illustrating the effects of all four processes that affect the genetic variability in the gene pool of a population: Mutation, natural selection, genetic drift, and migration. This allows connecting these four processes though a single case study. Contrasting natural selection (leads to adaptations) to random processes (mutation, genetic drift) allows illustrating that evolution is a non-directed process. This addresses the commonly found alternative idea that evolution leads to improvements of organisms based on their needs.
Novel example	The case study should be novel to the students, unlike the widely used Darwin finches, peppered moth, and sickle cell anemia studies.
Ability to simulate using a dynamic visualization	Inquiry-based learning through scaffolded experiments to introduce the population genetics view of evolution (Frequency change in gene pool). Experiments should allow contrasting the effects of different variables of the Hardy-Weinberg model.
Example of a positive mutation	Many students hold the alternative idea that mutations are inherently negative. For example, in movies "mutations" are usually depicted as negative aberrations. Students should learn that mutations can be positive, negative, or neutral, depending on how they effect the fitness of a phenotype in a certain environment.
Interesting to an ethnically diverse group of students	The case study should be interesting and relevant to an ethnically diverse group of students

B. Teaching Darwinism

Despite the advances of evolutionary synthetic theory over the past 150 years, the term "Darwinism" is still used as a synonym for evolutionary theory (Scott & Branch, 2009). Evolutionary theory owes much to Charles Darwin whose work provided the foundation of the discipline. However, current evolutionary theory includes many ideas that were not known to Darwin, such as Mendel's rules of inheritance, genetics, and the mathematical models of population genetics. Using the term Darwinism as a synonym for evolutionary theory is inaccurate and unfair to all the scientists who have contributed to the field before and since Darwin [See chapter 2: History of Modern Evolution Theory].

Judson (2008) commented that the term Darwinism suggests a false narrowness to the field of evolutionary biology, as if the field represents only the ideas of a single person 150 years ago, rather than the complex evolving subject to which many great researchers have contributed. Judson and Scott both suggest abandoning Darwinism as a synonym for evolutionary biology.

Focusing on Darwin and his theory of evolution by natural selection in textbooks illustrates the history of science and shows the human side of scientific research. However, a strong emphasis on Darwin and natural selection might lead to a simplistic view of evolution that does not correspond with modern evolution theory. The goal of evolution education should be to teach about the modern synthetic theory of evolution.

In addition, textbooks can include inaccurate information. Linhart (1997) surveyed fifty major college biology textbooks and concluded that the theory of evolution is not presented accurately in many of them. This is a matter of grave concern as proper understanding of evolution as the defining framework for modern biology is essential for all students of biology. Rees (2007) found that advanced level biology textbooks presented an inaccurate picture of Darwin by associating contributions of others to Darwin instead and mystifying his historic contribution. For example, the expression "survival of the fittest was coined by Herbert Spencer five years after Darwin's publication of "On the Origin of Species".

Evolution education instructional material needs to be carefully designed to present an accurate picture of the history of evolution and, most importantly, introduce the modern synthetic theory of evolution and its relevance for science and everyday life.

Evolution ideas are often presented for a short period of time. Berkman (2008) surveyed a random sample of 2000 high school science teachers across the U.S. in 2007. Of the 939 who responded, 2% said they did not cover evolution at all, with the majority spending between 3 and 10 classroom hours on the subject.

This dissertation research explored the iterative development of efficient WISE human evolution modules that focus on the modern theory of evolution.

IV. KIM Design Guidelines

This dissertation research developed the novel concept mapping form, Knowledge Integration Maps, as an efficient Knowledge Integration tool for evolution ideas [See table 63]. Findings suggest that KIM generation and/or critique activities can effectively support integrating evolution ideas. Design guidelines emerging from this work are in table 64.

Table 63: Concept mapping for knowledge integration

Knowledge Integration Process	Concept Mapping Activity
Eliciting existing Ideas	Concept maps can be used as a pretest activity to elicit' existing ideas.
Adding new ideas and connecting to existing ideas in repertoire	New ideas can be added to existing propositions in the concept map. If several alternative relationships between two ideas are possible, students have to decide which one to use in the map. If applicable, students decide which ideas to add to the map.
Distinguishing/ Critiquing Ideas	After adding new ideas, ideas can be rearranged into new groups, and the concept map network structure might need

	revision to reflect the new ideas.
Sorting out Ideas/ Refining	Different sources of evidence can as reference to sort out ideas and further refine the concept map.
Applying ideas	Concept maps can be used as resources to generate explanations of scientific phenomena.

Critiquing KIM plays an importance role in integrating evolution ideas: A) Generate criteria B) Elicit alternative ideas and missing connections C) Distinguish ideas using evidence [See chapter 2: Concept Maps as Metacognitive Tools]. Findings indicate that Knowledge Integration Maps can support each phase of knowledge integration. This dissertation research suggests that Knowledge Integration maps can effectively serve as a Knowledge Integration tool for evolution education.

As collaborative tools, KIMs constrain learners to decide on only one link between two ideas, which can encourage negotiation and systematic reflection [See chapter 2: Concept Maps as Collaborative Tools]. KIMs foster clustering of related idea in close spatial proximity by dividing the map into specific levels, for example phenotype and genotype ideas. The division into specific levels can highlight cross-connections among ideas in different levels. KIMs model what experts consider important ideas by providing a list of ideas to generate the map from.

KIMs can be used in different stages of curriculum development and implementation: As curriculum planning tools, KIMs can be used to identify core ideas and essential connections between ideas. As learning tools, KIMs can be used for individual or collaborative generation and critique activities [See chapter 2: Concept Maps as Learning Tools]. As assessment tools, KIMs can be used to identify alternative ideas, elicit existing and missing connections within and across levels, categorization of ideas, overall network structure, and prominence of important ideas [See chapter 2: Concept Maps as Assessment Tools].

KIM activities consist of A) a KIM training phase, B) a KIM task, C) and a KIM evaluation method [See chapter 2: Concept Map Activity Design]. This dissertation research developed efficient activities for each phase:

A) KIM training phase: Results indicate that the KIM training phase can efficiently introduce students to KIM generation and critique activities. The KIM training sequence consists of increasingly more challenging tasks that alternate between individual practice and classroom discussions. The goal of the training sequence is to familiarize students with the KIM technique and collaboratively develop criteria for KIM critique and revision. 1) KIM technique demonstration. 2) Individual KIM generation practice. 3) Individual KIM critique practice. 4) Classroom discussion of KIM critique. 5) Pretest KIM critique activity and KIM generation activity. [See study 3: KIM Training Phase for details].

B) KIM task phase: Study 1A suggested that concept maps need additional critique and revision after the initial generation step. Findings from study 2 suggested that peer critique or expert map comparisons can support concept map revisions. Study 3 suggests that critiquing KIMs can be more efficient than generating KIMs from scratch. Presenting KIMs as faux-student work for critique provided students with equivalent conditions and an opportunity to develop criteria and apply critique.

Findings suggest that using an electronic concept mapping tool for KIM tasks can expedite KIM generation and critique activities (also see Royer (2004)). Using an electronic concept mapping tool can make it easier for students to re-arrange ideas into groups, provide a repository of ideas and labels to be used, and scaffold students with prompts to label all their links. This can decrease the risk of students forgetting to use certain ideas or draw unlabeled links between them. An electronic concept mapping tool can improve readability of the maps and allow for possible automated scoring to provide additional feedback to the students about their learning progress.

Concept map format: Concept map activities range from open-ended to heavily constrained forms [See chapter 2: Types of Concept Map Tasks]. This dissertation research aimed to identify and develop a concept map form that represents a compromise between open and heavily constrained forms. Open-ended concept maps, where students can choose their own ideas, might reflect students' knowledge structures more accurately, but they can be more difficult to compare and require more time to generate. More constrained concept mapping forms can result in ceiling effect (Ruiz-Primo, 2000; 2001; Yin et al., 2005). Yin (2005) found that a forced choice design with a given list of expert-selected ideas to choose from allowed for a better comparisons between maps than free choice of ideas. Students had free choice in which ideas to connect, arrow direction, idea placement, and linking labels.

Knowledge Integration Maps follow several distinct guidelines [See table 64] that distinguish them from other concept mapping forms:

Table 64: Knowledge Integration Map design guidelines.

Biology-specific levels	This characteristic combines aspects of concept mapping with aspects of Venn diagrams. The concept map drawing area is divided into several biology-specific levels, for example genotype and phenotype. This arrangement requires learners to a) generate criteria and categorize ideas, b) sort out ideas into according levels (clustering), and c) generate connections between ideas within and across levels. Sorting out and grouping ideas spatially according to semantic similarity requires learners to generate criteria and make decisions about information structure that is latent in texts (Nesbit & Adesope, 2006). This is expected to support knowledge integration by showing ideas in contexts to other ideas and eliciting existing (and missing) connections within and across levels. Cross-links are especially desirable as they can be interpreted as "creative leaps on the part of the knowledge producer" (Novak & Canas, 2006) and support reasoning across ontologically different levels (Duncan & Reiser, 2007).
Given list of ideas, but free labels and links	Ruiz-Primo et al. (2000) compared concept mapping tasks with varying constraints and found that constructing a map using a given list of ideas (forced choice design) [See table 5 in sub-chapter Types of concept map tasks: Task #2] reflected individual student differences in connected

	understanding better than more constrained fill-the-map forms. Evolution consists of a large number of ideas that often make it challenging for novices to identify key ideas [See chapter 2: Difficult Use of Terminology]. Providing students with a small list of expert-selected key ideas can serve as signposts and limit complexity. Concept maps generated from the same set of ideas allow for better scoring and comparison. Students' alternatives ideas are captured in the idea placement, link labels, and link direction.
Concept map training activity	Students need initial training activities to learn the concept mapping method and generate criteria for concept map critique [See chapter 2: Concept Map Training]
Starter Map (optional)	Building a concept map from scratch can be challenging. Providing a starter map as a partially worked example could reduce anxiety (Czerniak & Haney, 1998; Jegede et al., 1990). Critiquing and revising concept maps with starter maps requires a completion strategy (Chang et al., 2000; Sweller et al., 1998; Van Merriënboer, 1990).
Faux-peer map	Students get few opportunities for critique or revision [See chapter 2: Critique]. Providing students with concept maps made by a peer (or a faux-peer) allow students to revisit their ideas by adding to, critiquing, or revising an existing concept map.
Collaborative concept map activity	Concept maps are generated collaboratively in dyads. As each proposition is constrained to only one link, students are required to negotiate which connection to revise or generate. Students are required to generate criteria [See chapter 2: Concept Maps as Metacognitive tools] and negotiate with their partner [See chapter 2: Concept Maps as Collaborative Tools].
Focus question	The biology-specific focus question guides the construction of the concept map as learners select ideas and generate links to answer the focus question (Derbentseva et al., 2007).
Feedback and Revision	Feedback and revision supports students' knowledge integration through revisiting, reflecting, and revising existing and new ideas. Concept maps often need several revisions to adequately answer the focus question [See study 1A].

C) KIM analysis phase: Study 1A illustrated that single analysis methods often do not allow distinguishing novice and expert concept maps. To capture the wide variety of students' alternative ideas, this dissertation research suggests using a combination of quantitative and qualitative concept map analysis methods. Findings suggest that analyzing KIM cross-links, indicator idea prominence, essential links, and network topologies can serve as more efficient ways to track changes in students' understanding than scoring each proposition.

Findings from study 1A suggest that expert-generated concept maps can strongly differ from each other and that there is no single ideal expert concept map that can be used as a benchmark [See study 1A: Concept Map Analysis and Benchmark Maps]. Using expert-generated benchmark maps might suggest that there is only one correct answer. Expert-generated benchmark maps can be used to identify such essential propositions and as a benchmark to determine a meaningful number of connections. Especially links between ideas at different levels can be seen as indicators for more coherent understanding.

V. Constraints

A. Time Constraints

The WISE evolution modules developed for this study were each only five to six hours in length. However, findings indicate that well-designed WISE modules can improve students understanding of complex scientific ideas, such as evolution, in a short amount of time.

B. Methodological Constraints

The WISE evolution modules consisted of a whole package of embedded learning tools, such as explanation generation, multiple choice with automated feedback, animations, pictures, texts, dynamic visualizations, drawing activities, and Knowledge Integration Map activities. Knowledge Integration maps were an integral part of the whole package of WISE evolution module activities. This dissertation could only describe the consolidated learning effects from different Knowledge Integration Map activities as an embedded knowledge integration tool.

Like all teaching and learning tools, KIMs are not a panacea. KIMs do not suit all learners or all learning situations. KIMs constrain ideas to only one connection with a short label using a given list of ideas. Qualitative observations suggest that aesthetic considerations might limit the complexity and re-arrangement of KIMs to avoid 'messy' maps with too many links and overlapping connections. KIMs can provide information about connection between ideas and idea placement, but only limited information about students' understanding of ideas themselves. Triangulating data from pre/posttests, embedded assessments, KIMs, qualitative classroom observations, and interviews allow describing and tracking students' understanding of evolution ideas. KIM activities need to be carefully designed to promote active knowledge integration and provide balanced levels of scaffolding.

It is interesting to note that across all three studies none of 400 students expressed religious ideas in the formative or summative assessments. This finding could be explained by a secular student body or by students' contextualization of religious and scientific ideas. Students might use scientific ideas only in the science classroom, but use their alternative religious ideas in other contexts.

Data collected for this dissertation illustrates the difficulties of gathering complete data sets from all students. Gaps in individual student's datasets indicate that students frequently missed biology classes. As evolution is taught only for an average of 3-10 hours [See chapter 2: Instruction Design and Evolution], missing one lesson could make a noticeable difference.

C. Technical Constraints

Implementing a technology-enhanced science learning environment like WISE often meet technological constraints, such as limited availability of computers, computer maintenance, server connection issues, and limited internet bandwidth.

VI. Implications

Overall, this dissertation research demonstrates that Knowledge Integration Map activities embedded within a technology-enhanced evolution curriculum focused on knowledge integration have the potential to transform learning in biology classrooms where time is limited and precious. This dissertation research developed and explored efficient forms of concept mapping activities that foster knowledge integration of evolution ideas.

Results suggest that critiquing KIMs can be an efficient alternative to generating KIMs from scratch. Additionally, critiquing KIMs can elicit criteria to distinguish alternative ideas and provide students with a genuine opportunity to negotiate and apply critique. For KIMs to provide maximum benefit to the student, KIM activities should be integrated with a variety of other learning activities. Learning how to generate KIMs and how to create and revise good KIMs takes time and practice. Ideally, KIMs would be introduced earlier in students' academic career rather than later, so they can integrate it into their developing study strategy (for example see (Santhanam, Leach, & Dawson, 1998)). KIM activities should not just be added to an existing curriculum but become an integral embedded part.

To capture the wide variety of students' alternative ideas, this dissertation research suggests using a combination of quantitative and qualitative KIM analysis methods. Findings suggest that analyzing cross-links, indicator idea prominence, essential links, and network topologies can serve as more efficient ways to track changes in students' understanding than scoring each proposition.

Learning evolution takes time. Instead of teaching evolution as an isolated topic for a short period of time, evolution ideas should be used as the unifying framework present in all biological ideas. Teachers need to be proficient and confident teaching evolution ideas. Teachers and students need efficient and effective tools to support the knowledge integration process for evolution ideas. Pre-service and professional development programs for biology teachers should focus on addressing alternative evolution ideas and introduce effective teaching tools.

Many students consider humans a special case of evolution. Using a human example as a pivotal case can help students to address alternative evolution ideas and connect evolution processes to everyday life observations. Knowledge integration aims to connect scientific ideas to everyday experiences. Applying scientific ideas in multiple contexts can foster the explanatory strength of an idea and give newly introduced normative ideas a higher cueing priority.

This research highlights the importance of design-based research in authentic classroom settings. The iterative design experiments in this dissertation research led to the findings of the role of collaboratively generating and critiquing Knowledge Integration Maps in classrooms.

VII. Extension of Work

This dissertation work could be extended in several different ways:

A. Knowledge Integration Maps

This dissertation research explored different KIM activities to integrate evolution ideas. Further research could develop KIMs for other subjects and topics, for example chemistry, physics, history, literature studies, political science, computer science, etc.

Students could discuss and negotiate in a whole class discussion which additional ideas should be added to the given list of KIM ideas.

KIM activities could be implemented into WISE to allow directly linking KIM ideas to evidence in WISE pages or other online resources. A WISE KIM tool would allow anonymous peer review of student-generated KIMs. The teacher could access student-generated KIMs and share selected examples with the class as models.

Students could add their KIM propositions to a shared space throughout the WISE module to create an idea database. KIMs could suggest multiple alternative connections between two ideas from the database. Students are then asked to negotiate which connection to choose by supporting their decision with links to evidence. Students could directly comment on and rank other students' propositions in the database. Alternatively, KIMs could allow multiple connections between two ideas at the same time.

KIMs provide a big-picture bare-bone view of connected ideas. Similar to study 1, students could be asked to flesh out ideas by writing more detailed explanations or essays added to each KIM proposition.

Other possible KIM treatment groups could be explored to investigate if the order of activities matters. For example, KIM generation followed by KIM critique vs. KIM critique followed by KIM generation.

Qualitative data from student discourse, video analysis, and interviews could further elicit what criteria students use to distinguish ideas in KIMs.

KIMs could be used continuously throughout the curriculum. Students could individually or collaboratively create KIMs to add new ideas to their growing cumulative understanding of scientific phenomena, revise their maps, link ideas to evidence, and critique other students' maps. Over time, KIMs can become integral elements in students' self-monitoring of their learning progress and support students' lifelong learning of science.

Observations from this dissertation research suggest that some students hesitate adding ideas or changing the location of ideas in KIMs for aesthetic reasons (to keep the KIM layout clear and orderly). Further research could explore to what extent aesthetic reasoning influences the generation and critique of KIMs.

KIMs can elicit connections between ideas but reveal little about the nature of ideas themselves beyond their context through connections to other ideas and maybe their spatial location. Students could be asked to elaborate the nature of ideas and link them to further evidence.

Automated KIM analysis methods could be developed to provide learners with instant feedback of their learning progress. However, such automated systems should not use a single benchmark map for comparison but allow for alternative expressions of students' ideas [See study 1B: Concept Map Analysis and Benchmark Maps].

B. Curriculum Design

Some evolution ideas are described in historical terms that can be confusing for novices. Two options could address the issue: First, new evolution ideas should be introduced conceptually before the historic term is used. Second, biology teachers could use alternative terms that are more intuitive descriptions. For example, alternative terms for natural selection could be "reproduction competition" or "natural competition"; the term "fitness" could be replaced by "reproductive success" or "fitted-ness"; and the misleading expression "survival of the fittest" could be avoided altogether.

C. Dynamic Visualizations

A dynamic visualization for population genetics could be developed that shows both changes in the gene pool and phenotypic traits. The visualizations should also illustrate the connections between genotype and phenotype level through the bridge of proteins, as suggested by Duncan and Reiser (2007).

CHAPTER 8: REFERENCES

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CHAPTER 9: APPENDICES

I. Appendix Chapter 1: Introduction

The importance of understanding evolution can be described from different perspectives:
Civic-Democratic-Utilitarian perspective:

Scientific literacy is required for a democracy. Democracies build on citizens being able to make informed personal and community decisions about issues in which scientific information plays a fundamental role, and they hence need a knowledge of science as well as an understanding of scientific methodology (Duschl, Schweingruber, & Shouse, 2007; Trefil, 2008). As John Dewey pointed out, only a "learning society" (democracy) comprised of scientifically literate citizens is adaptive enough to strive in the long run (Dewey, 1916).

Modern biology, in particular genetics, is on the brink of giving us unprecedented power, from personalized gene therapy to delaying the effects of aging. Society's views if and how this new knowledge should be used will be shaped by people's understanding of their evolutionary origins. Evolution is directly relevant to many policy decisions and allows citizens to make informed decisions, for example: Infectious diseases from tuberculosis to wheat rust are making a comeback as they evolve resistance to our defenses; Antibiotic-resistant bacteria are a growing problem; New deadly viruses might evolve the ability to jump species at any time and spread through our globalized world causing a devastating pandemic.

Grasping the reality and seriousness of such threats and making informed decisions requires citizens to understand evolution. Citizens need to be able to make informed decisions on a wide variety of evolution-related issues such as vaccinations, genetically-altered food, gene therapy, cloning, genetic counseling, and stem cell research. Understanding evolution allows us to understand the effects our changes to the environments have on many species: For example, fishing policies that allow fishermen to keep only large fish are leading to the evolution of smaller fish (Le Page, 2008); rats are becoming resistant to poison; and urban songbirds change their songs to counter noise pollution (Yong, 2008).

Education needs to empower and motivate students to continue learning about current scientific findings after they leave school. Situating evolution ideas in realistic contexts can make ideas meaningful and applicable. Only through lifelong continuous learning can we make evidence-based informed decisions, which is fostered by knowledge integration, including situating ideas in realistic contexts.

Vocational perspective:
Science education has a dual goal: To produce scientifically literate citizens and to produce scientifically proficient scientists (Duschl et al., 2007). For some students, careers depending on biology will become a lifelong vocation. Nations depend on the technical and scientific abilities of their citizens for their economic competitiveness and national needs. Professions in biotechnology, pharmaceutics, healthcare, and agriculture require a thorough understanding of genetics and evolution. The ideas of evolution are of increasing importance in a wide variety of research fields, for example evolutionary developmental biology, evolutionary psychology,

evolutionary engineering, evolutionary anthropology, evolutionary economics, evolutionary computation, evolutionary ecology, evolutionary medicine, evolutionary microbiology, evolutionary philosophy, evolutionary analysis in law, paleontology, exobiology, climate change, and even evolutionary religious studies.

Aesthetic perspective:
Understanding evolution means understanding the changes in organisms over time, both on a macroscopic and a genetic level. Understanding evolution on multiple levels allows us to connect current forms and events in nature to preceding processes. The world looks different depending on whether you view humans as the perfect finished product or as an imperfect animal thrown up by a cruel evolutionary process. Understanding evolution allows people to see the current world in a historic context and understand the mechanisms that lead to current forms. Understanding evolution allows people to have a historic perspective on changes in the world. It helps to understand the origins of human behavior and human society structures by looking at them as adaptations to certain environments (Wilson, 2005). Understanding evolution can enhance our personal view of the world, for example our appreciation of the complex beauty of nature. Catley (2006) notes that "[t]he sense of humility gained through an appreciation of the kinship of all life is a vitally important component in nurturing a stewardship ethic for a planet moving ever deeper toward ecological collapse… [which could] have momentous reverberations for future generations" (p. 781). Evolution and genetics ideas are frequently used in popular books and movies. Many books refer to evolutionary theory to explain a wide range of phenomena, from obesity (D'Adamo, D'Adamo, & Whitney, 1996), violent behavior (Brody, 1998; Wilson, 2000), disease control (Goode, 2000), to changing perceptions of race (Shane, 1999; Wolpoff & Caspari, 1997).

Historic-cultural-social perspective:
Evolution represents a major cultural achievement and a historic milestone in culturally understanding. Evolution fundamentally changed the way we see our world and ourselves. Understanding the origins and cultural impacts of evolution is an important aspect of being scientifically literate. Learning about evolution is closely connected to the history of science, nature of science, and epistemology. Teaching biology without evolution is the equivalent of teaching physics without the theory of gravity, or teaching about diseases without germ theory.

II. Appendix Chapter 3: WISE and design-based experiments

Table 65: Concept mapping software comparison

Name	**Developer**	**Source Code available**	**Custom Setup**	**Platform**	**Online/Offline**	**Multi-Languages**	**Cost**	**GUI**	**Online Collaboration**	**Comments**	**Website**
Cmap	Cornel University	Yes	Yes	Cross-Platform (Java-based)	Stand-alone + Web-based	Yes	Freeware	Well-designed GUI	Yes	Allows comparison with criterion map, recording of map creation	http://cmap.ihmc.us/
Inspiration	Inspiration Inc.	No	Yes	Win and OS X	Stand-alone	English only	Commercial	Well-designed GUI	No	Includes big picture database	http://www.inspiration.com/
Webinspiration	Inspiration Inc.	No	Yes	Web-based	Web-based	English only	Commercial	Well-designed GUI	Yes	Web-based version of Inspiration	http://www.mywebspiration.com
Compendium	Compendium Institute	GPL	Yes	Cross-Platform (Java-based)	Stand-alone	English only	Freeware	Well-designed GUI	Yes	Concept mapping tool which focuses on online collaboration	http://www.compendiuminstitute.org/community/showcase.htm
Vue	Tufts University	ECL	Yes	Cross-Platform (Java-based)	Stand-alone	Yes	Freeware	Well-designed GUI	No	Allows to define 'pathways', which highlight certain chains for presentations.	http://vue.uit.tufts.edu/index.cfm
Easy Mapping	German website	No	No	Web-based	Web-based	German only	Freeware	Limited	No	Simple functions possible	http://www.cognitive-tools.de/Easy-Mapping/Online_Mapping/online_mapping.html
C-Tools	U Michigan State	Yes	Yes	Java-based	Web-based + Stand-alone	English only	Freeware	Limited	No	Allows comparison with criterion map	http://ctools.msu.edu/ctools/index.html
jKSImapper	U Calgary	Yes	Yes	Java-based	Web-based + Stand-alone	English only	Freeware	Limited	No	Last updated 1999	http://pages.cpsc.ucalgary.ca/~robertof/jKSImapper/
Aibase	Aibase Inc.	No	Yes	Win only	Stand-alone	English only	Commercial	Limited	No	Mostly knowledge mapping & some concept mapping	http://www.aibase-cs.com/index.html

SMART ideas	MaNet	Lifemap	Knowledge Manager	Conzilla	Axon
SMART Technologies	IPN	Robert Abrams	Knowledge Manager Inc.	Conzilla.org	Axon Inc.
No	No	No	No	No	No
Yes	Yes	No	No	Yes	Yes
Win and OS X	Win only	Mac only	Win only	Java-based	Win only
Stand-alone	Stand-alone	Stand-alone	Stand-alone	Stand-alone	Stand-alone
English only	German only	English only	Yes	English only	English only
Commercial	Commercial	Freeware	Commercial	Freeware	Commercial
Well-designed GUI	Limited	Limited	Limited	Limited	Well-designed GUI
No	No	No	Yes	No	Yes
Designed for use on SMART interactive whiteboards	Allows comparison with criterion map, intuitive handling, interesting: has drop down menus for link labels	Allows drawing of concept maps, V diagrams, Y diagrams, Venn diagrams	Similar to Inspiration, but fewer options. Interesting feature: Allows to define pathways through the map	More flowchart than concept mapping	Offers dozens of visualization methods, including concept mapping
http://www2.smarttech.com/st/en-US/Products/SMART+Ideas/	http://www.marescom.net/index.htm	http://www.robertabrams.net/conceptmap/lifemaphome.html	http://www.knowledgemanager.us/default-eng.htm	http://www.conzilla.org/wiki/Overview/Main	http://web.singnet.com.sg/~axon2000/

III. Appendix Chapter 4: Study 1A

A. Study 1A worksheet for first and second task

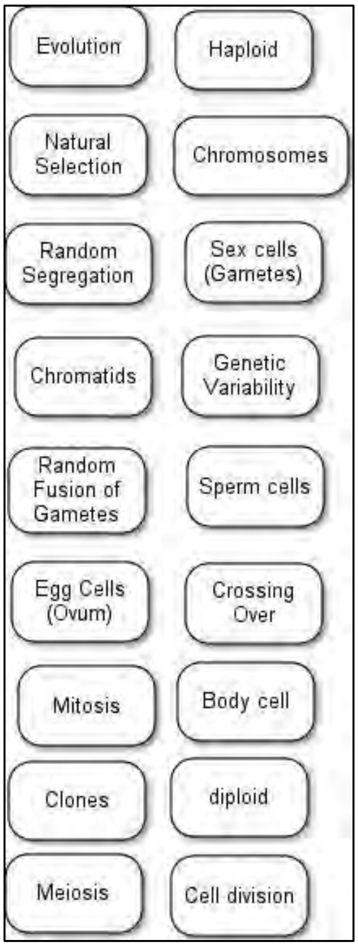


Figure 70: Study 1A first task. Organize these 18 ideas into a hierarchical concept map.

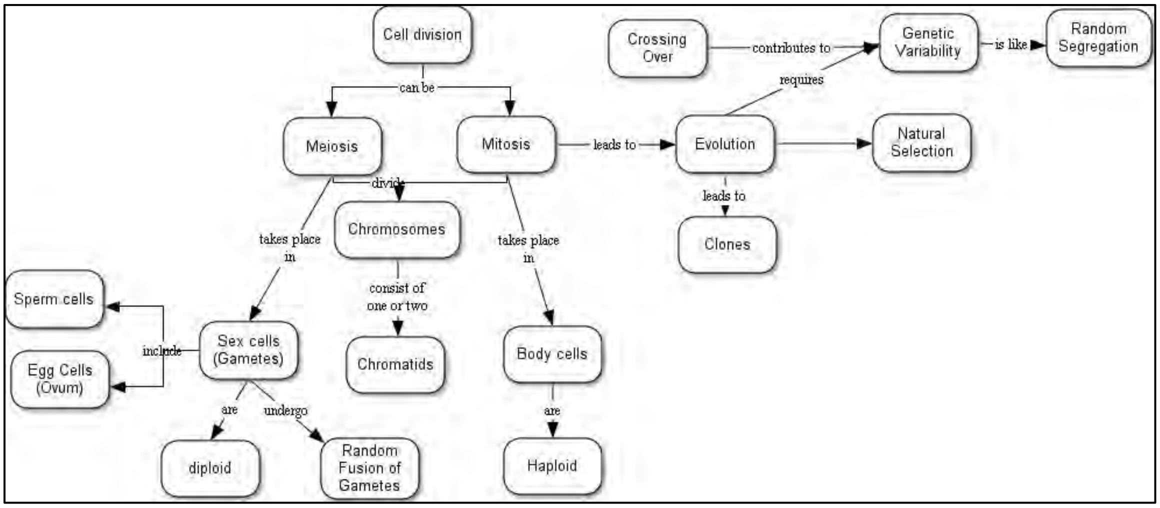


Figure 71: Study 1A second task. Identify any erroneous links and/or labels (if any) in this map.

B. Study 1A Concept maps created by experts and students

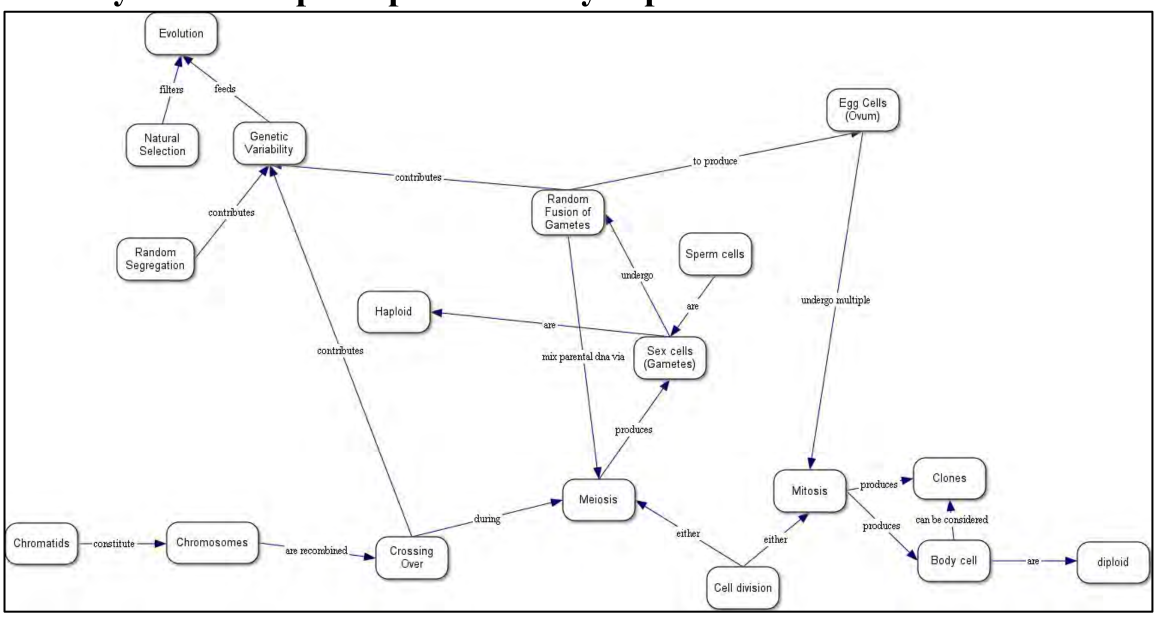


Figure 72: Study 1A concept map expert A.

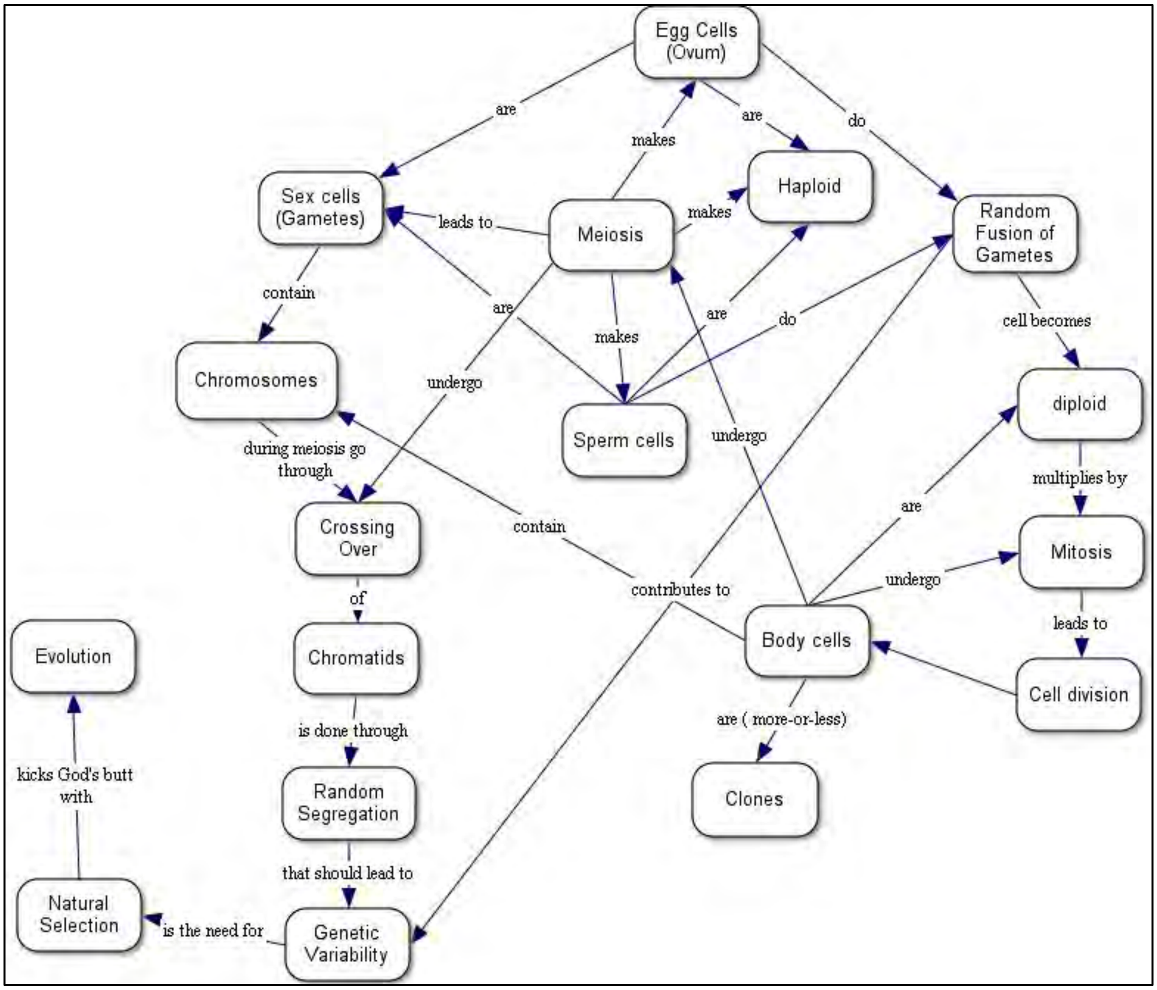


Figure 73: Study 1A concept map expert B.

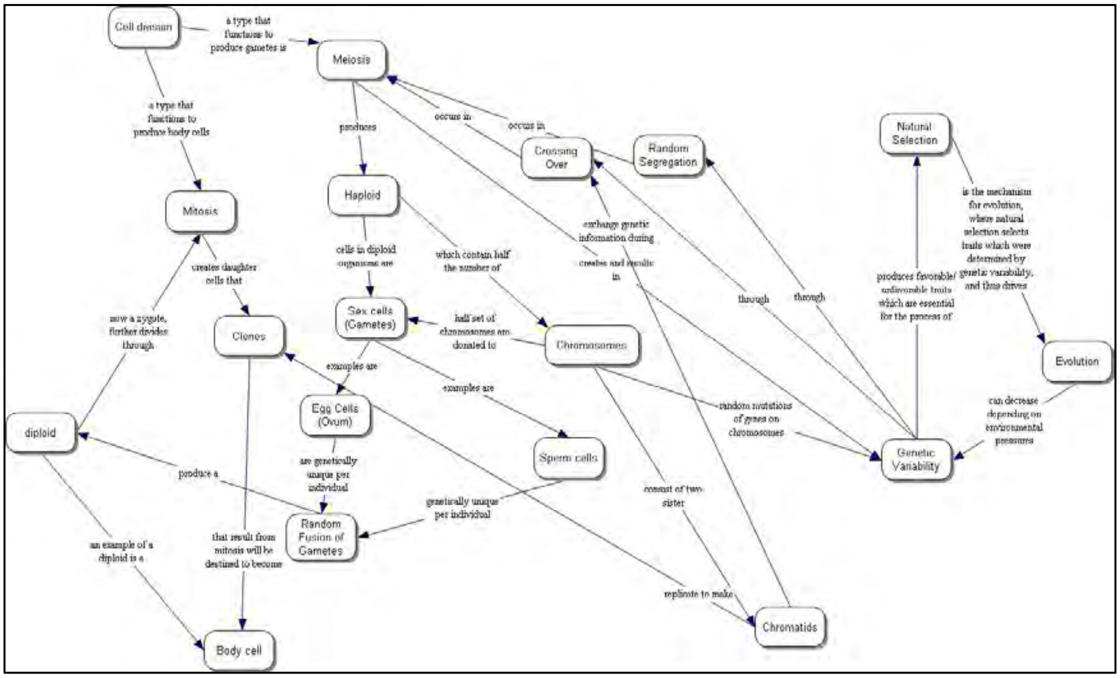


Figure 74: Study 1A concept map expert C.

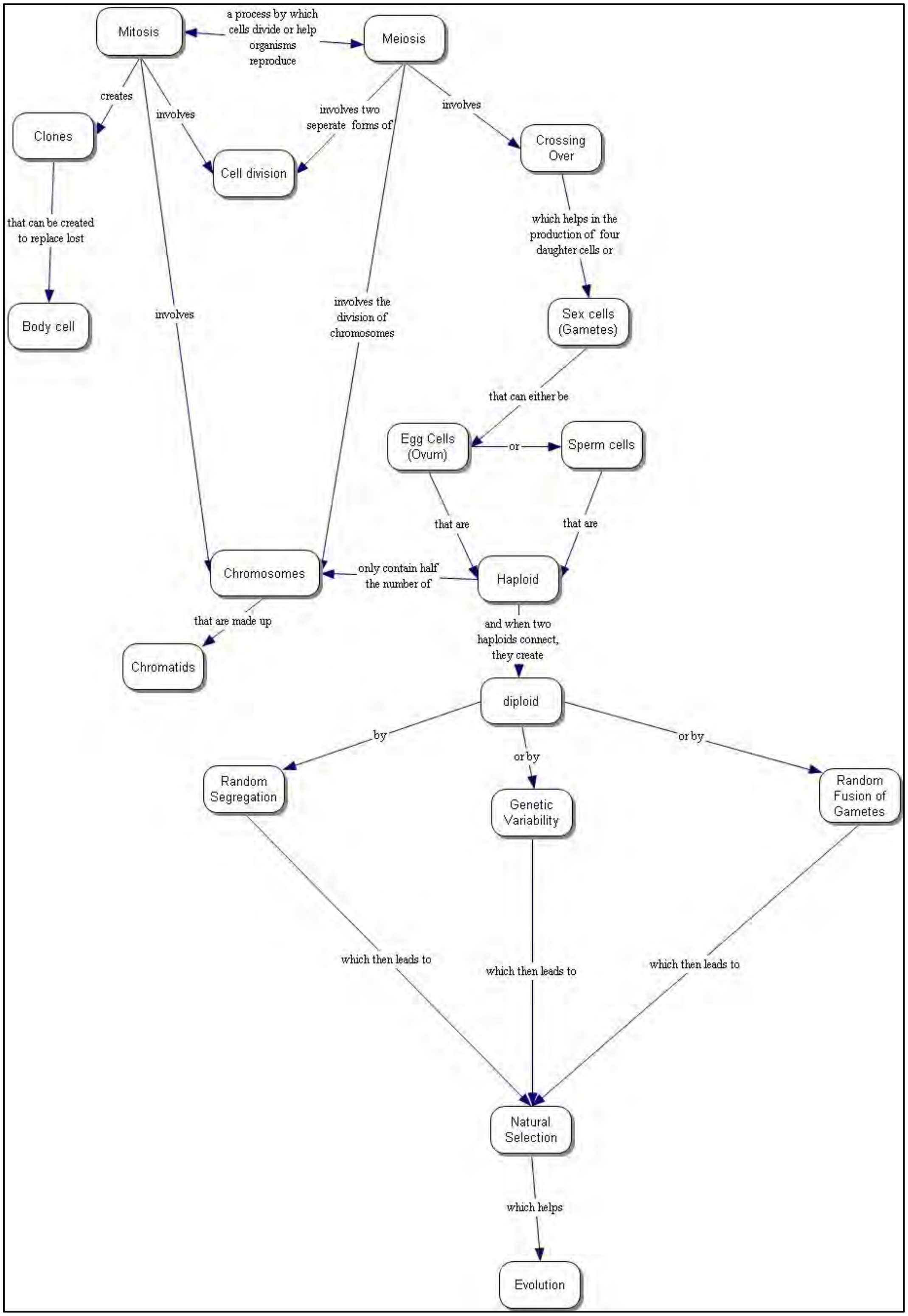


Figure 75: Study 1A concept map student D.

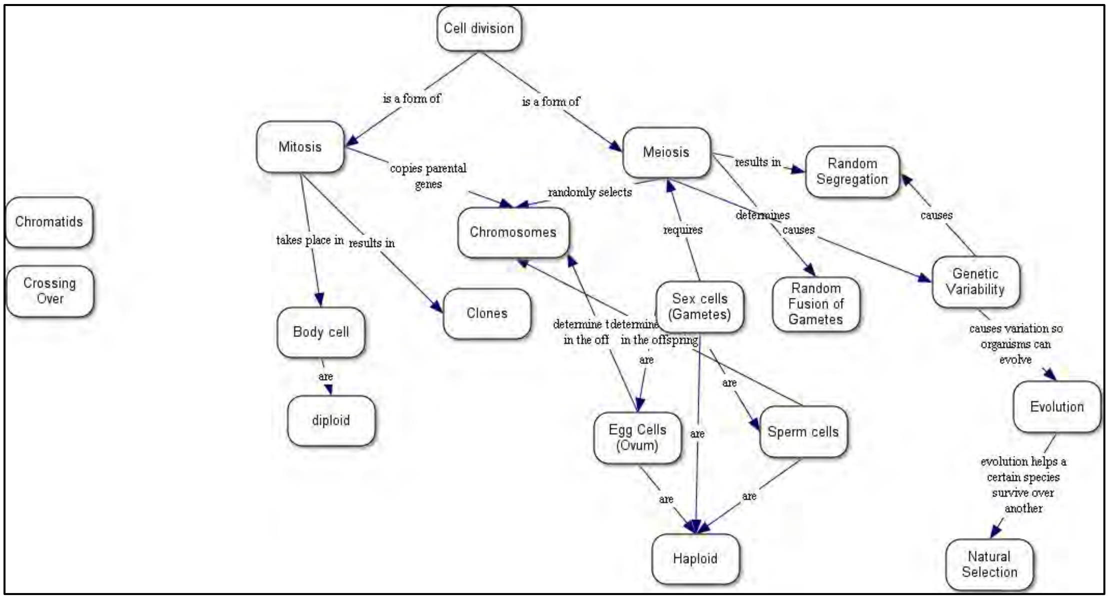


Figure 76: Study 1A concept map student E.

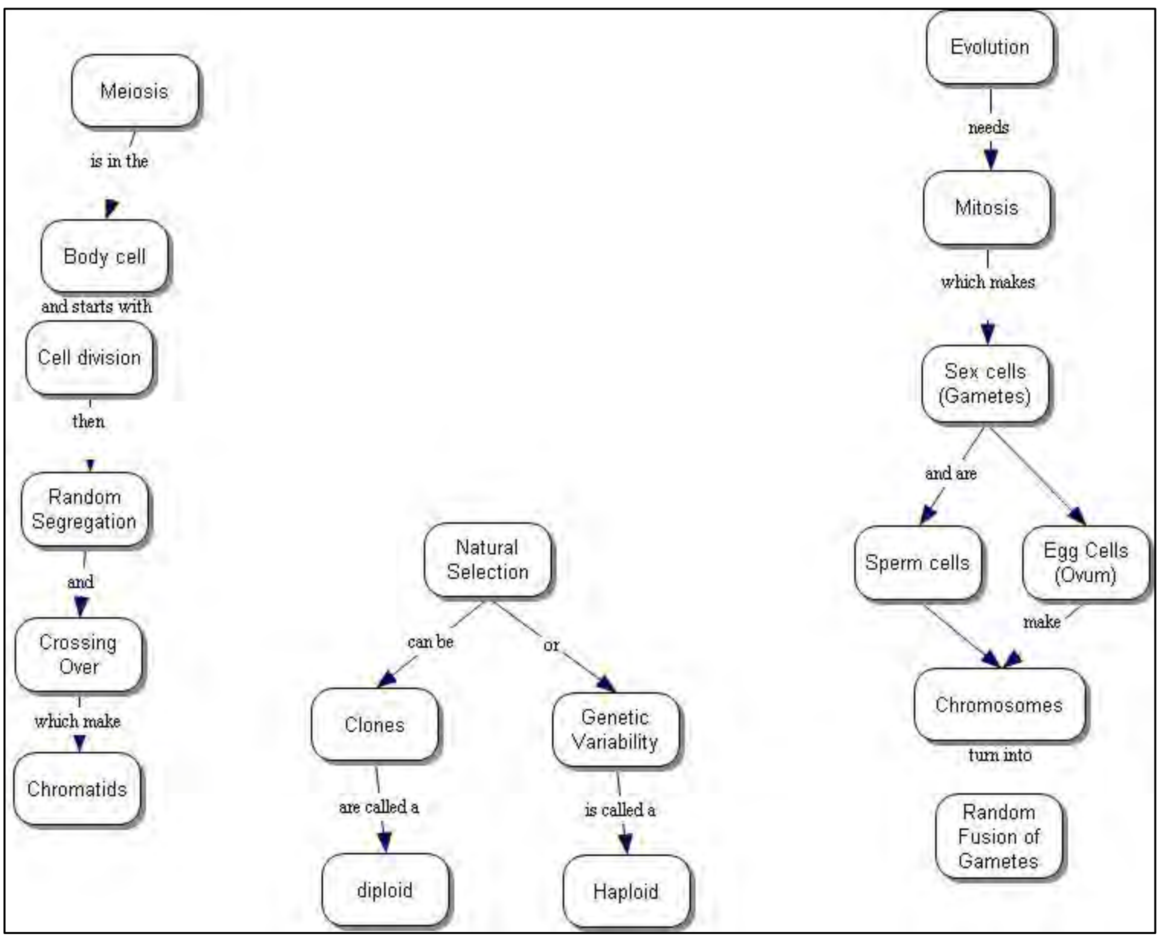


Figure 77: Study 1A concept map student F.

IV. Appendix Chapter 4: Study 1B

A. Study 1B KI rubrics for pretest/posttests

1) Prediction rubric
Is the outcome of mitosis more predictable than the outcome of meiosis?
(Circle One)…Yes……No
Explain your answer.

Yes → 1 (correct)
No → 2
No answer → 0
Multiple answers → 9

Table 66: Study 1B KI rubric item 1.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked (nothing scientific)		I don't know
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	Scientifically incorrect statements	Because something could go wrong. Because meiosis has more steps than mitosis/ is short/ is only half the process of mitosis. In meiosis egg and sperm meet randomly. Because Meiosis has the genes of both parents. Meiosis leads to four daughter cells, mitosis to only two. Both just make copy of themselves

			Mitosis goes from diploid to haploid. Something different happens every time *(no additional information)* Meiosis needs two organisms, mitosis only one. Mitosis has fewer mutations than meiosis
3	**Partial** Have a relevant idea but do not fully elaborate links between several ideas in a given context. Do not actually compare meiosis and mitosis	Mitosis is asexual reproduction, and meiosis sexual reproduction. Mitosis makes a copy of the cell. *(No comparison, does not mention what happens in meiosis)* Meiosis passes on only 50% of the parent's genes, but mitosis 100%.	Meiosis makes non-identical copies with random variations. Mitosis makes (exact) copies of itself. Mitosis you end up with the same exact DNA (split evenly) In mitosis it breaks evenly, in meiosis it doesn't break but just pulls. *[Anaphase I, Independent assortment of chromosomes]* Meiosis is done through sexual reproduction/ mitosis through asexual reproduction. In both of them mutations can happen.
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context.	Mitosis leads to two exact copies of the original cell (clones), meiosis leads to four genetically different cells.	Mitosis just makes a copy of itself, but meiosis turns out different each time!
5	**Complex** Elaborate two or more scientifically	Two or more correct statements. Same as in 4, but with more detailed explanation. E.g.	In mitosis chromosomes split in the middle and you get two identical cells, in

	valid links among ideas relevant to a given context.	Variation through -Independent assortment of chromosomes -Crossing over	meiosis they don't split in the middle and get randomly assigned to either side.

Within the same sentence containing …
-Two linked statements: One correct, one wrong -> Give the lower Code
-Two unlinked statement: One correct, one wrong -> Give the higher Code

2) Advantage Rubric
Does sexual reproduction (meiosis) have an advantage over asexual reproduction (mitosis) in organisms? *(Circle One)* *Yes* *No*
Explain your answer.

Yes → 1 (Correct, if consistent with explanation)
No → 2 (Correct, if consistent with explanation)
No answer → 0
Multiple answers → 9

Table 67: Study 1B KI rubric item 2.

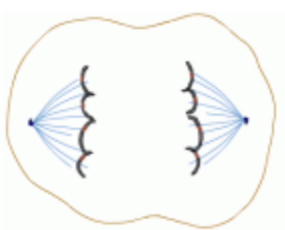
Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	Scientifically incorrect statements	The both have the same amount of organisms. Because mitosis is more common than meiosis. Mitosis is shorter/ less complex, therefore less things can go wrong. Because meiosis makes more offspring; leads to more/four daughter cells/chromosomes. Both are forms of

			reproduction/ They are the same. Meiosis develops new traits. Meiosis produces more chromosomes. Both processes are the same.
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context.	Meiosis increases genetic diversity/ is more random/ more possibilities/ variations in traits *(but no explanation why this is favorable).* Mitosis leads to clones. Meiosis improves evolution/ allows for easy adaptation the environment. With meiosis you have a greater chance of being successful. *Also correct:* Asexual reproduction does not need a partner.	Because meiosis leads to more <u>variation</u> *(without explanation why this is favorable)* Meiosis is able to adjust to changing environments *(without mention of variability)* Because asexual reproduction is <u>shorter</u>/ happens more *(Argument for 'no')* Meiosis can better compensate for genetic disorders (of one parent) Sexual reproduction needs a partner. Asexual can therefore reproduce more *(argument for 'no' answer)*
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context.	Sexual reproduction leads to genetic variety, which is an advantage for survival (-> Varieties to choose from for natural selection). *Also correct:* Through asexual reproduction, 100% of a parent's genes are passed on.	Sexual reproduction leads to a variation which is an advantage in the environment/ natural selection.
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a	The environmental conditions <u>change</u>. Genetic variety through sexual reproduction (Meiosis) allows for an increased chance that some organisms will be	Meiosis leads to <u>variations</u> that can enhance the chances of <u>survival</u> in a <u>changing environment</u>.

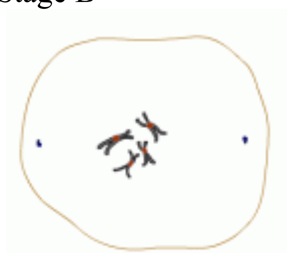
	given context.	better adapted to the new environment. Also correct: In a <u>stable</u> environment (which is rare!), asexual reproduction can be more advantageous because it creates more offspring, without the need of a partner, exact copies of an already successfully adapted organism	

3) Two Stage Rubric
The two pictures below show different stages of the skin cell division process.

Stage A



Stage B



Which of these two phases occurs *first*? (Circle One) Stage A Stage B

Stage A → 1
Stage B → 2 (correct)
No answer → 0
Multiple answers → 9

Explain your choice.

Table 68: Study 1B KI rubric item 3.

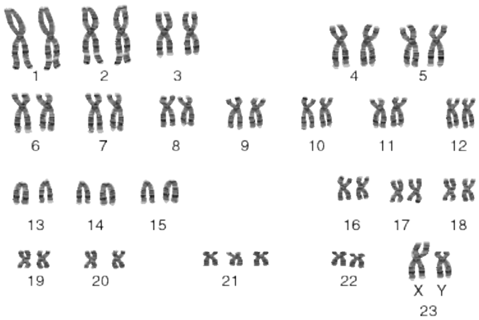
Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or “I don’t know.” Student writes some text, but it does not answer the question being asked.		

2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	Scientifically incorrect statements	They have not broken up yet *(without referencing to the picture or who and where)* Stage B is first *(repeating answer of 3a)*
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context.	**Only one stage:** Describes chromosome shape or movement correctly for <u>only one stage</u>. **Correct labeling, but no order**: Describes Stage B is prophase and stage A is anaphase but does not mention Prophase comes before Anaphase. **Order correct, but no labeling:** Describes prophase comes before anaphase but does not identify stage A or B with proper name. Chromosomes must condense and line up before they can split	
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context.	Elaborates one of the following links: **Correct <u>labeling</u> and <u>order</u>:** Stage B is <u>Prophase</u> and Stage A is Anaphase and says Prophase comes <u>before</u> Anaphase. **Chromosome shape about <u>both</u> stages:** Elaborates a difference between two phases scientifically in terms of <u>chromosome shape</u> **Chromosome movement about <u>both</u> stages:** Elaborates a difference between two phases scientifically in terms of <u>chromosome movement</u>	
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a	List two of the following links: **Labeling and order**: Stage B is Prophase and Stage A is Anaphase and says Prophase comes before Anaphase.	

	given context.	**Shape** Elaborates a difference between two phases scientifically in terms of chromosome shape **Movement**: Elaborates a difference between two phases scientifically in terms of chromosome movement	

4) Trisomy 21 Rubric

The diagram below represents the chromosomes of a person.

	(a) After examining the diagram above, a doctor determined that this person has a genetic disorder. Using the diagram above, write the evidence that supports the doctor's decision.

Looking at the diagram above, do you think this person has a genetic disorder?

Yes → 1 (correct)
No → 2
No answer → 0
Multiple answers → 9

Table 69: Study 1B KI rubric item 4.

Code	Level	Description	Examples
0	**No answer** Nothing is written.		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have	Pick <u>incorrect evidence</u> from the chart, which means anything other than trisomy in 21. Any wrong scientifically invalid	The person has three sets of chromosome #23, and chromosomes 13, 14, and 15 aren't crossed. The 23rd chromosome is deformed. There are only 23 pairs not 24 and the 23rd pair has a dominant and recessive

	incorrect/irrelevant ideas.	connections or ideas	trait. The extra chromosome 21 might lead to cancer.
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context.	Having three 21 chromosomes	There are three 21 chromosomes. *(without mentioning that two would be normal).* This person has down syndrome *(without mentioning the additional chromosome).*
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context.	Three 21 chromosomes & normal is two 21 chromosomes OR Three 21 chromosomes (Trisomy 21) = Down syndrome	There are three of the 21st chromosome. There should only be two homologous versions of every chromosome. Chromosome pair #21 has three sets of chromosomes, which is abnormal.
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context.	States both of the following: Having three #21 chromosomes-Down syndrome AND Additional scientifically information such as defective meiosis mechanisms that lead to this genetic this order.	This person has trisomy of chromosome 21 that results in Down syndrome. Normally there are only two of each chromosome. On chromosome 21 there is a trisomy which probably resulted in an error in meiosis most likely this person would have Down syndrome.

5) Turner Rubric

Females have two X chromosomes in the 23rd pair. A female with Turner's Syndrome has only one X chromosome. In which of the following cell division processes does this genetic disorder occur?

(Circle One) Mitosis Meiosis

Mitosis → 1
Meiosis → 2 (correct)
No answer → 0
Multiple answers → 9

Explain your answer.

Table 70: Study 1B KI rubric item 5.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	Scientifically incorrect statements	
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context.	Mentions that <u>mitosis for regular cell division</u> and <u>meiosis for sex cell division</u> but does **not** describe mechanisms.	
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context.	Elaborates either How XO combination occurs at this female (X from one parent and <u>O from the other parent)</u> OR How one parent can produce 'O' during meiosis	
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context.	Elaborates BOTH How XO combination occurs at this female (X from one parent and O from the other parent) AND How one parent can produce 'O' during meiosis	

B. Study 1B Concept map worksheet for students

You have heard a lot about meiotic cell division in the past section. It included many new terms and concepts.

You will create a concept map in which you connect/use ALL the important terms with each other. This will help you see the connections between all these new terms.
The important terms of this activity are (in random order):

- *Crossing Over*
- *Random Segregation (of chromosomes)*
- *Genetic Variability*
- *Diploid*
- *Clone*
- *Mitosis*
- *Egg Cells (Ovum)*
- *Cell division*
- *Chromosomes*
- *Chromatid*
- *Random Fusion of Gametes*
- *Evolution*
- *Sperm cells*
- *Body cell*
- *Haploid*
- *Meiosis*
- *Sex cells (Gametes)*
- *Natural Selection*

How to create a great concept map:
1. Look through the list of keywords and group them together in a way it makes sense to you.
2. Order the terms: More general terms are at the top, more detailed terms at the bottom.
3. Link the terms with arrows: Arrows can go in only one direction or both ways.
4. Label the connections with link words: Try to find short but precise link words.
5. A good concept map can be read like a long chain sentence from the top down.
6. Add cross-links between the terms (if needed).
7. Revise your concept map again
8. Check your concept map to make sure that you used ALL the terms from the table above.

C. Study 1B Essay worksheet for students

You have learned a lot about meiotic cell division in the past activities. They included many new terms and concepts.
Your assignment is to write an essay (400-500 words) in which you connect ALL of the important terms in the list below in meaningful sentences with each other. This will help you see the connections between all these new terms.

- *Crossing Over*
- *Random Segregation (of chromosomes)*
- *Genetic Variability*
- *Diploid*
- *Clone*
- *Mitosis*
- *Egg Cells (Ovum)*
- *Cell division*
- *Chromosomes*
- *Chromatid*
- *Random Fusion of Gametes*
- *Evolution*
- *Sperm cells*
- *Body cell*
- *Haploid*
- *Meiosis*
- *Sex cells (Gametes)*
- *Natural Selection*

Your essay topic is:
'You learned about mitosis and meiosis. Aunt Tilda claimed at the beginning of the TELS tutorial that certain traits of a baby could be predicted. Explain to her if you agree with her claims or not. To which degree can the traits of a baby be predicted? To which degree are they random? Support your answer with evidence from the TELS tutorial.'

-> Make sure that you use ALL the terms listed above in your essay. You can use terms several times if needed.

D. Study 1B KI rubric for concept maps

Table 71: Study 1B concept map rubric item 1: Crossing over (or Meiosis) contributes to genetic variability.

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	b) Crossing over is **caused by** genetic variability (Wrong direction) • Crossing over **by** genetic variability c) Genetic variability **allowed by** crossing over (vague) • Crossing over **makes** genetic variability (vague) • Genetic variability **includes** crossing over • Crossing over is **a form of** genetic variability • Crossing over is **an example** of genetic variability
3	Only arrow (no label) Indicate causality	Correct arrow	
4	Partially correct, but weak	Correct arrow	• Crossing over **creates** genetic variability • Genetic variability **through** crossing over • Crossing over **contributes** to genetic variability • Crossing over **results** in genetic variability • Crossing over **leads to** genetic variability • Crossing over **increases** genetic variability • Crossing over **causes** genetic variability
5	Fully correct, strong	Correct arrow	• Crossing over randomly breaks up and reforms Parental homologue chromosomes and thus increases Genetic variability

Table 72: Study 1B concept map rubric item 2: Random segregation of chromosomes contributes to genetic variability

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction (reversed causality) c) Correct arrow	b) Genetic variation causes random segregation (reversed causality) • Genetic variation uses random segregation (reversed causality) • Genetic variation is like random segregation. c) Genetic variation is allowed by random segregation (vague). • Random segregation is a form of crossing over
3	Only arrow (no label) Indicate causality	Correct arrow	
4	Partially correct, but weak	Correct arrow	• Random segregation of chromosomes results in genetic variation. • Random segregation causes genetic variation. • Genetic variation through random segregation of chromosomes. • Random segregation contributes to genetic variation. • Random segregation leads to genetic variation. • Random segregation increases genetic variation. • Random segregation produces genetic variation.
5	Fully correct, strong	Correct arrow	• Random segregation of chromosomes leads to a different set of chromosomes in each gamete and thus increases genetic variation.

Table 73: Study 1B concept map rubric item 3: Random fusion of gametes contributes to genetic variability

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	

2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	d) Genetic variability is random fusion of gametes • Random Fusion from genetic variability
3	Only arrow (no label) Indicate causality	Correct arrow	
4	Partially correct, but weak	Correct arrow	• Random fusion of gametes results in genetic variation. • Random fusion of gametes contributes to genetic variation. • Random fusion of gametes leads to genetic variation. • Random fusion of gametes causes genetic variation. • Random fusion increases genetic variation.
5	Fully correct, strong	Correct arrow	• Random fusion of gametes combines one sperm cell (one out of millions) with one egg cell (one out of 400,000) thus increasing genetic variation.

Table 74: Study 1B concept map rubric item 4: Natural selection requires genetic variability

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	
2	Inconsistent/vague : a) Only line (indicates connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	c) Genetic variability leads to natural selection (causality) • Genetic variability to natural selection • Natural selection is caused by genetic variability • Natural selection results in genetic variability • Genetic variability causes natural selection • Genetic variability contributes to natural selection • Natural selection happens because of genetic variability • Natural selection is cause for genetic variability
	Only arrow (no	Correct arrow	

3	label) Indicates causality		
4	Partially correct, but weak	Correct arrow	• Genetic variability needed for natural selection • Genetic variability creates diversity in the population which leads to natural selection • Natural selection requires genetic variability • Genetic variability is essential for the process of natural selection • Natural selection acts on genetic variability • Genetic variability is opposite to natural selection • Natural selection changes genetic variability
5	Fully correct, strong	Correct arrow	• Genetic variability contributes the raw material which is then filtered by natural selection • Natural selection selects traits that show improved fitness out of the pool of genetic variability.

Table 75: Study 1B concept map rubric item 5: Evolution requires natural selection

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	• Evolution helps a certain species to survive over Another through natural selection
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	b) Natural selection allows for evolution (vague) • Evolution leads to natural selection (causality) c) Natural selection helps evolution (-> vague) • Natural selection turns into evolution • Natural selection makes evolution • Natural selection contributes to evolution (vague) • Natural selection filters evolution • Evolution by natural selection (vague) • Evolution is cause for natural selection (causality)
3	Only arrow (no label)	Correct arrow	

	Indicate causality		
4	Partially correct, but weak	Correct arrow	• Natural selection drives evolution • Natural selection causes evolution • Natural selection results in evolution • Natural selection leads to evolution
5	Fully correct, strong	Correct arrow	• Natural selection selects traits which are favorable for a certain environment and thus drives evolution • Natural selection is the mechanism where traits are selected and thus drives evolution

Table 76: Study 1B concept map rubric item 6: Genetic variability is the basis of evolution

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow	
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	c) Evolution is caused by genetic variability (causality) Genetic variability speeds up evolution Evolution allows genetic variability (causality)
3	Only arrow (no label) Indicate causality	Correct arrow	
4	Partially correct, but weak	Correct arrow	• Genetic variability is basis of evolution • Evolution needs genetic variability • Genetic variability causes variations so that organisms can go through evolution • Genetic variability feeds evolution • Evolution requires genetic variability • Genetic variability allows for evolution • Genetic variability helps to cause evolution • Genetic variability contributes to evolution
5	Fully correct, strong	Correct arrow	• Genetic variability delivers the raw material for natural selection that chooses the best suited for the current environment, leading to evolution. • Evolution can through natural selection decrease genetic variability

E. Study 1B KI rubric for essays

1) Identify six core ideas in each essay.
2) Generate a concept map according to connections between core ideas.
3) Analyze concept map according to KI rubric [See table 77].

Table 77: Study 1B KI rubric for essays.

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	No connection at all
1	Wrong label	Wrong arrow	Clearly wrong connection
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow	Very ague (general) connection Wrong causality
3	Only arrow (no label) Indicate causality	Correct arrow	Unspecified but causal connection (A leads to B)
4	Partially correct	Correct arrow	Description but with somewhat less precise
5	Fully correct, strong	Correct arrow	Full description of connection (like in concept map rubric)

V. Appendix Chapter 5: Study 2

A. Study 2 KIM training worksheet

Make a map of your knowledge!

Training Phase
"During this project, you will create several concept maps. These graphical maps between important keywords will help you see the connections between the important ideas."

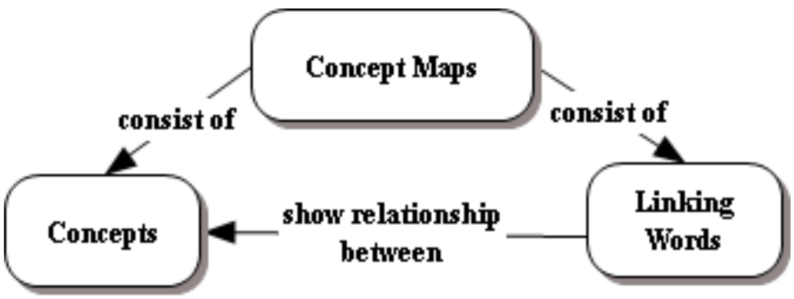


Figure 78: Study 2 Demonstration concept map.

Follow these steps to create your map:

9. **First explore the list of concepts – called 'parking lot'.**
10. **Look for two concepts that have a connection, e.g. 'Hungry person needs a phone'**
11. **Write the concepts into the drawing area to the right.**
12. **Link the terms with arrows. Arrows can go in only one direction or both ways.**
13. **Label the connection with link words: Try to find short but precise link words.**
14. **Add the remaining concepts to your map.**
15. **Revise your concept map and check your concept map to make sure that you used all the terms and added all links you think are important.**

Practice Map (5 min)

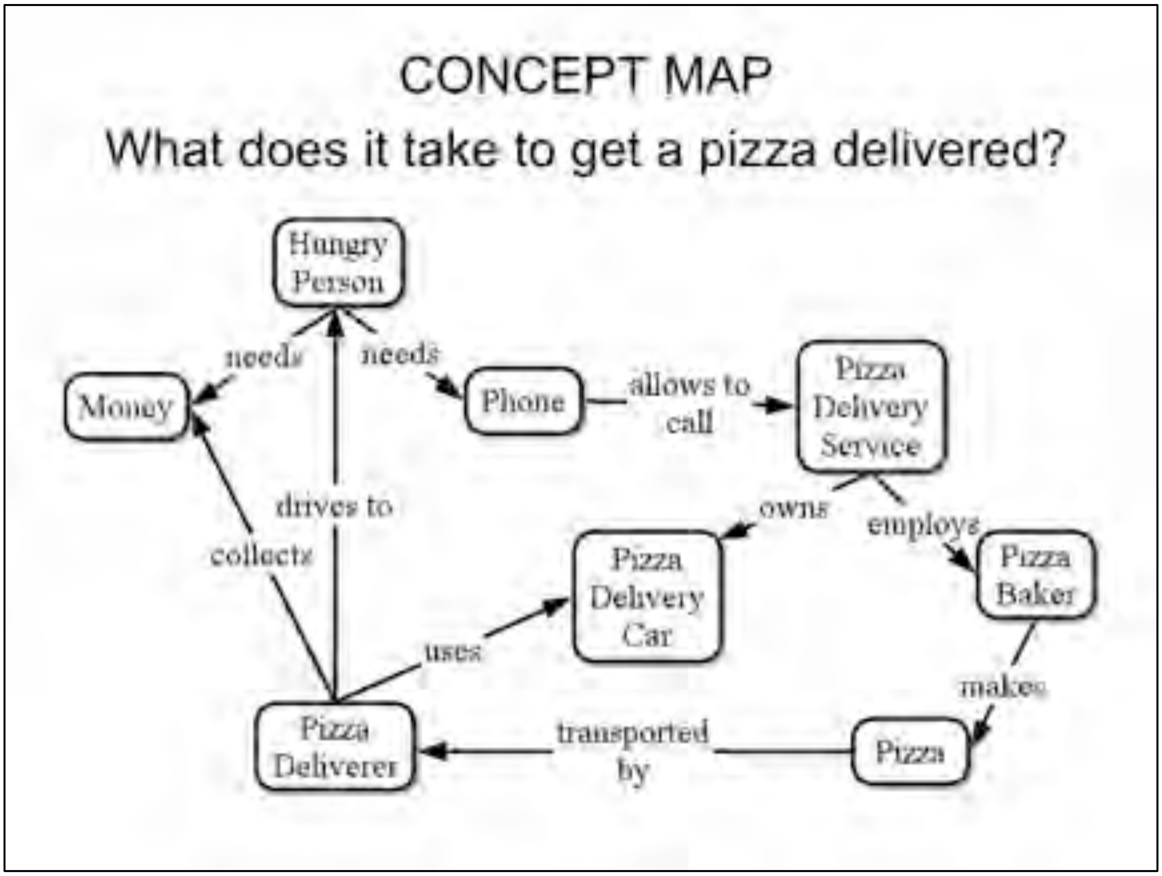


Figure 79: Study 2 training concept map.

Criteria for a good concept map:

- *Groups of concepts that belong together.*
- *You can read along a chain (or its branches) like a long sentence.*

B. Study 2 Pretest/posttest Knowledge Integration rubrics

Item 1 (Sex prediction): Understanding of sex determination
Item 2 (Mitosis instead of meiosis): Understanding of meiosis as "reduction division"
Item 3 (Seedless grapes): Understanding of advantage of sexual diversity through sexual reproduction for survival
Item 4 (Fish example): Understanding of mutation as source of genetic diversity/ Passing on genes to the next generation (Bottleneck effect)/ Change of gene pool/ Genetic determination of traits for survival
Item 5 (Concept map): Understanding of conceptual connections between genetic terms/ Ability to read a concept map

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Item 1 (Pre-test) – Item 2 (Post-test)
a) Mrs. and Mr. Smith have four children together. What do you predict for the fifth child?

Table 78: Study 2 rubric item 1A.

Pre-Test	Post-Test
Most likely another girl → 1 Most likely a boy → 2 Equal chances for a boy or a girl → 3 Multiple anwers → 9 No answer → 0	Equal chance for a boy or a girl. → 1 Most likely a girl → 2 Most likely another boy. → 3 Multiple anwers → 9 No answer → 0

b) Explain your answer.

Table 79: Study 2 KI rubric item 1B.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		• I don't know • No idea
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.		• The male/female gene seem to be dominant.
3	**Partial**		• Because you can never

	Have relevant ideas but do not fully elaborate links between them in a given context. -Describes reasons for either sexual OR asexual reproduction WITHOUT explanation.		tell. (No mention of sperm cell or probability)
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.	• Probability does not have a memory. -> Always 50% chance.	• It depends on the father's X and Y-chromosomes. (Sperm cells) • Because there is always a 50/50 chance (Probability)
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context. -Gives elaborate reasons (what kind of advantage) for BOTH sexual and asexual reproduction.	• Each sperm cell can carry either an X- or a Y-chromosome. • There is an equal chance for each sperm cell to fertilize the egg cell. • Probability does not remember previous cases/ has no memory.	• Sex Cells + Probability

Item 3) Advantage of sexual reproduction Rubric
Why do grapes (with seeds) that reproduce sexually have a greater chance to survive a new disease than (seedless) grapes that reproduce asexually?
Explain your answer.

Table 80: Study 2 KI rubric item 3.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		• I don't know • No idea

2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.	Scientifically incorrect statements OR just rephrase the question. e.g. plants eat their seeds to survive e.g. diseases kill the plant but the seeds survive	• Because grapes with seeds can replant themselves • Because they can fight of the disease better (no explanation) • Because they have seeds to fight off the disease • Seeds help resist disease • Because seeds have a protective shell • The seeds allow the pass on disease free genes to the next generation. • They have a stronger immune system because of the seeds.
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context. -Describes reasons for either sexual OR asexual reproduction WITHOUT explanation.	• Sexual reproduction increases GENETIC DIVERSITY/ is more random/ more possibilities/ variations in traits *(but no explanation why this is favorable -> increases chances of survival).*	• Sexual reproduction leads to better combination of genes. • They pass on different genes. • The seedless grapes are all genetically identical.
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.	• SEXUAL reproduction leads to higher GENETIC DIVERSITY that improves SURVIVAL chances in a changing environment (e.g. new disease)	• Sexual reproduction allows for combination of genes that is better suited to the environment. • Seedless grapes are all the same, but grapes with seeds have better chance and traits to survive [but does not mention GENES]
5	**Complex** Elaborate two or more scientifically valid	• SEXUAL reproduction leads to higher GENETIC DIVERSITY that improves	• Grapes that reproduce sexually have more genetic diversity in their

	links among ideas relevant to a given context. -Gives elaborate reasons (what kind of advantage) for BOTH sexual and asexual reproduction.	SURVIVAL chances in a changing environment (e.g. new disease) • + ASEXUAL reproduction leads to clones/ identical organisms with low genetic diversity. • OR additional explanation of mechanism for diversity (crossing over/assortment of chromosomes/ random fusion of gametes)	gene pool through crossing over and independent assortment. This allows for a greater array of organisms from which natural selection may choose – allowing some to survive and propagate. On the other hand, asexually produced organisms have less genetic diversity (clones)

Item 4) Fish Rubric
Pablo has a fish tank with guppies that need a water temperature between 65°F and 75°F. One night, the thermostat failed and the temperature dropped to 50°F. All but two guppies, a male and a female, died
A) Explain the survival of these two fish?

Table 81: Study 2 KI rubric item 4A.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		• I don't know • No idea
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.	• Scientifically incorrect statements	• The surviving fish got lucky • They were better/ tougher/ fittest. • The surviving fish were younger than the others. • Survival of the fittest. [Too general] • They ate all the food. • Natural Selection.
3	**Partial** Have relevant ideas but do not fully elaborate links	• The survivors ADAPTED to the changed environment (without explanation why/how)	• They were the most adapted (no connection to genes) • They could adapt better.

	between them in a given context. -Describes reasons for either sexual OR asexual reproduction WITHOUT explanation.		• They had good genes. • They received the trait [not genes] from the parents.
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.	• Describes a GENETIC reason for the survival (but does not mention mutation)	• The survivors had genes that allowed adaptation to the lower temperature. • They had the genes/alleles to survive. • The survivors received a trait [not gene] from their parents that helped them survive.
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context.	• Cites MUTATION as the reason for the GENETIC difference of the survivors.	• The two surviving fish had a (random) mutation that made them more resistant to low temperatures. • These fish had temperature tolerant genes passed on from their parents.

B) The surviving male and female fish had many offspring. Do the offspring of the survivors have the same genetic diversity as the original fish in Pablo's tank?

B-I) Multiple Choice
More genetic diversity → 1
Less genetic diversity → 2 (Correct choice)
The same → 3
No answer → 0
Multiple answers → 9

B-II) Explain your choice

Table 82: Study 2 KI rubric item 4B-II.

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is		• I don't know • No idea

	irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		• I guessed
	Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.	Scientifically incorrect statements	• There are only two fish (confuses # of fish and diversity) • They are all the same type/species of fish [confusion of species and genetic diversity] • They are smaller. [confusion that the offspring is less diverse because they are smaller] • The mutation of the parents caused increase in genetic diversity [confusion of mutation in the parents and genetic diversity of the whole population] • Because half of each parent gives their genetic material. • Because they get genes from both parents. • Have more genetic diversity because they survived. [Confusion of genetic diversity with fitness] • There are only two genes left to choose from. [Confusion that the parent fish had only one gene each e.g. the mutated one] • The offspring is the same as the parents [the same what? Clones?] • More diverse because they have both mother's

			and father's chromosomes [confusion of population diversity and recombination]
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context. -Describes reasons for either sexual OR asexual reproduction WITHOUT explanation.		• They have the same genes as the parents [does not mention LIMITED GENETIC DIVERSITY] • Because all had the same parents • Because there were only two fish to get genes from.
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.		• Because their parents were the survivors and they passed on their genes. [No link to genetic diversity] • Less genetic diversity because there will be fewer diverse genes to choose from [NO link to parents] • There are only two fish to make up the gene pool.
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context.	-> Connection: ALL current fish offspring of same PARENTS that had only limited GENETIC DIVERSITY • All genes of the offspring are inherited from the parents, including the mutation for low temperature resistance. • Parents have only limited amount of genetic diversity -> Offspring also limited genetic diversity	• The gene pool (Genetic variety) less diverse because all organisms share the same GENES of the original surviving pair/parents. [Bottleneck effect/ Founder effect]

C-I PRE-TEST) All or most will die [All but two will die] → 1
About half will survive → 2
All or most will survive → 3 (Correct choice)
No answer → 0
Multiple answers → 9

C-II PRE-test) Explain your choice.

Table 83: Study 2 KI rubric item 4C-II (pretest).

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.		I don't know No idea
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.	Scientifically incorrect statements	• Because it already happened the first time / The same thing will happen. • Good genes • Because they got stronger • Some might survive by chance. • Because of genetic diversity, some fish would still not be resistant to the cold. • The fish have genetic diversity for different temperatures. [Confusion of tolerance and genetic diversity]
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context. -Describes reasons for either sexual OR		• Because they were fit for a cold environment [NO mention of GENES or INHERITANCE] • These fish have to genes to adapt [but no mention of inheritance from parents]

	asexual reproduction WITHOUT explanation.		• Mom and Dad could survive it and they passed that trait down [no mention of GENES] • [Good observation: If the mutation were recessive, then half of the offspring would have the trait.]
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.		
5	**Complex** Elaborate two or more scientifically valid links among ideas relevant to a given context.	• The current fish are all offspring of the same PARENTS and therefore (have a high chance of having) inherited the GENE for 'low temperature tolerance'.	

C-I POST-TEST) All but two will die → 1 (Alternative correct choice)
About half will survive → 2
All or most will survive → 3 (Correct choice)
No answer → 0
Multiple answers → 9
C-II POST-test) Explain your choice.
NOTE: There are two ways to argue in this question:

a) The mutation was only a 'low temperature tolerance'. Therefore most would die in high temperature -> Option 1 would be most likely.
b) The mutation was a 'general temperature tolerance'. Therefore most would survive also in higher temperature -> Option 3 would be most likely.

Table 84: Study 2 KI rubric item 4C-II (posttest).

Code	Level	Criteria	Examples
0	No Answer		
1	**Offtask** Response is irrelevant or "I don't know." Student writes some		I don't know No idea

	text, but it does not answer the question being asked.		
2	**Irrelevant/Incorrect** Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas.	Scientifically incorrect statements	• Because some fish became more diverse [doesn’t address mutation] • They’ll learn to adapt. • [Confusion: More genetic diversity in a population is no guarantee for survival of an individual] • [Confusion: Adaptation/’get used to a certain environment’ vs. genetic changes] • Genetic diversity (just the term without explanation) • Survival of the fittest • The same thing will happen.
3	**Partial** Have relevant ideas but do not fully elaborate links between them in a given context. Describes reasons for either sexual OR asexual reproduction WITHOUT explanation.	• Talks about traits/adaptation instead of genes/mutations	• They were adapted to the cold and could not survive the warmer temperature. • They inherited the temperature tolerance from their parents. [No mention of possible new mutations or genes].
4	**Basic** Elaborate a scientifically valid link between two ideas relevant to a given context. -Describes reasons WITH explanation.	• NEW MUTATION for hot temperature tolerance might be possible.	
5	**Complex**	• Being the offspring of the	

	Elaborate two or more scientifically valid links among ideas relevant to a given context.	cold-temperature survivors, most fish will have the GENE FOR COLD temperature tolerance. • They will most likely NOT SURVIVE in hotter water. • NEW MUTATION for hot temperature tolerance might be possible.	

5) Mini-concept map
a-I) Multiple choice:
Everything is correct → 1
There is an error → 2
No answer → 0
Multiple answers → 9

a-II) Circle in map

Table 85: Study 2 rubric item 5.

Pre-Test	Post-Test
Gene & Chromosome → 1 Alleles & Mutation → 2 Nucleus & Cells → 3 Other circle → 4 No circle → 0 Multiple circle → 9	Genetic Diversity & Evolution → 1 Environment & Natural Selection → 2 Environment & Fitness → 3 Other circle → 4 No circle → 0 Multiple circle → 9

b) Suggest a correction
Correct improvement → 1
Incorrect improvement → 2
No answer → 0

C. Study 2 Knowledge Integration Map coding

A) Placement:

Did students understand onto which level an idea belongs to?

→ Code for each idea and each level.

B) Cross-connections:

Number and quality of cross-connections?

→ Number of cross-connections

→ Quality of link-label of the connections (code for missing, incorrect, correct)

Did students make certain essential connections, e.g. gene and evolution?

C) Review:

What kind of review did the students provide? For example, link, idea placement, off-topic, missing.

Was the review an improvement (correct) or worsening (incorrect)?

D) Revision:

How did the students respond to the review?

Agreement, Disagreement, Off-topic, Empty

Improvement (correct), worsening (incorrect)

A) Placement

1) Each idea and each level gets a code.

2) Put all the codes into an excel sheet.

3) Then recode for correct/incorrectly placed ideas (0=incorrect) (1=correct).

Phase I codes:

Table 86: Study 2 KIM placement.

Level	Code
Missing	0
DNA-Level	1
Cell-Level	2
Organism/Population-Level	3

Table 87: Study 2 KIM possible connections rubric. 15 possible combinations (n=6, r=2)

Connection	Cross-link #	Cross-Link (normative)
Genetic Variability + Mutation	1	2
Genetic Variability + Cell	2	3
Genetic Variability + Allele	3	2
Genetic Variability + Natural Selection	4	0 (Non-Crosslink)
Genetic Variability + Gene	5	2
Mutation + Cell	6	1
Mutation + Allele	7	0 (Non-Crosslink)
Mutation + Natural Selection	8	2

Mutation + Gene	9	0 (Non-Crosslink)
Cell + Allele	10	1
Cell + Natural Selection	11	3
Cell + Gene	12	1
Allele + Natural Selection	13	2
Alelle + Gene	14	0 (Non-Crosslink)
Natural Selection + Gene	15	2

Quality of connection

Table 88: Study 2 KIM quality of connection rubric.

Code	Link label quality	Link Arrow	Examples
0	None (missing connection)	None	
1	Wrong label	Wrong arrow direction	
2	Inconsistent/vague : a) Only line (indicate connection, but unspecified) b) Correct label c) Incorrect label	a) Only line b) Wrong arrow direction c) Correct arrow direction	b) Crossing over is caused by genetic variability (Wrong direction) • Crossing over by genetic variability c) Genetic variability allowed by crossing over (vague) • Crossing over makes genetic variability (vague) • Genetic variability includes crossing over • Crossing over is a form of genetic variability • Crossing over is an example of genetic variability
3	Only arrow (no label) Indicate causality	Correct arrow direction	
4	Partially correct, but weak	Correct arrow direction	• Crossing over creates genetic variability • Genetic variability through crossing over • Crossing over contributes to genetic variability • Crossing over results in genetic variability • Crossing over leads to genetic variability • Crossing over increases genetic variability • Crossing over causes genetic variability
5	Fully correct, strong	Correct arrow direction	• Crossing over randomly breaks up and reforms Parental homologue chromosomes and thus increases Genetic variability

Cross-Link-Coding

Cross-Link	**Code**
No cross-link	**0**
DNA - Cell	**1**
DNA - Pop	**2**
Cell - Pop	**3**

Table 89: Study 2 KIM review rubric.

Kind of review	**Example**	**Code**
Missing		0
Off-Topic	I am tired	1
General	All is correct Make more specific links labels. Make links between your concepts.	2
Critique of concept placement	Mutation should be in DNA-Level	3
Critique of missing concept	You forget to add 'mutation'.	4
Critique of arrow-direction	Your arrow should go in the other direction	5
Critique of missing link	You missed to connect 'mutation' and 'allele'.	6
Critique of missing link-label	Genetic variability does not affect alleles (review of an un-labeled link)	7
Critique of existing link-label	Connection between 'Allele' and 'Mutation' should be 'leads to' and not 'includes'.	8

Table 90: Study 2 KIM revision rubric.

Kind of revision	**Example**	**Code**
Missing		0
Off-Topic	I am tired	1
General	I would fix it in the future.	2
Revision of concept placement	Mutation should be in DNA-Level	3
Revision of missing concept	You would add 'mutation'.	4
Revision of arrow-direction	I would change arrow direction	5
Revision of missing link	I would add link between 'mutation' and 'allele'.	6
Revision of missing link-label	I would add link-label between 'mutation' and 'allele'.	7
Revision of existing link-label	I would change link-label between 'mutation' and 'allele'.	8
Decision NOT to make a revision	I do not agree with the reviewers.	9

Table 91: Study 2 KIM review content rubric.

Connection	**Code**
None	0
Genetic Variability + Mutation	1
Genetic Variability + Cell	2

Genetic Variability + Allele	3
Genetic Variability + Natural Selection	4
Genetic Variability + Gene	5
Mutation + Cell	6
Mutation + Allele	7
Mutation + Natural Selection	8
Mutation + Gene	9
Cell + Allele	10
Cell + Natural Selection	11
Cell + Gene	12
Allele + Natural Selection	13
Allele + Gene	14
Natural Selection + Gene	15
Placement: Genetic variability	16
Placement: Mutation	17
Placement: Cell	18
Placement: Allele	19
Placement: Natural Selection	20
Placement: Gene	21

Table 92: Study 2 KIM quality of revision rubric.

Specific revision suggested?	**Correctness of revision suggestion**	**Code**
Empty		0
No	Cannot be determined	1
Yes	Incorrect	2
Yes	Partially correct	3
Yes	Fully correct	4

D. Study 2 Knowledge Integration Map worksheets

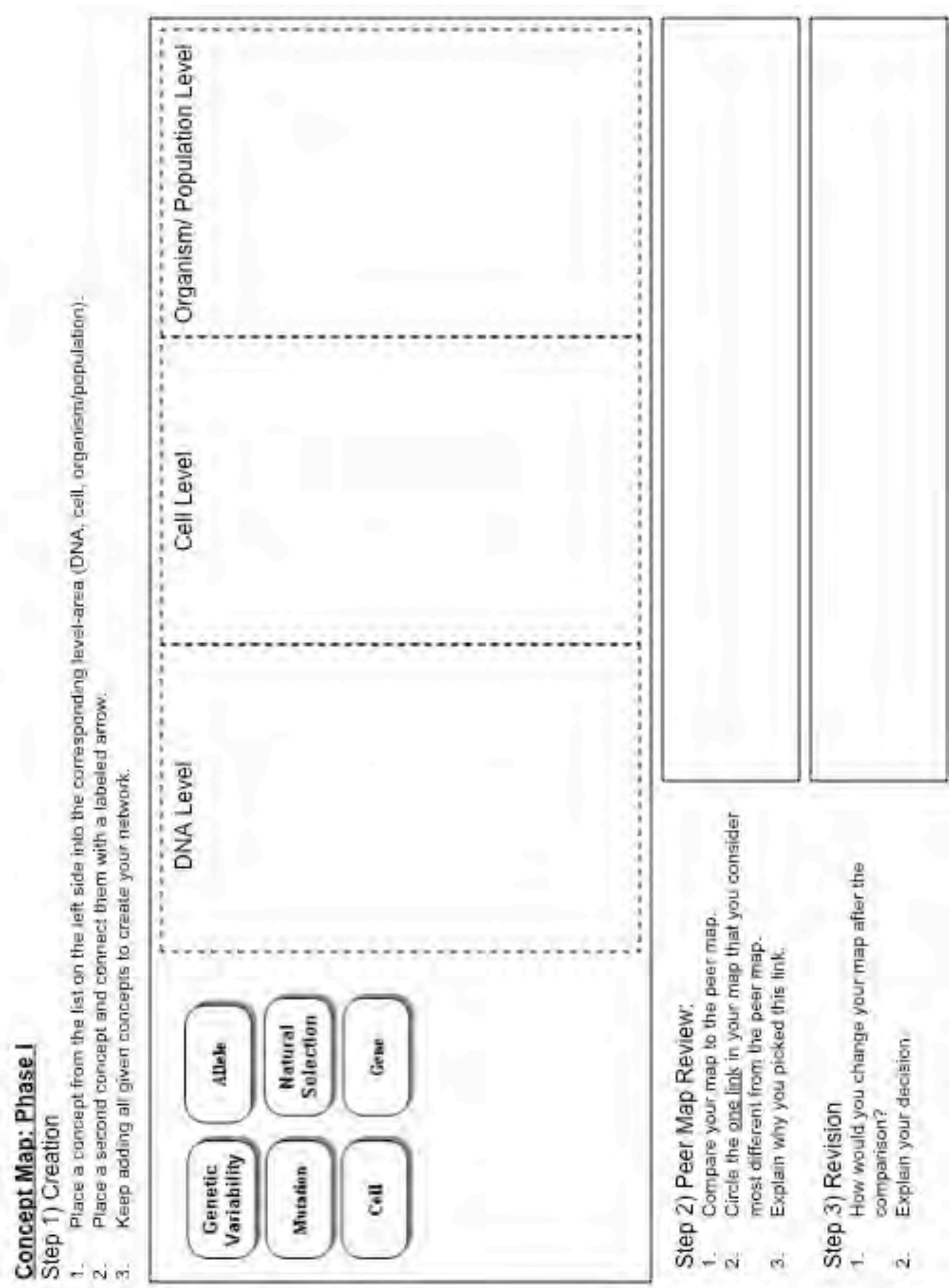


Figure 80: Study 2 KIM worksheet 1 (peer review group).

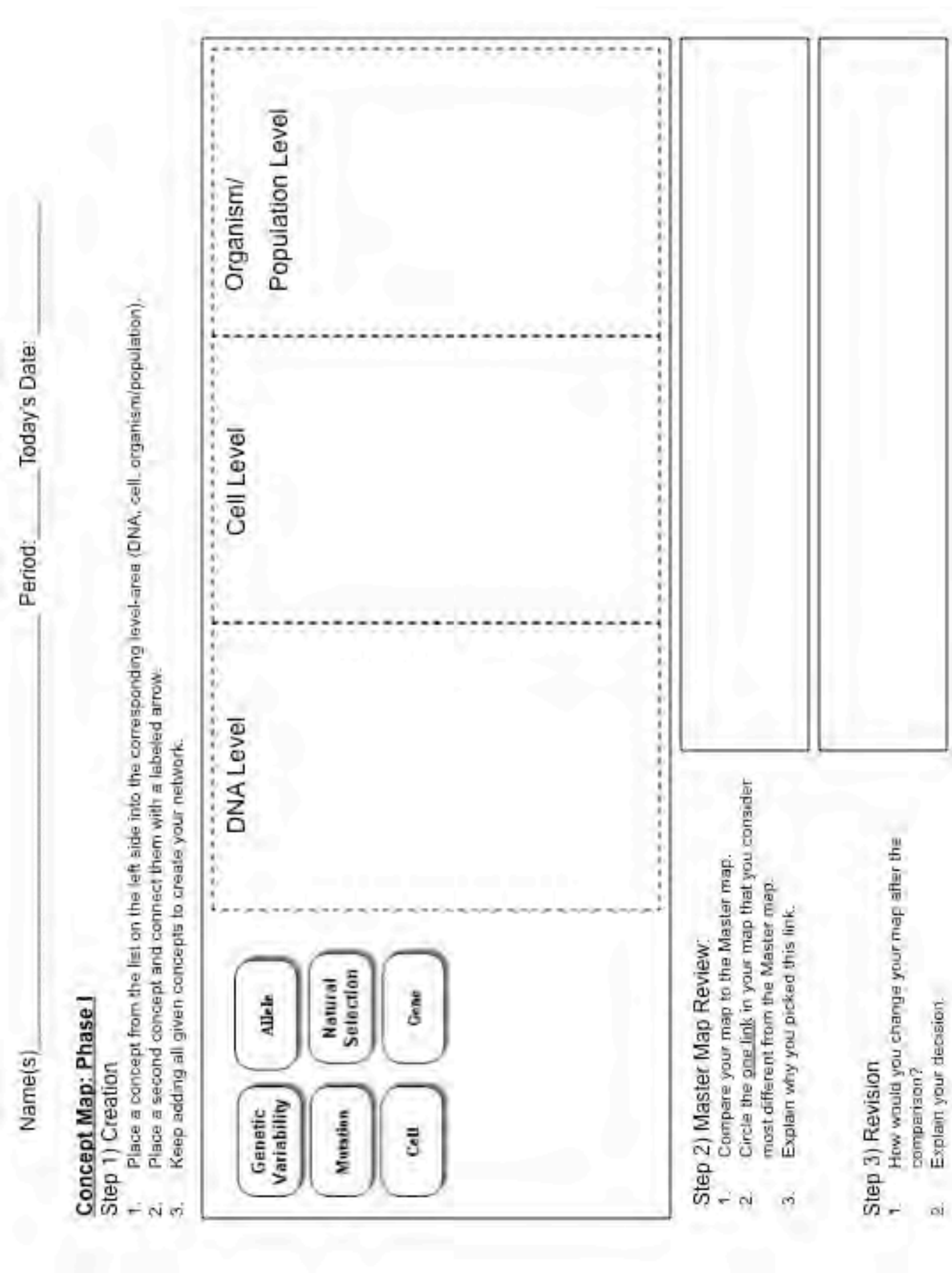
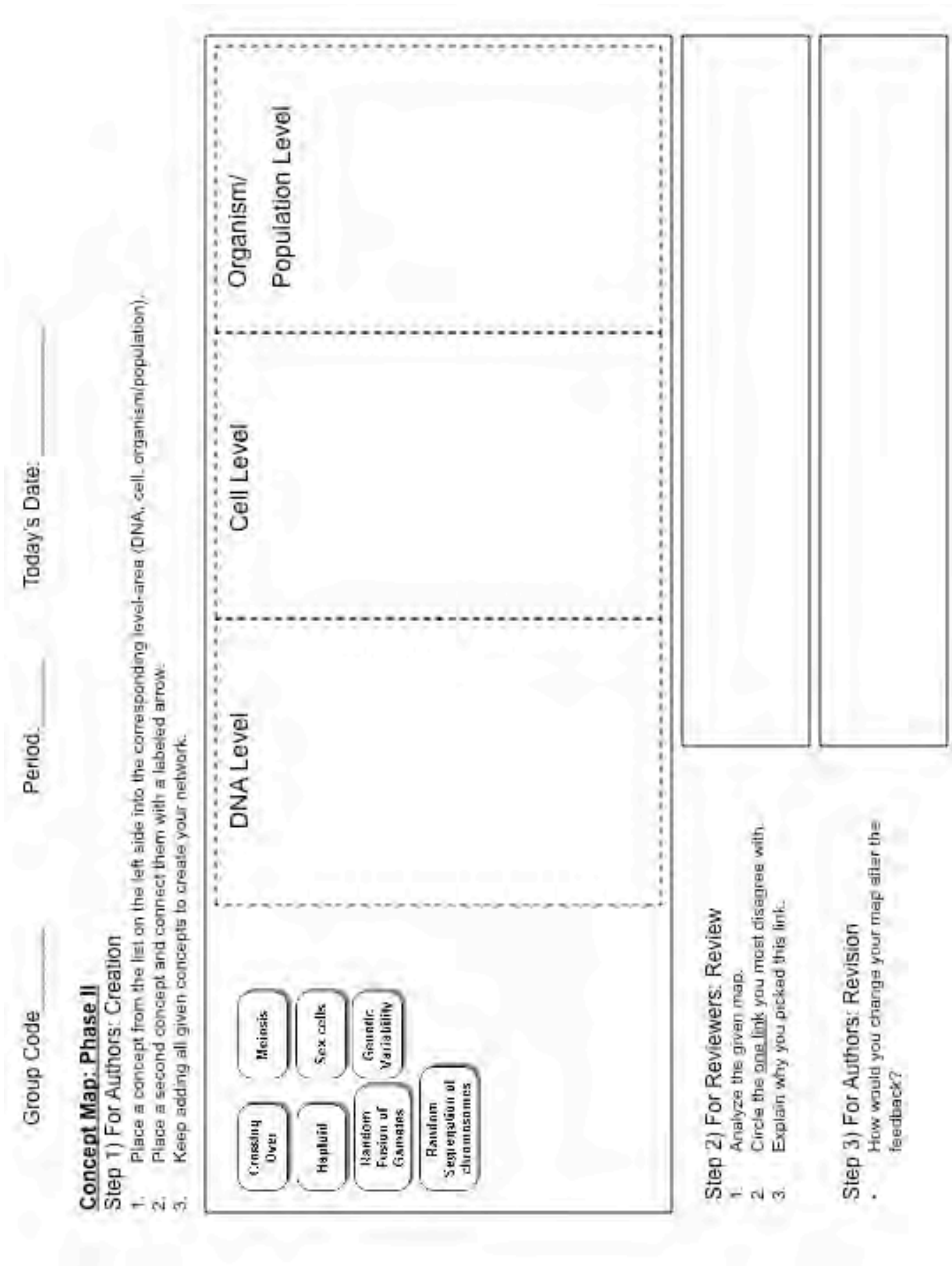


Figure 81: Study 2 KIM worksheet 1 (expert comparison group).


Group Code______ Period______ Today's Date: ______

Concept Map: Phase II

Step 1) For Authors: Creation

1. Place a concept from the list on the left side into the corresponding level-area (DNA, cell, organism/population).
2. Place a second concept and connect them with a labeled arrow.
3. Keep adding all given concepts to create your network.

Crossing Over

Meiosis

Haploid

Sex cells

Random Fusion of Gametes

Genetic Variability

Random Segregation of chromosomes

DNA Level

Cell Level

Organism/ Population Level

Step 2) For Reviewers: Review

1. Analyze the given map.
2. Circle the one link you most disagree with.
3. Explain why you picked this link.

Step 3) For Authors: Revision

- How would you change your map after the feedback?

Figure 82: Study 2 KIM worksheet 2 (peer review group).

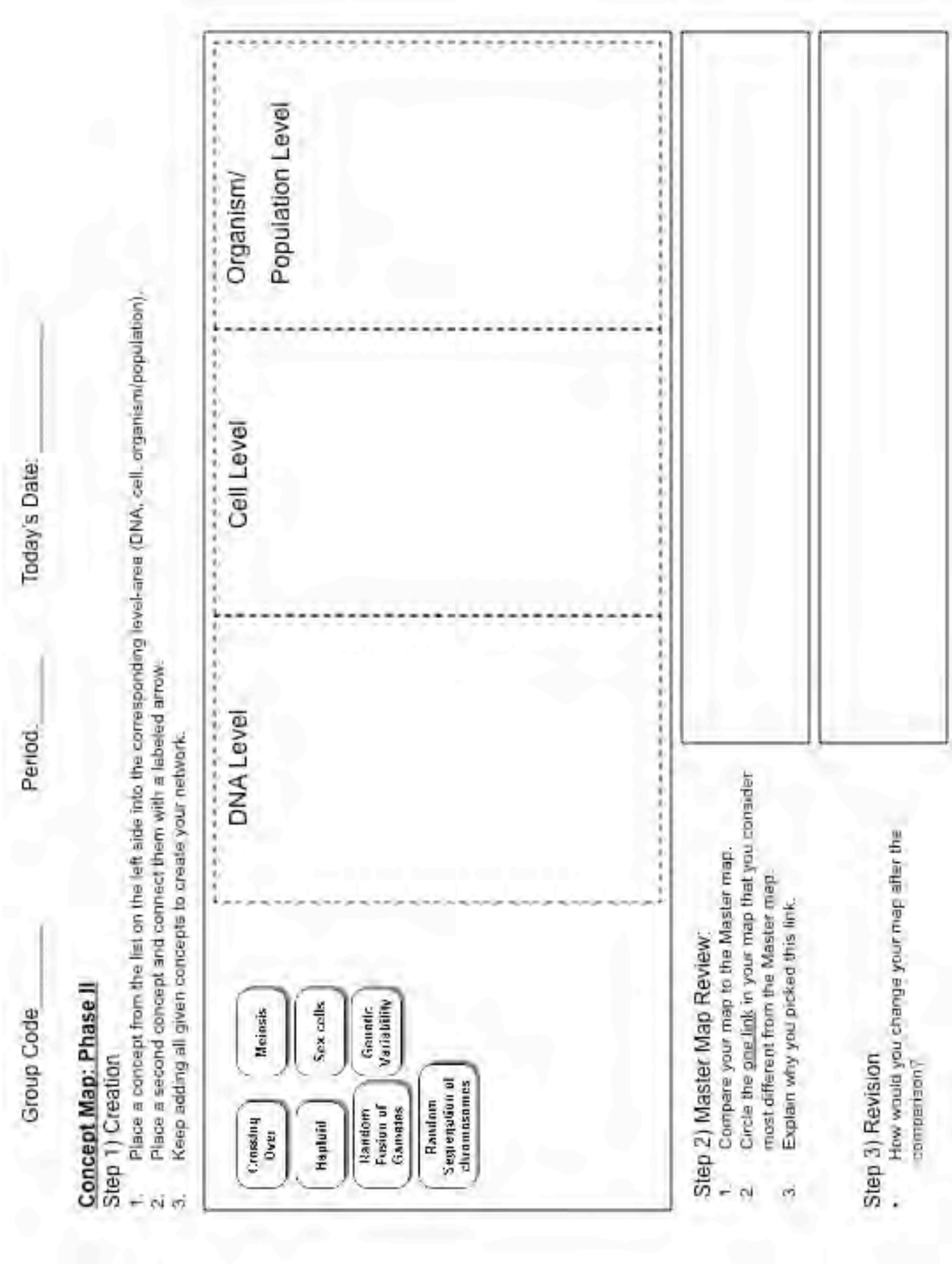
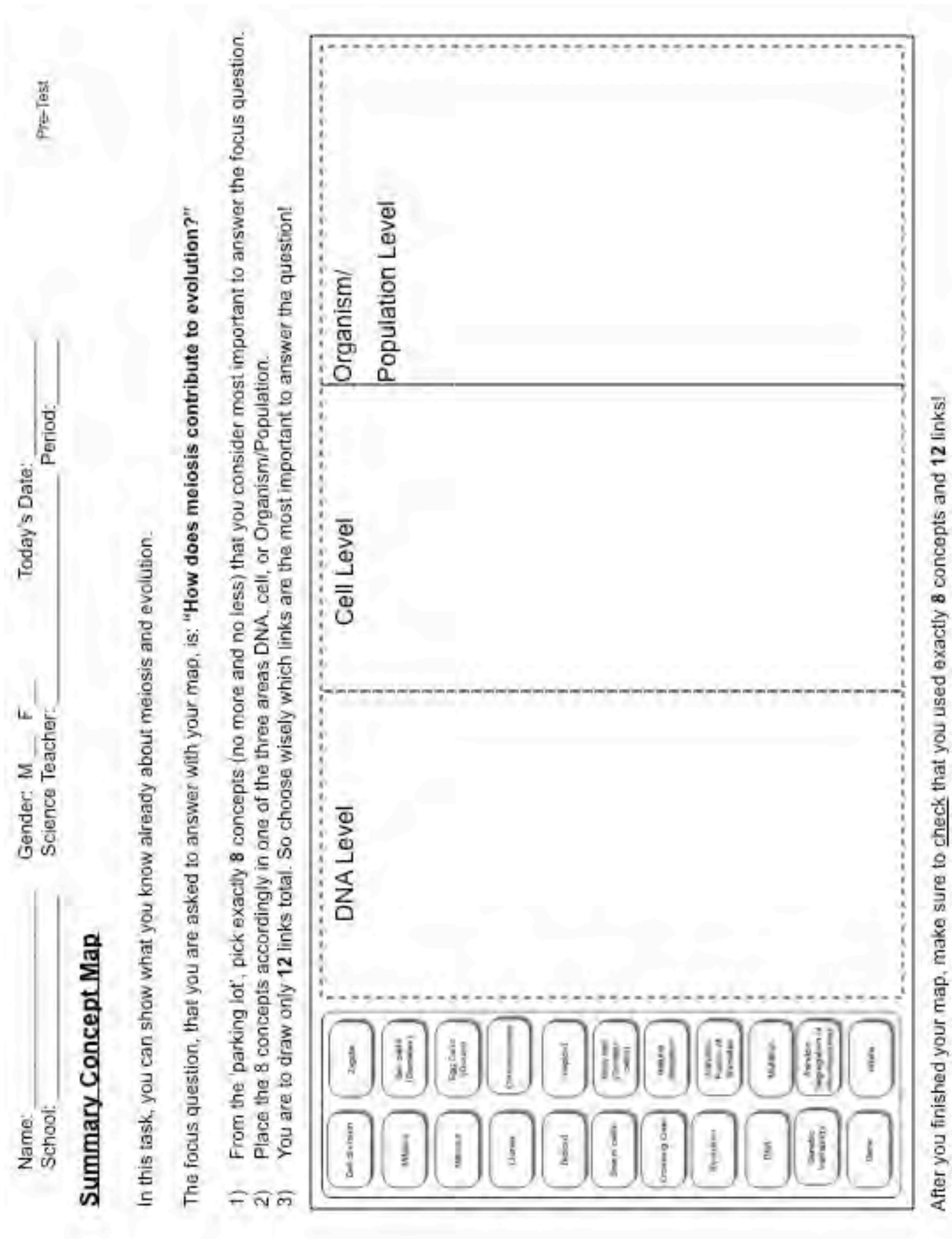


Figure 83: Study 2 KIM worksheet 2 (expert comparison group).



Name: ______ Gender: M __ F __ Today's Date: ______ Pre-Test

School: ______ Science Teacher: ______ Period: ______

Summary Concept Map

In this task, you can show what you know already about meiosis and evolution.

The focus question, that you are asked to answer with your map, is: **"How does meiosis contribute to evolution?"**

1) From the 'parking lot', pick exactly **8** concepts (no more and no less) that you consider most important to answer the focus question.
2) Place the 8 concepts accordingly in one of the three areas DNA, cell, or Organism/Population.
3) You are to draw only **12** links total. So choose wisely which links are the most important to answer the question!

DNA Level

Cell Level

Organism/ Population Level

After you finished your map, make sure to check that you used exactly **8** concepts and **12** links!

Figure 84: Study 2 Pretest/posttest KIM worksheet.

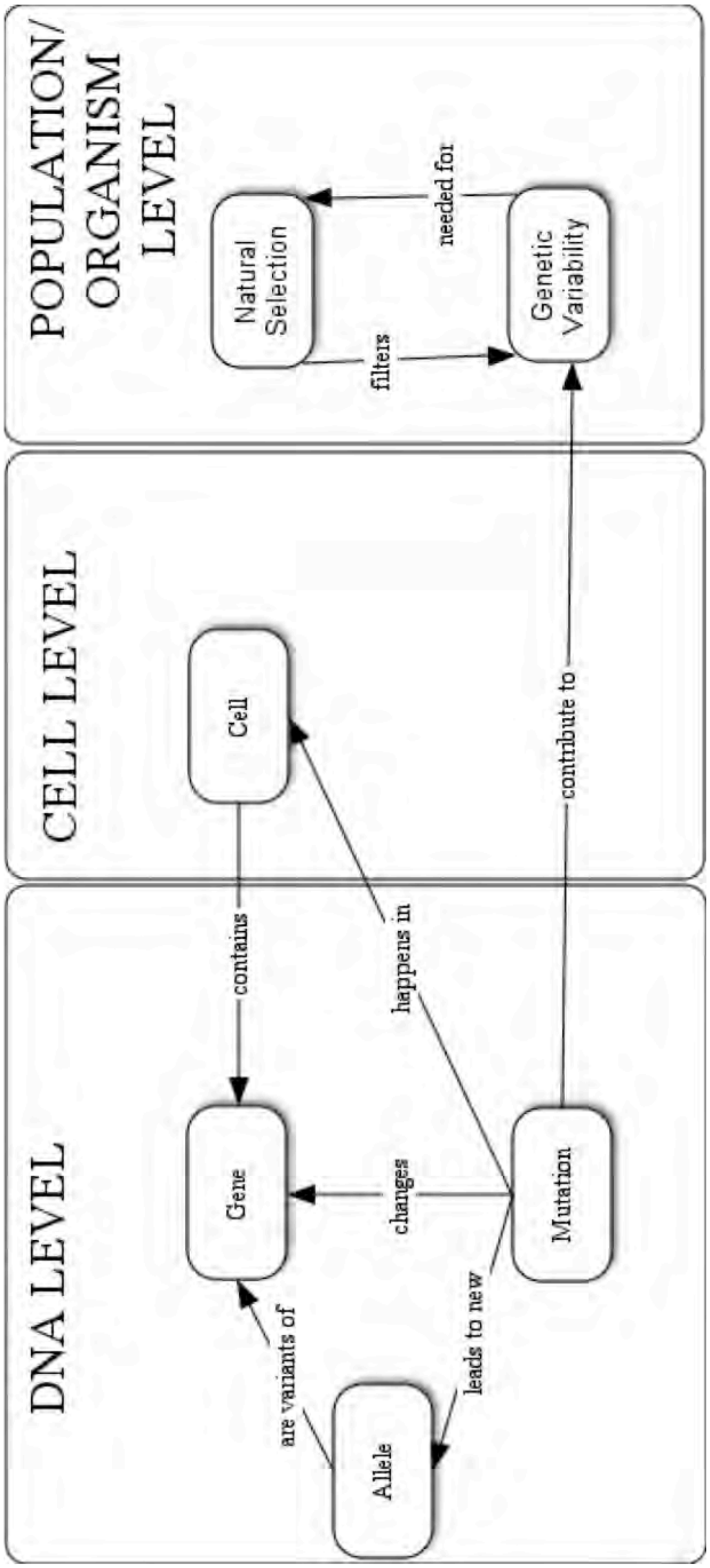


Figure 85: Study 2 expert-generated KIM for comparison.

E. Study 2 Student Knowledge Integration Map samples

A) Peer review group

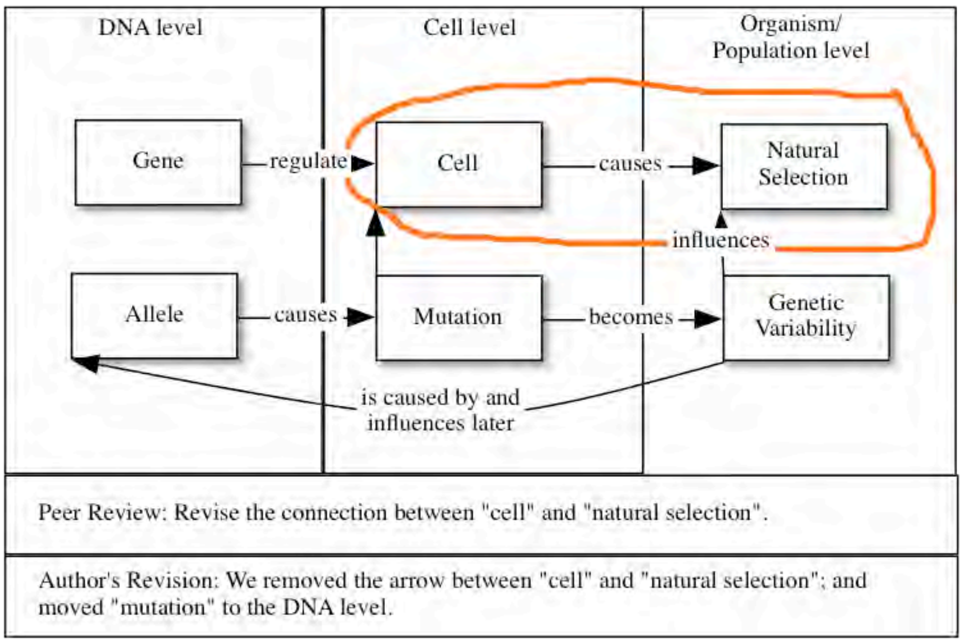


Figure 86: Study 2 peer review group KIM 1 sample.

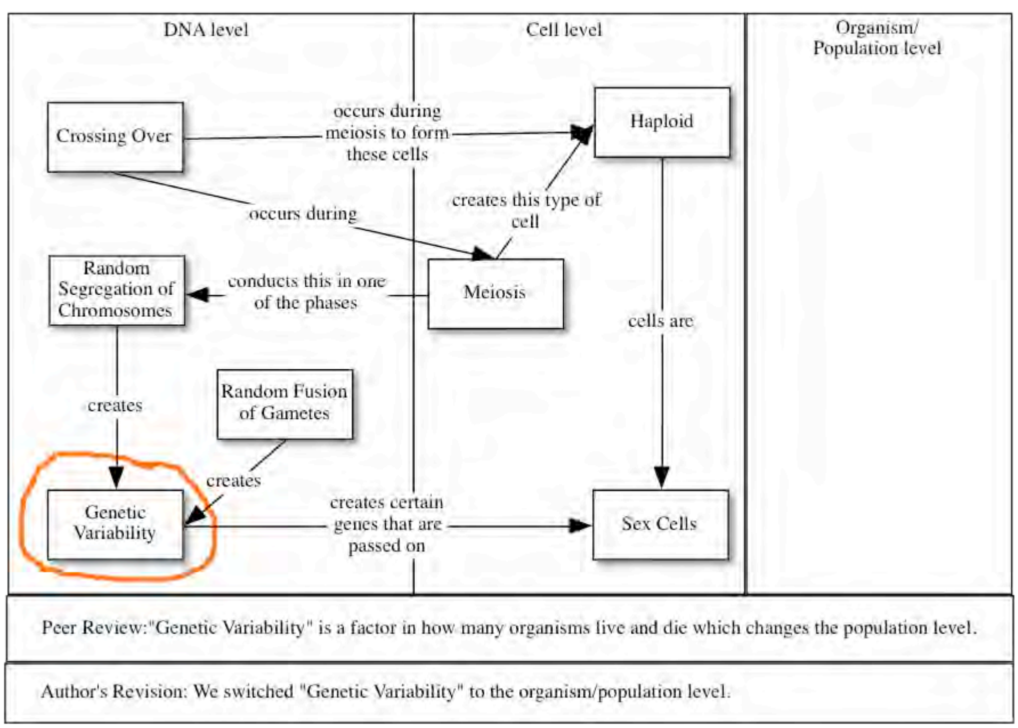


Figure 87: Study 2 peer review group KIM 2 sample.

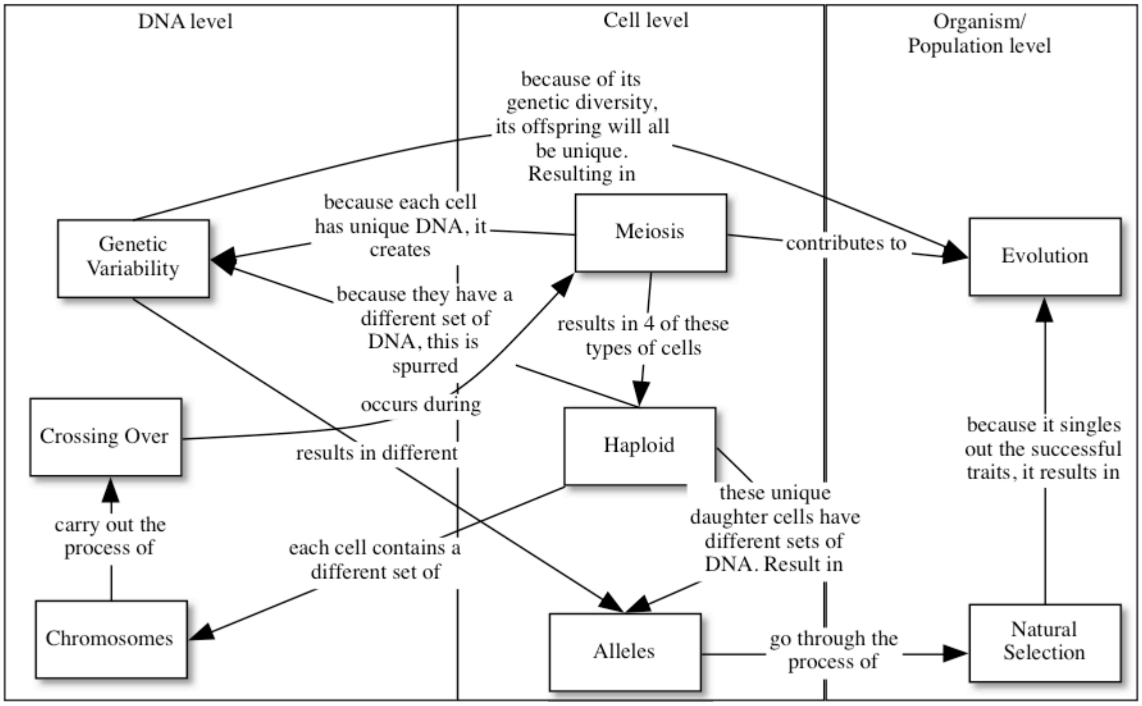
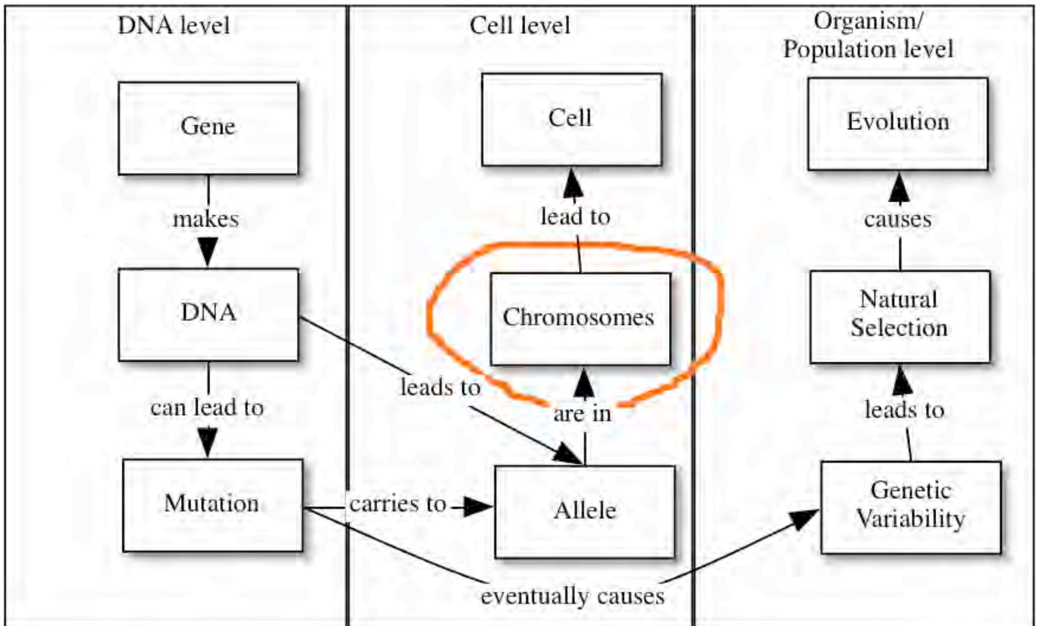


Figure 88: Study 2 peer review group posttest KIM sample.

B) Expert map comparison group



Expert Map Comparison: Chromosomes seem to be in the cellular level because they contain DNA created previously.

Author's Revision: We moved alleles and chromosomes to the DNA level and adjust some arrows.

Figure 89: Study 2 expert comparison group KIM 1 sample.

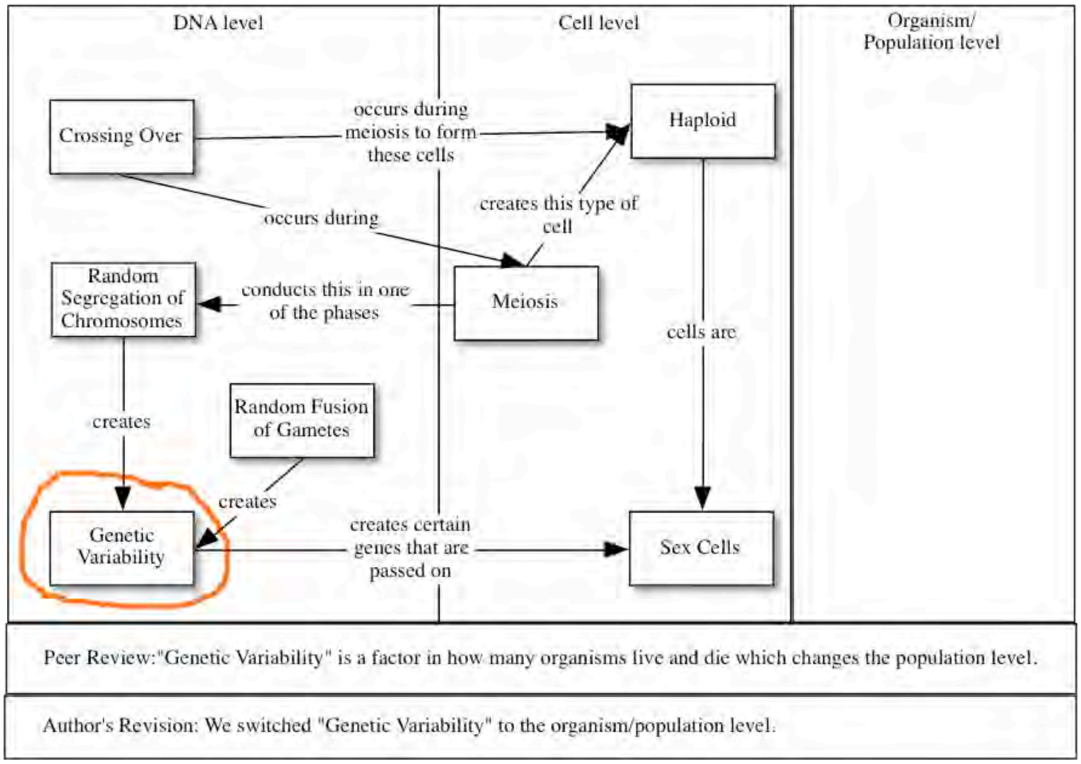


Figure 90: Study 2 expert comparison group KIM 2 sample.

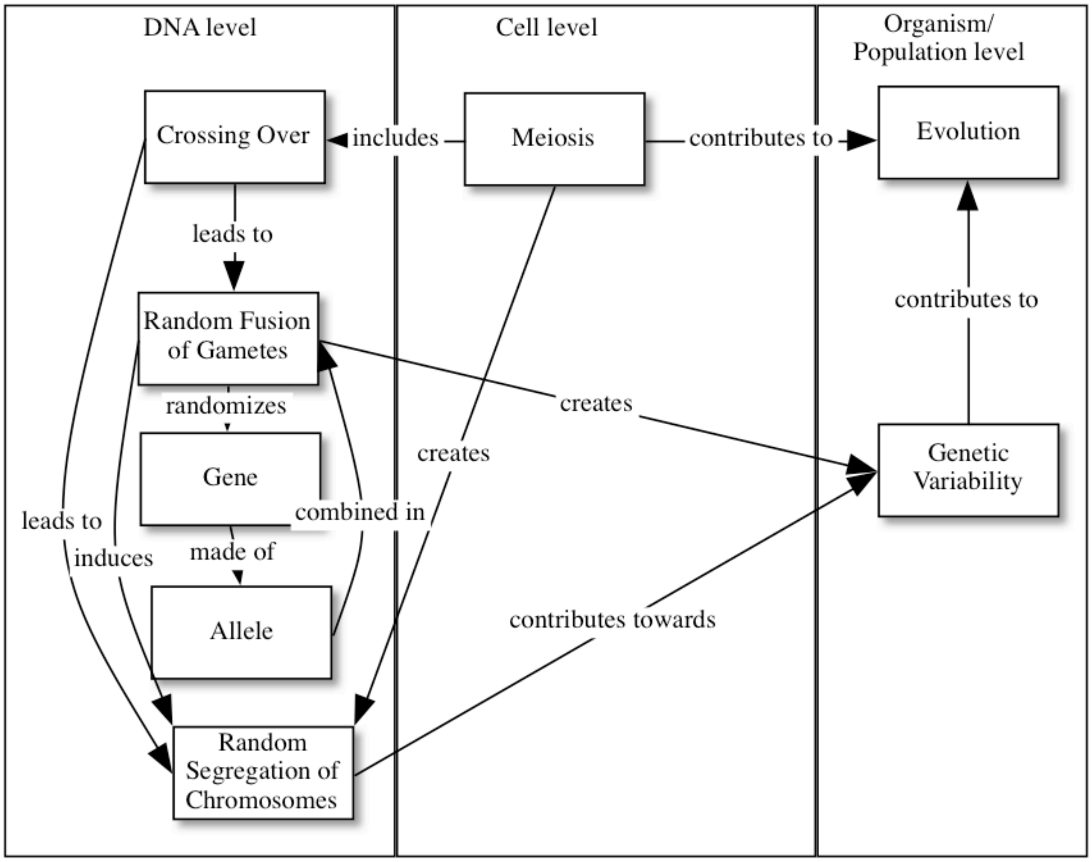


Figure 91: Study 2 expert comparison group posttest KIM sample.

VI. Appendix Chapter 6: Study 3

A. Study 3 Pretest/posttest items

1) a) Which type of variation is passed on from one generation of wolves to the next?
Check all that apply:

1. Any behaviors that were learned during a parent wolf's lifetime.
2. All characteristics that are genetically determined.
3. Only characteristics that were beneficial during a parent wolf's lifetime.
4. Any characteristics that were positively influenced by the environment during a parent wolf's lifetime

b) Please explain.

2) a) What feature of rabbits do biologists consider most important when determining "fitness"?

1. Ability to run quickly away from predators.
2. Ability to compete for food
3. Highest number of offspring that life to reproductive age.
4. Long life

b) Please explain.

3) a) Mutations within a DNA sequence ...

Check all that apply:

1. Frequently increase genetic diversity.
2. Frequently decrease genetic diversity.
3. Rarely influence genetic diversity.

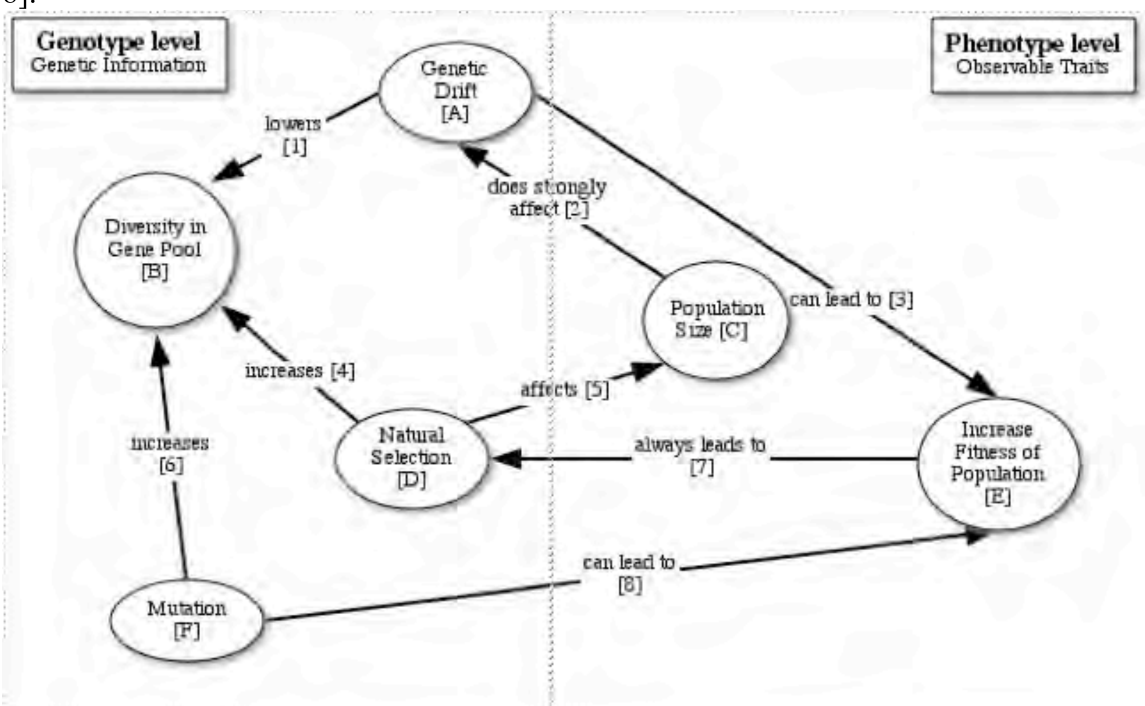
b) Please explain.

---

4) The concept map below might contain up to three mistakes.

For each mistake:

a) Indicate wrongly placed concept [letter A-F] or incorrect link (label or direction) [number 1-8].



b) Explain how each mistake should be improved.

5) a) What changes occur gradually over time in groups of finches that live in different

environments?

Check all that apply:
1. The beaks of each finch within the group gradually change.
2. The number of finches having different beaks changes with each generation.
3. Successful behaviors learned by certain finches are passed on to their children.
4. Mutations occur to meet the needs of individual finches when the environment changes.

b) Please explain.

6) a) Some adult humans can digest cow milk while others cannot. According to the theory of evolution, where did variations in the ability to digest cow milk most likely come from?

Check all that apply:
1. People needed to digest cow milk to survive.
2. The availability of cow milk caused some people to become able to digest milk.
3. People wanted to digest cow milk.
4. Random genetic changes created the ability to digest cow milk in some people.

b) Please explain.

7) a) About 10,000 years ago, a famine killed all but very few cheetahs.
What happened among the cheetahs when there was very little food available?
Check all that apply:
1. The cheetahs cooperated to find food and shared what they found.
2. The cheetahs fought for the available food and the strongest cheetah killed the weaker ones.
3. Genetic changes that allowed the cheetahs to eat different foods occurred.
4. The cheetahs least successful in the competition for food died of malnutrition.

b) Please explain.

c) How did the famine impact the genetic diversity of the cheetah gene pool? Explain.

d) How does genetic drift affect the small group of cheetahs that survived the famine?

Check all that apply:

1. Genetic drift does not affect the genetic diversity of cheetahs.
2. Genetic drift acts most strongly in small cheetah populations and leads to further loss of genetic diversity.
3. Genetic drift acts most strongly in larger cheetah populations by increasing their genetic diversity.
4. Genetic drift acts only in small cheetah populations by increasing their genetic diversity.

e) Please explain.

---

8) If biologists wanted to speed up evolutionary change, how would they do it?

9) a) Some ivy plants produce poison in their leaves while others do not. According to the theory of evolution, where did variations in the ability to produce poison most likely come from? [Same item as “6: Lactose tolerance”: Comparison of different contexts.]
Check all that apply:

1. Ivy plants wanted to produce poison to be better protected.
2. Random genetic changes created ability to produce poison in some ivy plants.
3. The environment caused genetic changes in the ivy plants.
4. Ivy plants needed to produce poison to survive.

b) Please explain.

---

10) Explain why natural selection always leads to better-adapted organisms.

B. Study 3 Pretest/posttest rubrics

1) a) Which type of variation is passed on from one generation of wolves to the next?
Check all that apply:

1. Any behaviors that were learned during a parent wolf's lifetime.
2. All characteristics that are genetically determined. [correct]
3. Only characteristics that were beneficial during a parent wolf's lifetime.
4. Any characteristics that were positively influenced by the environment during a parent wolf's lifetime.

Table 93: Study 3 rubric item 1a.

Answer #	Item Code	KI Code
1	1	1
2	2	3 (Correct)
3	3	1
4	4	1
1+2	5	2
1+3	6	1
1+4	7	1
2+3	8	2
2+4	9	2
3+4	10	1
1+2+3	11	2
1+2+4	12	2
1+3+4	13	1
2+3+4	14	2
1+2+3+4	15	2

Table 94: Study 3 codes item 1a.

For rubric above:	KI Code (increasingly better)
Wrong: One or multiple wrong answers, but not the correct one	1
Mixed: Correct and wrong answer	2

Only correct answer	3

b) Please explain.

Table 95: Study 3 KI rubric item 1b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	• I don't know • No idea
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• Acquired behaviors get passed on. • Everything that proofed beneficial/is wanted is passed on. • They would need to adjust to new environments in order to survive.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Selective inheritance -Says 'trait' or 'characteristic', but not 'gene'.	3	• Only beneficial mutations can be passed on. • The parents adapted to their environment with a trait that helps them survive. since it is helpful, it is passed down to the offspring.
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. -Needs to mention: Only 'mutation' or 'genes' are passed on -ALL genetic traits are passed on (not just the beneficial ones)	4	• Only genetic traits are passed on. • Because animals do not pass on acquired traits onto their offspring, only genetic traits.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. -Need to mention: Only 'mutation in sex cells' can be passed on (not changes in body	5	• Only mutations in the sex cells can be passed on (germ line mutation), but not in the body cells (somatic mutation) or acquired traits or learned behaviors. • Only things that are genetic are passed on to the next wolves. Skills

cells/ learned behavior)		they may have learned are not passed on.

2) a) What feature of rabbits do biologists consider most important when determining "fitness"?
1. Ability to run quickly away from predators.
2. Ability to compete for food
3. Highest number of offspring that life to reproductive age. [correct]
4. Long life

Table 96: Study 3 rubric item 2a.

Answer #	Item Code	KI Code
1	1	1
2	2	1
3	3	2 (correct)
4	4	1

b) Please explain.

Table 97: Study 3 KI rubric item 2b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• So they can evolve and not go extinct.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Talk about individual 'survival' (food, flight) instead of offspring	3	• Food is most important to survive. • They need to be able to run away in order to survive.

Basic Elaborate a scientifically valid link between two ideas relevant to a given context. -Talk about 'having offspring being important' (survival or long life in order to reproduce)	4	• Because high fitness scientifically would mean having more offspring that live to reproductive age. • Surviving longer allows the rabbits to have more offspring.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. -Elaborates why having offspring is important -> Pass on genes	5	• Fitness is measured by the number of offspring produced. This influences the allele frequency in the gene pool over time.

3) a) Mutations within a DNA sequence ...

Check all that apply:

1. Frequently increase genetic diversity. [correct]
2. Frequently decrease genetic diversity.
3. Rarely influence genetic diversity.

Table 98: Study 3 rubric item 3a.

Answer #	Item Code	KI Code
1	1	3 (correct)
2	2	1
3	3	1
4	4	1
1+2	5	2
1+3	6	2
1+4	7	2
2+3	8	1
2+4	9	1
3+4	10	1
1+2+3	11	2
1+2+4	12	2
1+3+4	13	2
2+3+4	14	1

b) Please explain.

Table 99: Study 3 KI rubric item 3b

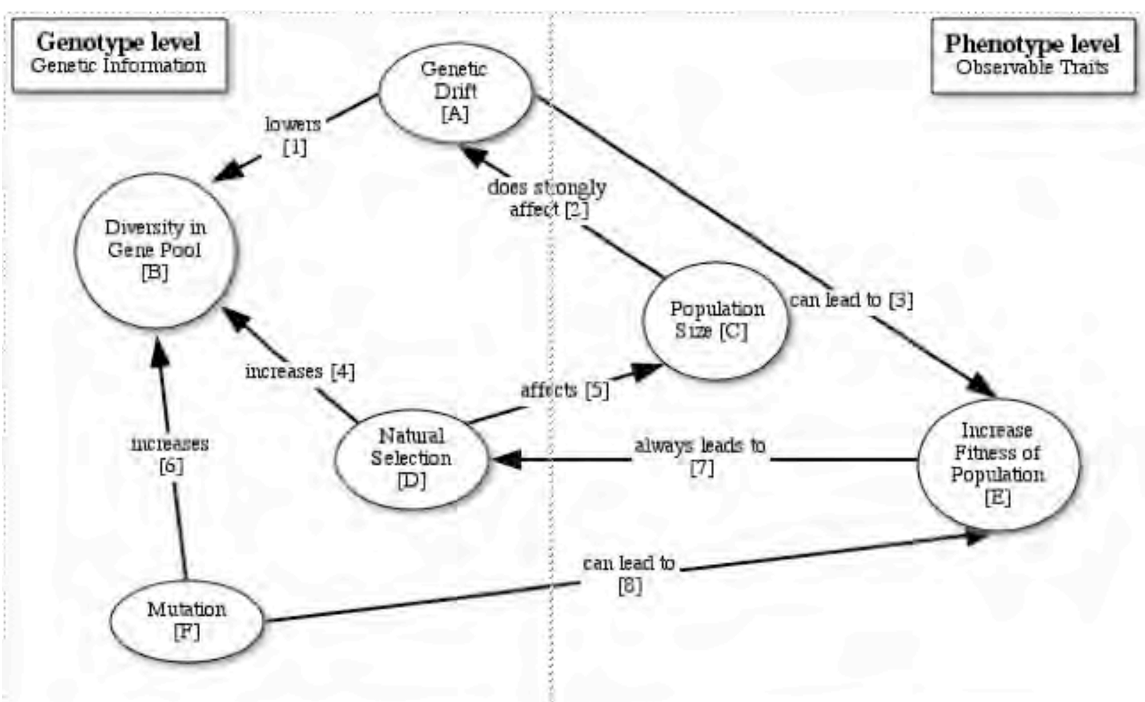
KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	

Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• The DNA gets the wrong information and is sent to the wrong part of the body and therefore there is a mutation. • Changes in the DNA do not influence the phenotype/genotype/genetic diversity.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Mutations are changes in traits (Does not mention 'genes')	3	• Mutations make new diverse traits. • It decreases because a mutation can sometimes kill. • Mutations increase genetic diversity because they make an organism appear differently or have different adaptions then their species members. This would enable them to do things better and potentially live longer. • Offspring have the mutation. • When mutation occur it usually don't come out better, usually become worst, since organism have already adopt to their environment.
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. -Talk about mutations being changes in 'genes' or 'alleles'	4	• Mutations change the DNA, create new alleles, increase genetic diversity in the gene pool. • It changes the genes so that the same genes aren't passed down to offspring. • Mutations add different alleles to add to genetic diversity.
Complex	5	• Mutations cause new phenotypes

Elaborate two or more scientifically valid links among ideas relevant to a given context. -Mutations affect the genetic diversity of the next generation/ in offspring or -Not all mutations influence the phenotype		and genotypes to appear that were not there before, thus increasing the gene pool and the variety of traits that offspring can inherit from their parents. • A mutation in the DNA sequence can increase genetic diversity, however it does not always affect the phenotype of the organism. • Mutations within a DNA sequence increase genetic diversity frequently, because they are a random change in the original DNA of and organism, which maybe be passed on to later generations resulting in some organisms with a certain DNA sequence and another species with differences in the DNA sequence because of the mutation.

4) a) The concept map below might contain up to three mistakes.

For each mistake, indicate wrongly placed concept [letter A-F] or incorrect link (label or direction) [number 1-8].



Deliberate Mistakes:

- 4: Label error: Should be ‘**decreases’ [label error]**
- 7: Arrow **direction** error: Should be the other way around **[direction error]**
- D: Natural Selection should be **placed** in Phenotype level **[placement error]**

a) Error Detection

Table 100: Study 3 error detection rubric item 4a.

Level	Score
No answer	0
Irrelevant answer (e.g. replaced a correct answer with another correct answer)	1
One or multiple false positives (Type I error)	2
One mistake correctly identified, but also one or more false positives (Type I + Type II error)	3
One mistake correctly identified, and no false positives (Type II, but no Type I error)	4
Two mistakes correctly identified, but also one or more false positives (Type I error + Type II error)	5
Two mistakes correctly identified, and no false positives (Type II error, but no Type I error)	6
All three mistakes correctly identified, but also one or more false positives (Only Type I error)	7
All three mistakes correctly identified, and no false positives (no errors Type I or II)	8

Type I error (false positive): The hypothesis can be inappropriately rejected: Falsely identified a correct element as a mistake.
Type II error (false negative): Inappropriately retain the hypothesis: Missed detecting a deliberate error.

b) Error Correction -> Only coded for the three specified items.
Explain how each mistake should be improved.

4bL: Label Error

Table 101: Study 3 label error rubric item 4b.

Level	Score	Sample answer
No Correction	0	
False Correction	1	
Weak correct Correction	2	Leads to; affects
Strong correct Correction	3	Decrease

4bD: Direction Error

Table 102: Study 3 direction error rubric item 4b.

Level	Score	Sample answer
No Correction	0	
False Correction	1	Wrong arrow direction
Correct Correction	2	Correct arrow direction

4bP: Placement Error

Table 103: Study 3 placement error rubric item 4b.

Level	Score	Sample answer
No Correction	0	
False Correction	1	Place in wrong area
Correct Correction	2	Placed in corresponding area

5) a) What changes occur gradually over time in groups of finches that live in different environments?

Check all that apply:

1. The beaks of each finch within the group gradually change.
2. The number of finches having different beaks changes with each generation. [correct]
3. Successful behaviors learned by certain finches are passed on to their children.
4. Mutations occur to meet the needs of individual finches when the environment changes.

Table 104: Study 3 rubric item 5a.

Answer #	Item Code	KI Code
1	1	1
2	2	3 (correct)
3	3	1
4	4	1
1+2	5	2
1+3	6	1
1+4	7	1
2+3	8	2
2+4	9	2
3+4	10	1
1+2+3	11	2
1+2+4	12	2
1+3+4	13	1
2+3+4	14	2
1+2+3+4	15	2

b) Please explain.

Table 105: Study 3 KI rubric item 5b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas. -Lamarckian' argument: Change because of 'need'	2	• Beaks/finches change because they need to adapt. • Finches develop new beaks to adapt to a new environment • Finches adapt different beaks and passed them on to their offspring. (Acquired changes are passed on) • Finches change according to the environment.
Partial Have relevant ideas but do not fully elaborate links between them in a given context.	3	• Finches inherit traits from their parents. (Inheritance) • The mutation is passed down. (Genetic changes + inheritance) • Each finch has a slightly different beak. (Individual variation)
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. • Changes in the gene pool • Mutations/ Genetic changes happen in individuals • Natural selection	4	• Because the finches will adapt new beaks to better live in their environment with the help of natural selection.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given	5	• Random mutations in the sex cells of finches change the frequency of alleles in each following generation. The new environment defines the

context. -Inheritance -Individual variation -Changes in DNA/Genes/Genotype -Mutations cause changes in the phenotype		selection criteria. • Over time there are different beaks on the birds. No two birds will have exactly the same beaks. So they may start off similarly at first but throughout the generation they will change. • If a mutation in a finch occurs to match the change in environment, the DNA will change any Physical features of the finches in order to meet the needs of each one. • Natural selection causes those finches with helpful mutations to their beaks to be more genetically fit and adapt to the environment better. Therefore, the finches with the beaks adapted to their environment survive and the trait gradually becomes dominant in the group.

6) a) Some adult humans can digest cow milk while others cannot. According to the theory of evolution, where did variations in the ability to digest cow milk most likely come from?

Check all that apply:

1. People needed to digest cow milk to survive.
2. The availability of cow milk caused some people to become able to digest milk.
3. People wanted to digest cow milk.
4. Random genetic changes created the ability to digest cow milk in some people. [correct]

Table 106: Study 3 rubric item 6a.

Answer #	Item Code	KI Code
1	1	1
2	2	1
3	3	1
4	4	3 (correct)
1+2	5	1
1+3	6	1
1+4	7	2
2+3	8	1
2+4	9	2

3+4	10	2
1+2+3	11	1
1+2+4	12	2
1+3+4	13	2
2+3+4	14	2
1+2+3+4	15	2

b) Please explain.

Table 107: Study 3 KI rubric item 6b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas. -Lamarckian understanding: People wanted to digest milk/ people needed to digest milk	2	• People need to digest milk in order to survive. • People wanted to digest milk. • People developed the ability to digest milk because they lived in dairy farming cultures/ because there was no water available. • Some times you have to change to meet the standards of you environment • In places where they had cow milk to drink but could not, they gradually became able to digest it • People can digest milk because they got used to it due to exposure to milk
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Mentions 'mutations'/ gene as a contributing factor but in a vague way	3	• People adapted to digest cow milk, with mutations playing a role. • Everyone when you are younger can digest milk because everyone has the gene. But as you grow older some people lose the gene to digest milk which then makes you lactose

-Traits inherited from parents (does not explain where they had it from)		intolerant.
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. Mentions one of these: -Mentions 'mutations'/ random genetic changes' as the source for the variability -Mentions 'natural selection' as a reason why certain traits persist	4	• Random genetic changes happened in some people.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. Mentions two reasons: -Random genetic changes (=mutations) in genes occurred in some people. -Mutations occurred in sex cells -> Inheritable trait -Natural selection favored the trait in dairy farming cultures.	5	• You can't make yourself lactose intolerant or not. It just randomly comes in your genes as a child.

7) a) About 10,000 years ago, a famine killed all but very few cheetahs.
What happened among the cheetahs when there was very little food available?
Check all that apply:

1. The cheetahs cooperated to find food and shared what they found.
2. The cheetahs fought for the available food and the strongest cheetah killed the weaker ones. [correct]
3. Genetic changes that allowed the cheetahs to eat different foods occurred.
4. The cheetahs least successful in the competition for food died of malnutrition. [correct]

Table 108: Study 3 rubric item 7a.

Answer #	Item Code	KI Code
1	1	1
2	2	3 (correct-part)
3	3	1
4	4	3 (correct-part)
1+2	5	2
1+3	6	1
1+4	7	2

2+3	8	2
2+4	9	5 (correct-combined)
3+4	10	2
1+2+3	11	2
1+2+4	12	4
1+3+4	13	2
2+3+4	14	4
1+2+3+4	15	4

-Both 2 and 4 are considered correct answers. The best answer is 2+4.

Table 109: Study 3 codes item 7a.

Choice	KI points
Wrong: Only incorrect ones	1
Mixed: 1 correct + incorrect one(s)	2
Part Correct: 1 correct, no incorrect ones	3
Mixed: 2 correct + incorrect one(s)	4
Only correct answers: 2 correct (combination), no incorrect ones	5

b) Please explain.

Table 110: Study 3 KI rubric item 7b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• The cheetahs ate each other. • The cheetahs had to adapt in order to survive. • Adaptations were made over generations to help them survive
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Mentions only one of these elements e.g. mentions natural selection (survival) but not reproduction.	3	• Cheetahs vary individually in their ability to survive the famine • Survivors pass on their genes to the next generation/ offspring • Loss of genetic variability
Basic Elaborate a scientifically valid	4	• When there are few resources and more consumers, survival of the

link between two ideas relevant to a given context. -Mentions both natural selection (survival in environment) + more frequent reproduction of survivors (but not genes)		fittest occurs by the process of natural selection. The fittest animals survive in the environment, and the weaker are destroyed, resulting in the reproduction of more fit animals and less weak.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. -Individual genetic varieties -> More offspring/ pass on to next generation -> More frequent in gene pool -Mentions genetic level	5	• Natural selection determined that the cheetahs that most genetically fit would survive and pass on their traits to the next generation. The cheetahs that were less genetically fit did not have the chance to pass on their traits and perished. If a cheetah was not fit enough to obtain enough food, they were not as genetically fit and died.

c) How did the famine impact the genetic diversity of the cheetah gene pool? Explain.

Table 111: Study 3 KI rubric item 7c.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or “I don’t know.” Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• Genetic diversity increased • It killed of badly adapted ones.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Lower genetic diversity -Left only good alleles -Some traits got lost	3	• Genetic diversity lowered [no explanation] • The famine left only good alleles in the gene pool (that supported survival during the famine). • Some traits got lost and can no longer be passed on to the next generation.

Basic Elaborate a scientifically valid link between two ideas relevant to a given context.	4	• Genetic diversity lower because only few individuals survived.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context.	5	• Genetic diversity lower because only few individuals survived, but frequency of certain alleles higher/lower.

d) How does genetic drift affect the small group of cheetahs that survived the famine?
Check all that apply:

1. Genetic drift does not affect the genetic diversity of cheetahs.
2. Genetic drift acts most strongly in small cheetah populations and leads to further loss of genetic diversity. [correct]
3. Genetic drift acts most strongly in larger cheetah populations by increasing their genetic diversity.
4. Genetic drift acts only in small cheetah populations by increasing their genetic diversity.

Table 112: Study 3 rubric item 7d.

Answer #	Item Code	KI Code
1	1	1
2	2	3 (correct)
3	3	1
4	4	1
1+2	5	2
1+3	6	1
1+4	7	1
2+3	8	2
2+4	9	2
3+4	10	1
1+2+3	11	2
1+2+4	12	2
1+3+4	13	1
2+3+4	14	2
1+2+3+4	15	2

e) Please explain:

Table 113: Study 3 KI rubric item 7e.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	

Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• The smaller a population, the fewer mutations. • When the population is larger, there is more room for genetic drift • They need genetic drift to evolve. • Genetic drift helped the strongest to reproduce. • Genetic drift randomly changes the genes in the organisms • Genetic drift can affect them by pulling in new traits
Partial Have relevant ideas but do not fully elaborate links between them in a given context.	3	One of those answers: • Genetic drift always acts, but more strongly the smaller a population gets. • The famine led to the loss of many alleles (genetic diversity) in the cheetah gene pool. • Lower genetic diversity lowers the fitness of a population (e.g. adaptability of a population to environmental changes and increases the chance for inbreeding).
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. -Two of the above	4	• Because of genetic drift in a small population it can adversely affect the genetic diversity and can lead to a loss and a loss to the overall fitness of the population.
Complex Elaborate two or more scientifically valid links among	5	• The reduction in numbers of cheetahs also lowered their genetic diversity. This leads to lower fitness

ideas relevant to a given context. -Three of the above		of the population and stronger genetic drift effects.

8) If biologists wanted to speed up evolutionary change, how would they do it?

Table 114: Study 3 KI rubric item 8.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• Evolution can not be influenced • By making some changes [too vague]
Partial Have relevant ideas but do not fully elaborate links between them in a given context. According to Hardy-Weinberg: • Increase the genetic diversity (Mutation, migration) • Increase the selection pressure (natural Selection: Change selection conditions) Mentions one way.	3	• Mutations (through radiation or chemicals) • Increase of (natural) selection pressure, e.g. by frequently changing the environmental conditions or move the organisms to a novel environment • Have organisms with frequent and high number of offspring • By adding or removing organisms to the gene pool • Artificially: Through genetic engineering
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. • Mentions two different ways how to increase diversity and/or increase selection	4	• Scientists could increase both the rate of mutations and the selection pressure.

pressure.		
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. • Mentions three different ways how to increase diversity and/or increase selection pressure.	5	• Increase the genetic diversity in the gene pool through mutations and adding new alleles (migration) and increasing selection pressure.

9) a) Some ivy plants produce poison in their leaves while others do not. According to the theory of evolution, where did variations in the ability to produce poison most likely come from?

Check all that apply:
1. Ivy plants wanted to produce poison to be better protected.
2. Random genetic changes created ability to produce poison in some ivy plants. [correct]
3. The environment caused genetic changes in the ivy plants.
4. Ivy plants needed to produce poison to survive.

Table 115: Study 3 rubric item 9a.

Answer #	Item Code	KI Code
1	1	1
2	2	3 (correct)
3	3	1
4	4	1
1+2	5	2
1+3	6	1
1+4	7	1
2+3	8	2
2+4	9	2
3+4	10	1
1+2+3	11	2
1+2+4	12	2
1+3+4	13	1
2+3+4	14	2
1+2+3+4	15	2

b) Please explain.

Table 116: Study 3 KI rubric item 9b.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• The ivy plants started producing poison because they needed it. • The environment caused the production of poison so the plants could survive better.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. -Mentions 'mutations'/ gene as a contributing factor but in a vague way -Traits inherited from parents (does not explain where they had it from)	3	• They inherited changes from their parents • It's not something the Ivy chose to get, it just happened.
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. Mentions one of these: -Mentions 'mutations'/ random genetic changes' as the source for the variability -Mentions 'natural selection' as a reason why certain traits persist	4	• Because of evolution and natural selection, the ivy that produced the poison was better suited for surviving in its environment and had an increased fitness.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. Mentions two reasons: -Random genetic changes (=mutations) in genes occurred in some plants. -Mutations occurred in sex	5	• Some ivy plants had a random mutation in their sex cells that lead to the production of poison. This mutation lead to a trait that proved beneficial in natural selection. The offspring of these plants will inherit the new trait.

cells -> Inheritable trait.		

10) Explain why natural selection always leads to better-adapted organisms.

Table 117: Study 3 KI rubric item 10.

KI code (increasing)	Level	Sample Answers
No Answer (blank)	0	
Offtask Response is irrelevant or "I don't know." Student writes some text, but it does not answer the question being asked.	1	
Irrelevant/Incorrect Have relevant ideas but fail to recognize links between them. Make links between relevant and irrelevant ideas. Have incorrect/irrelevant ideas.	2	• Only good genes are passed on to the next generation.
Partial Have relevant ideas but do not fully elaborate links between them in a given context. Mentions one of the elements below, but not connected. • Natural selection eliminates non-well adapted organisms • Natural selection favors well adapted organisms • Survivors pass on their genes/ have offspring. • Well-adapted organisms have more offspring.	3	• It makes them more fit to live successfully in their environment.
Basic Elaborate a scientifically valid link between two ideas relevant to a given context. -Talk about successful reproduction, but not about genes	4	• Because natural selection kills of the weaker organisms while the stronger ones survive and reproduce leading to the species being better adapted to surviving in their environment. • Natural selection leads to better-

		adapted organisms because the weaker die, and the strong survive. Therefore the strong reproduce and create strong offspring that adapt easily to whatever environment they are born into.
Complex Elaborate two or more scientifically valid links among ideas relevant to a given context. -Only natural selection is determined by adaptation to the environment (Mutation and genetic drift are random) -Inheritable traits (Genes)	5	• Natural selection is defined by the environment and acts upon phenotypic traits. Successful organisms can pass on their inheritable traits to their offspring. • Natural selection kills of weak organisms and their weak genes are lost in the process while organisms that are fit for a certain environment can pass on their alleles.

C. Study 3 Training KIM for students

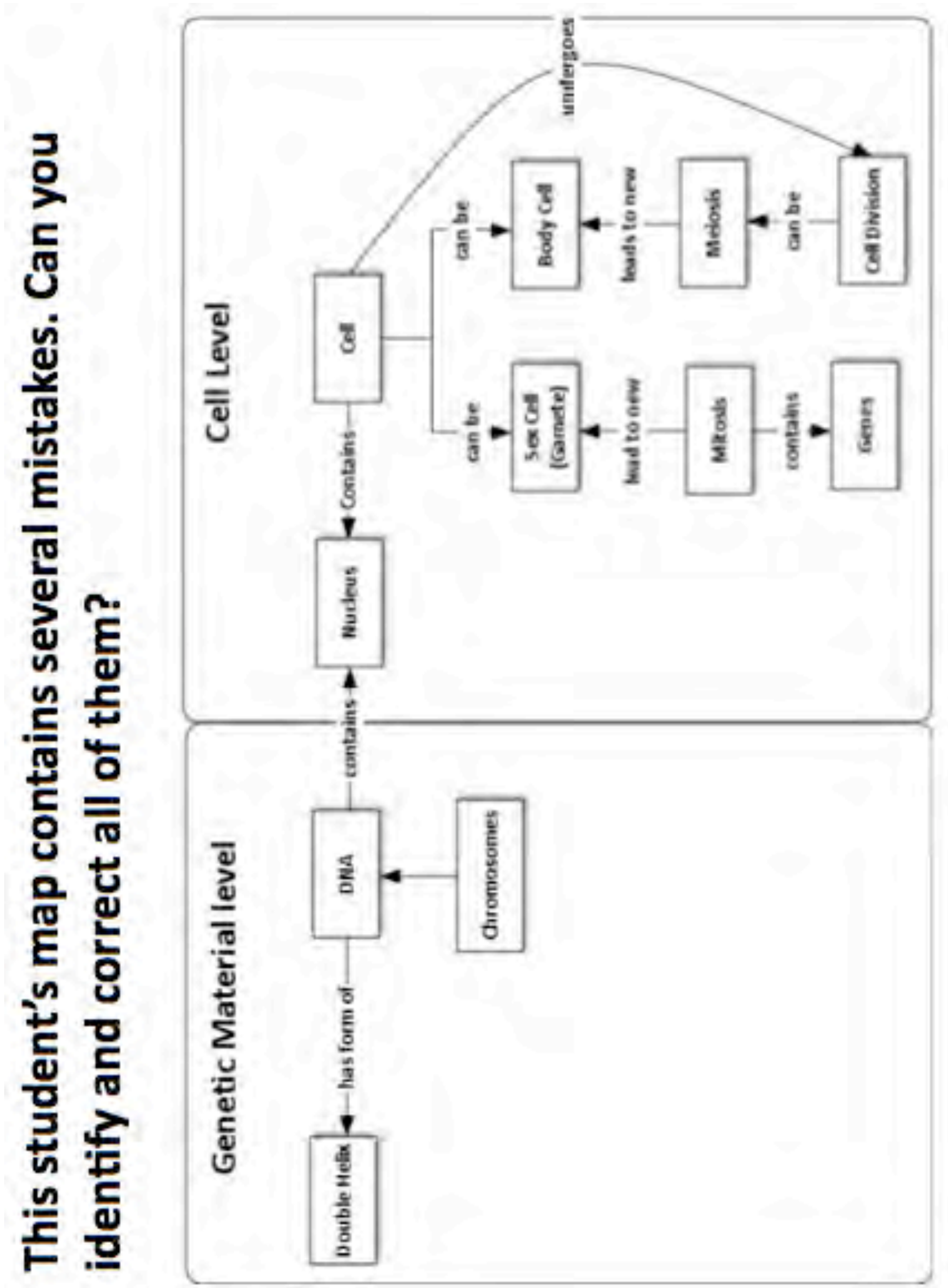


Figure 92: Study 3 training KIM (for students).

D. Study 3 Training KIM for teacher

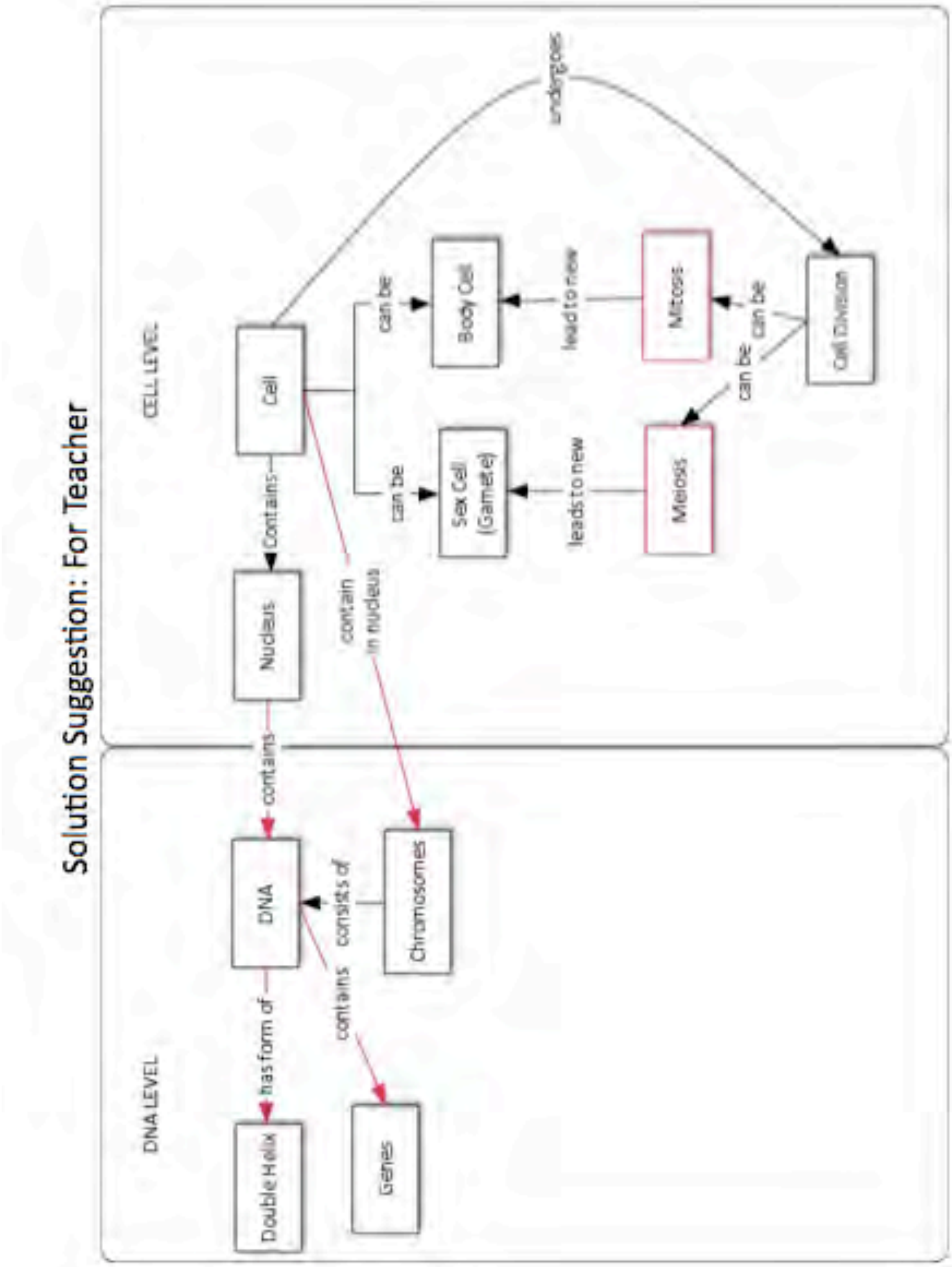


Figure 93: Study 3 training KIM (for teacher).

E. Study 3 Training KIM instructions for teacher

- Introducing the map for classroom discussion after the training phase:
  - "This is a concept map created by another student. It contains several errors. What kind of errors do you see?"
- Criteria to ask students to look for:
  - Has the concept been placed in the correct area?
  - Are important connections missing?
  - Are any existing link descriptions wrong?
  - Is the direction of the arrows correct?
  - Are all connections labeled?
  - Have all concepts from the list been used?

F. Study 3 Critique KIM 1

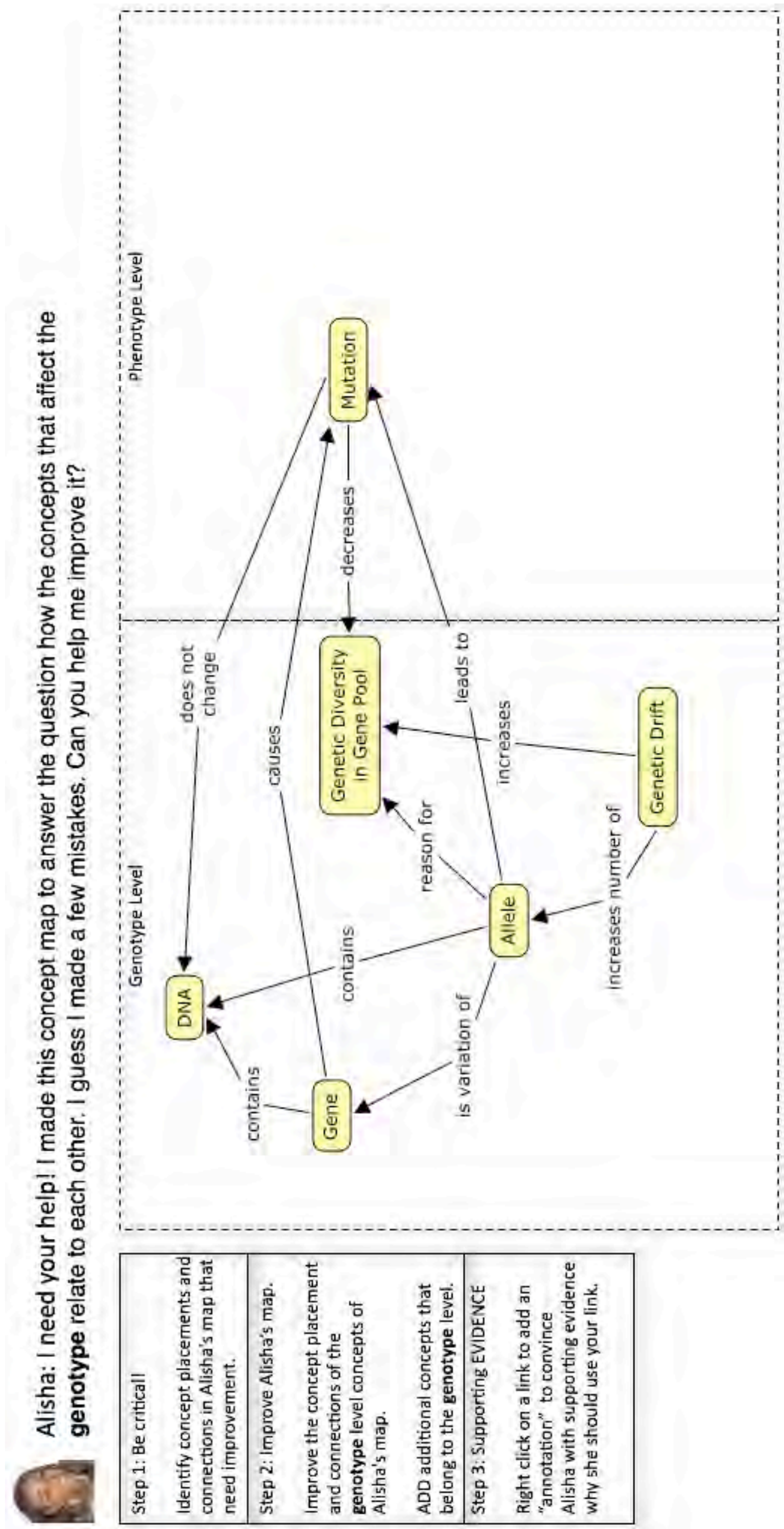


Figure 94: Study 3 critique KIM 1 worksheet.

G. Study 3 Critique KIM 2

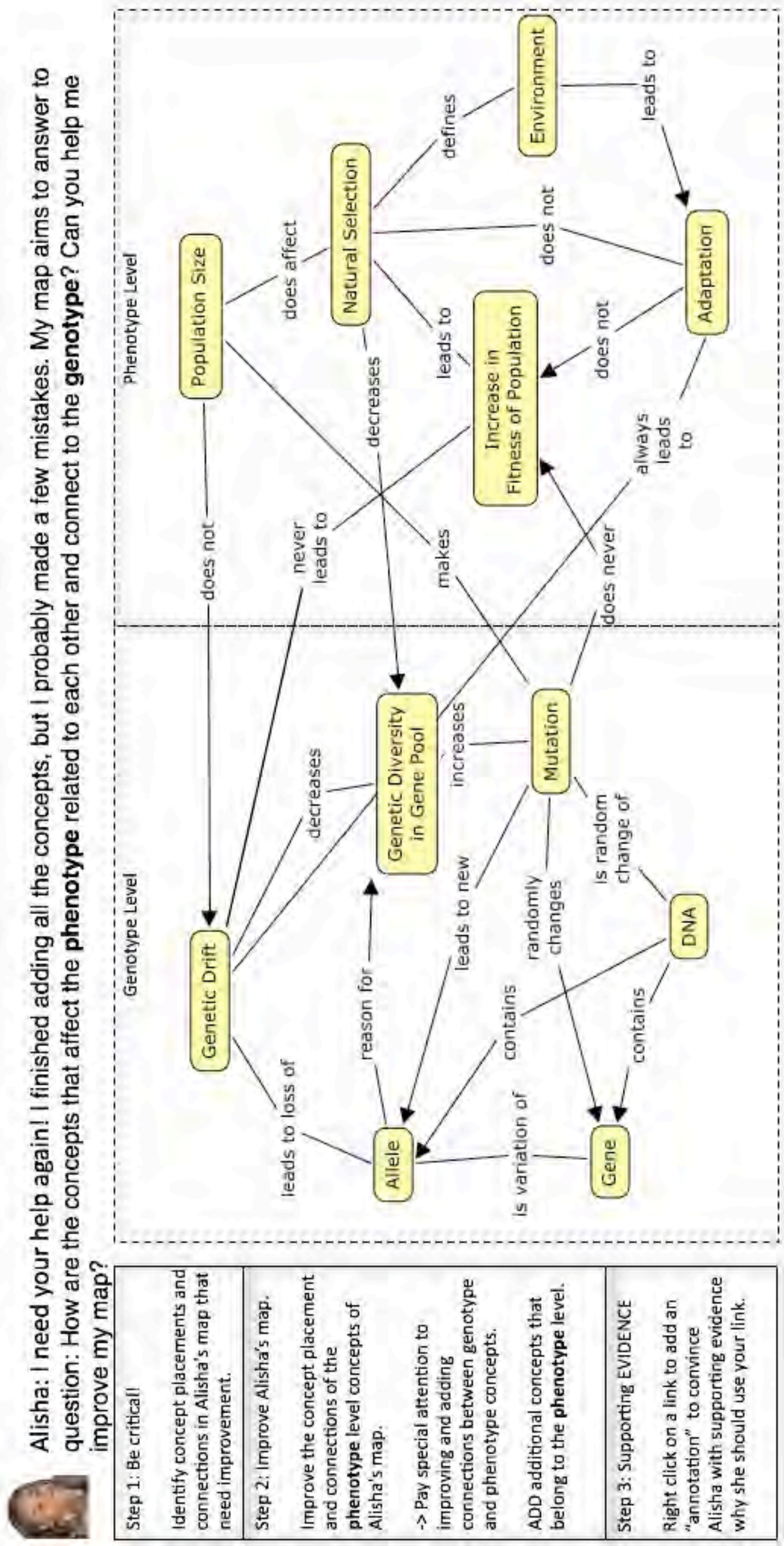


Figure 95: Study 3 critique KIM 2 worksheet.

H. Study 3 Generation KIM 1

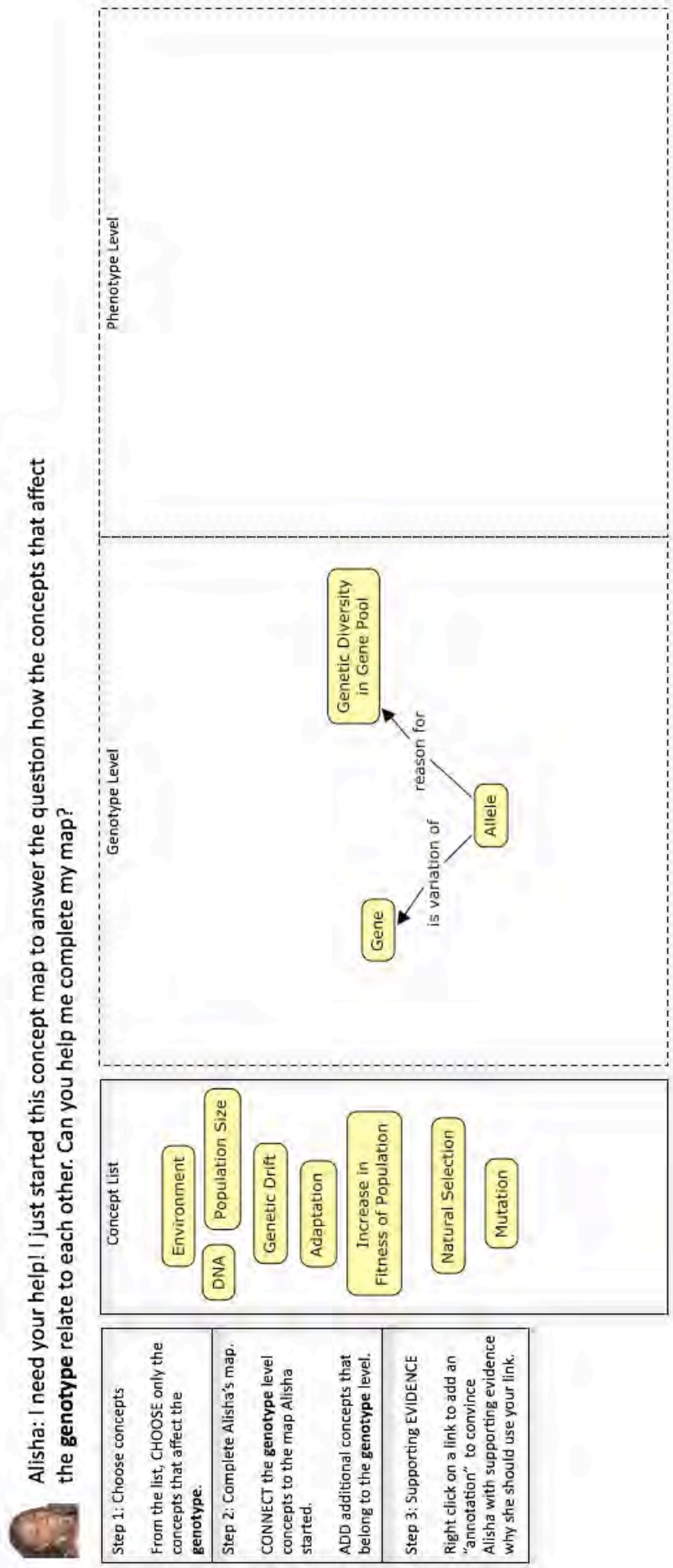


Figure 96: Study 3 generation KIM 1 worksheet.

I. Study 3 Generation KIM 2

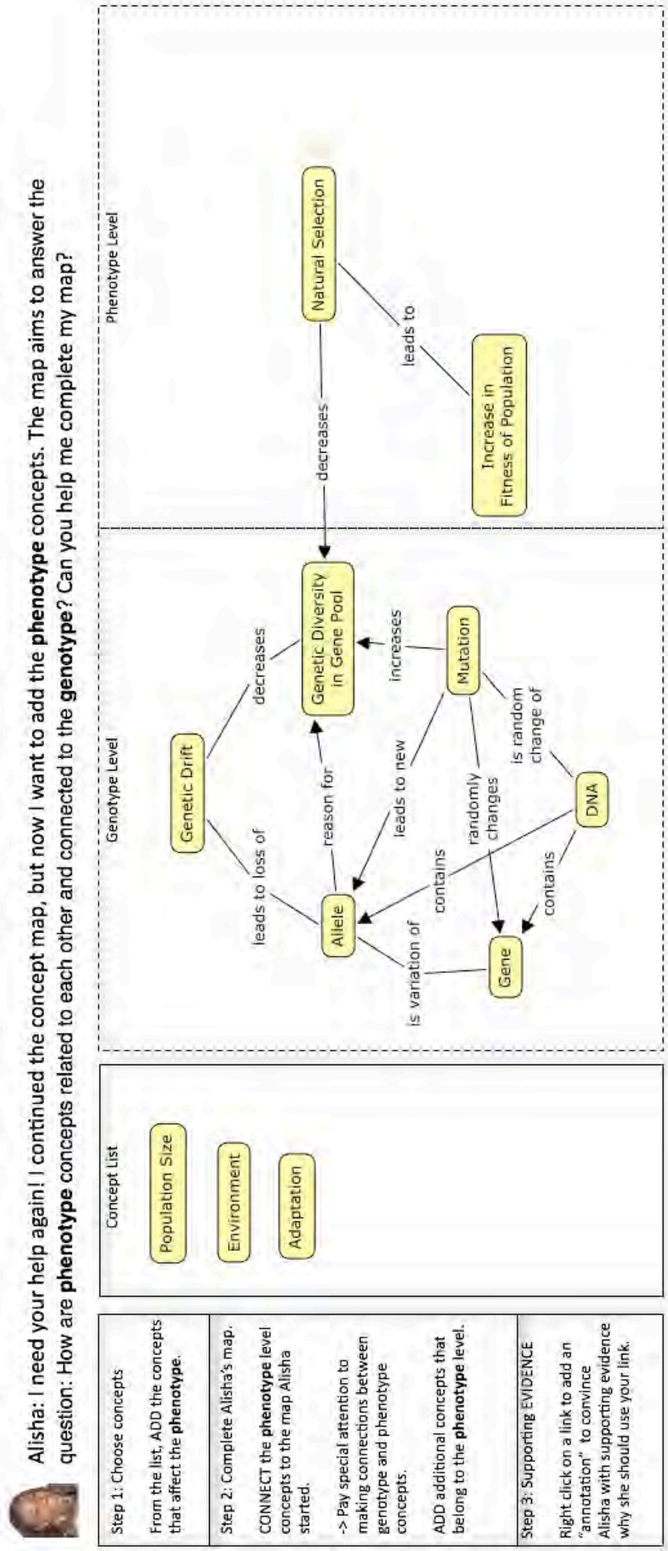
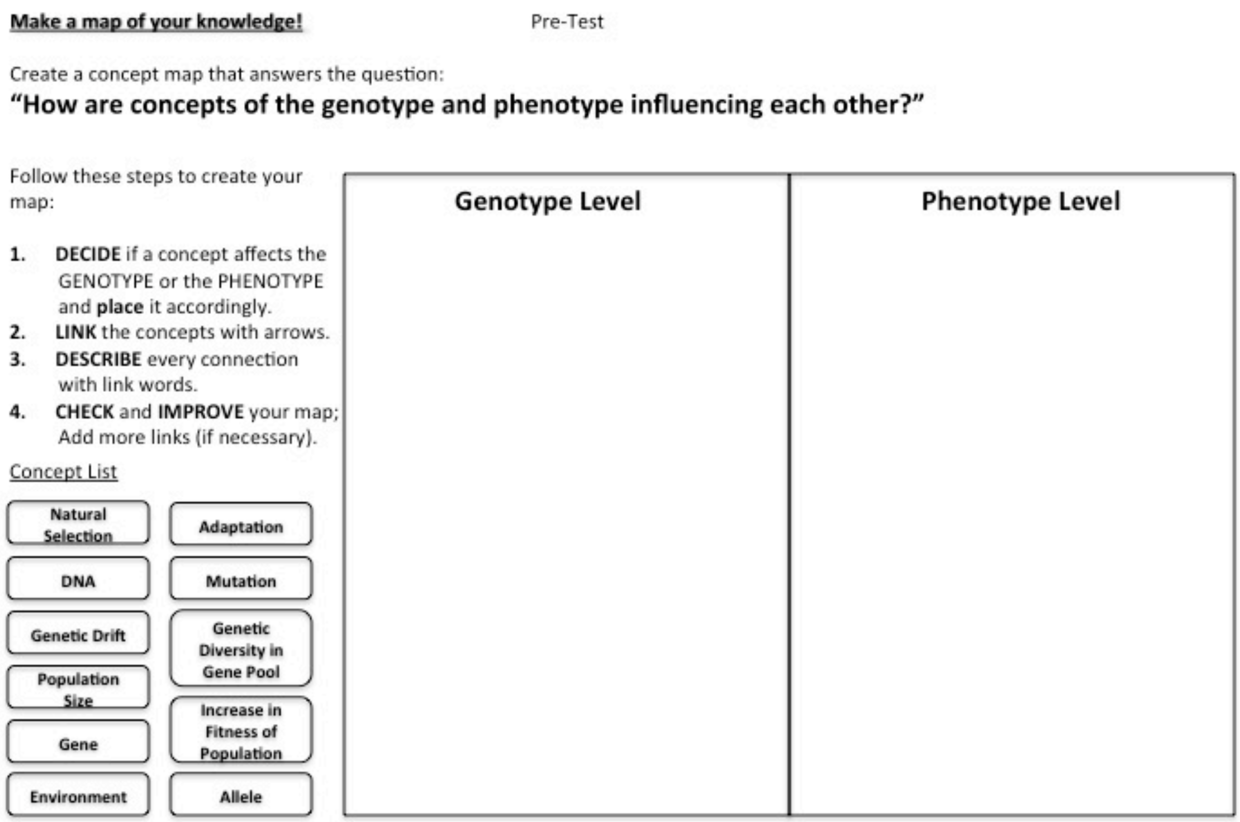


Figure 97: Study 3 generation KIM 2 worksheet.

J. Study 3 KIM Worksheet



Make a map of your knowledge! Pre-Test

Create a concept map that answers the question:

"How are concepts of the genotype and phenotype influencing each other?"

Follow these steps to create your map:

1. **DECIDE** if a concept affects the GENOTYPE or the PHENOTYPE and **place** it accordingly.
2. **LINK** the concepts with arrows.
3. **DESCRIBE** every connection with link words.
4. **CHECK** and **IMPROVE** your map; Add more links (if necessary).

Concept List

Natural Selection	Adaptation
DNA	Mutation
Genetic Drift	Genetic Diversity in Gene Pool
Population Size	Increase in Fitness of Population
Gene	
Environment	Allele

Genotype Level	Phenotype Level

Figure 98: Study 3 KIM pre/posttest worksheet.

K. Study 3 Benchmark KIM

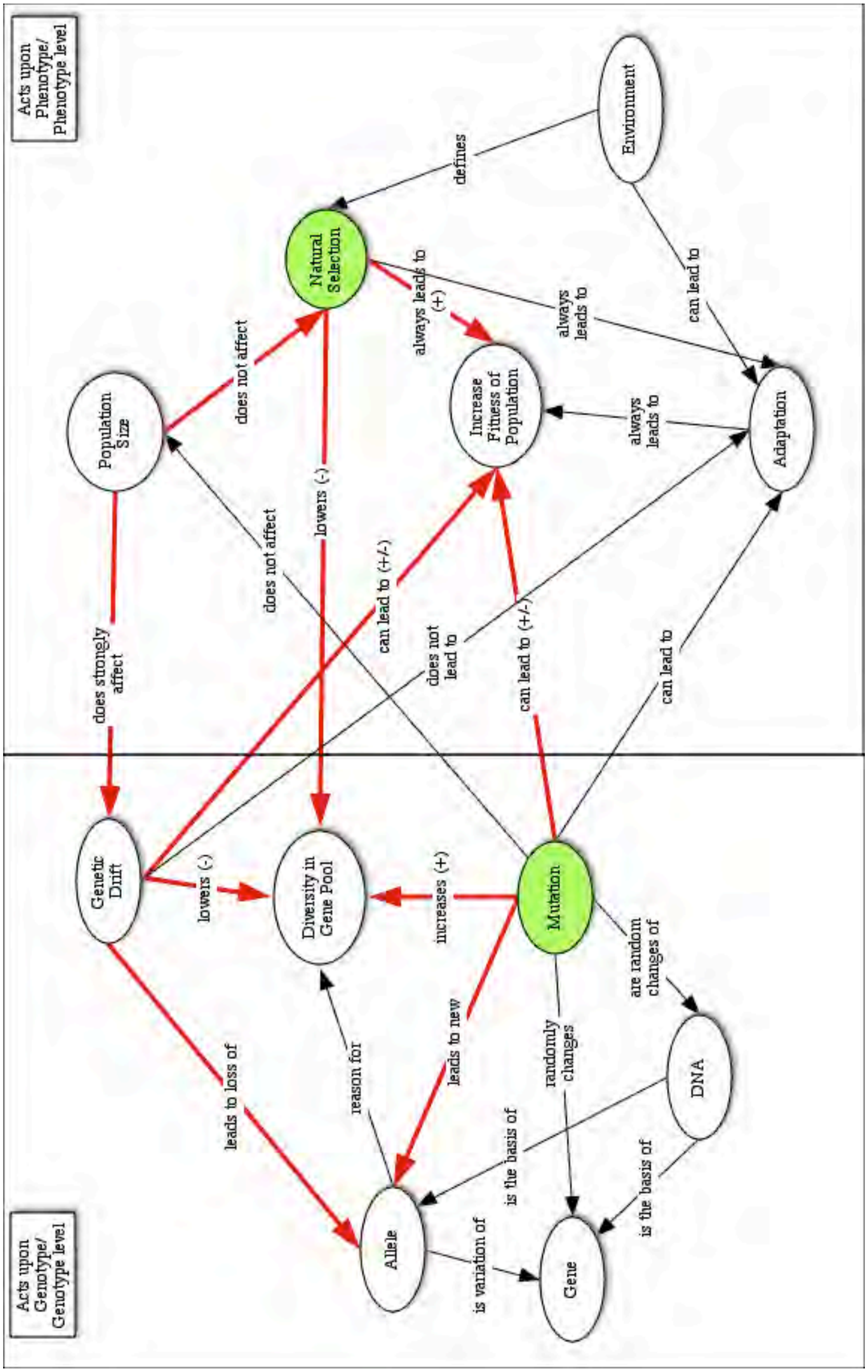


Figure 99: Study 3 benchmark KIM.

L. Study 3 Categories of Different Types of KIM Relationships.

The relationship categories also include negations, e.g. "does not lead to", or "is not part of".

Table 118: Study 3 categories of different types of KIM relationships.

Super-Category	Sub-Category	Code	Examples
UNRELATED	No Connection	0	
	No Label (just line)	1	
	Unrelated label	2	
STRUCTURE [What is the structure (in relation to other parts)?]	Part-Whole [Hierarchical)]	3	Is a/are a
			Is a member of
			Consist of
			Contains
			Is part of
			Made of
			Composed of
			Includes
			Is example of
	Similarity/ Comparison/ Contrast	4	Contrasts to
			Is like
			Is different than
	Spatial Proximity	5	Is adjacent to
			Is next too
			Takes place in
	Attribute/Property/ Characteristic (Quality (permanent) or State (temporary)	6	Can be in state
			Is form of
BEHAVIOR [What action does it do? How does it work/ influence others?	Causal-Deterministic (A always influences B)	7	Contributes to
			Produces
			Creates
			Causes
			Influences
			Leads to
			Effects
			Depends on
			Adapts to
			Changes
			Makes

			Results in
			Forces
			Codes for
			Determines
	Causal-Probability (modality)	8	Leads to with high/low probability
			Often/rarely leads to
			Might/could lead to
			Sometimes leads to
	Causal-Quantified	9	Increases/Decreases
	Mechanistic	10	Explains domain-specific mechanism/ Adds specific details or intermediary steps
	Procedural-Temporal (A happens before B)	11	Next/ Follows
			Goes to
			Undergoes
			Develops into
			Based on
			Transfers To
			Happens before/ during/ after
			Occurs when
			Forms from
FUNCTION [Why is it needed?]	Functional	12	Is needed
			Is required
			In order to
			Is made for
	Teleological	13	Intends to
			Wants to

M. Study 3 Topological Categories to Describe the Geometrical Structure of KIMs.

Table 119: Study 3 topological categories of KIMs.

One Level	Other Level	Code	Comments
Empty	Empty	0	Empty (main structure in one level, but no main structure in other (but maybe single ideas)
Fragmented	Empty	1	
Linear	Empty	2	
Tree	Empty	3	
Hub	Empty	4	
Circular	Empty	5	
Network	Empty	6	
Fragmented	Fragmented	7	
Linear	Linear	8	
Tree	Tree	9	
Hub	Hub	10	
Circular	Circular	11	
Network	Network	12	
Fragmented	Linear	13	
Fragmented	Tree	14	
Fragmented	Hub	15	
Fragmented	Circular	16	
Fragmented	Network	17	
Linear	Tree	18	
Linear	Hub	19	
Linear	Circular	20	
Linear	Network	21	
Tree	Hub	22	
Tree	Circular	23	
Tree	Network	24	
Hub	Circular	25	
Hub	Network	26	
Circular	Network	27	
Full Network		28	Networks in both levels with at least one cross-link