THE INFLUENCE OF PEDAGOGICAL CONTENT KNOWLEDGE (PCK) FOR TEACHING MACROEVOLUTION ON STUDENT OUTCOMES IN A GENERAL EDUCATION BIOLOGY COURSE

A Dissertation

presented to

the Faculty of the Graduate School

University of Missouri

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

---

by

EMILY MARIE WALTER

Dr. Patricia J. Friedrichsen, Dissertation Supervisor

MAY 2013

The undersigned, appointed by the dean of the Graduate School,

Have examined the dissertation entitled

THE INFLUENCE OF PEDAGOGICAL CONTENT KNOWLEDGE (PCK) FOR TEACHING MACROEVOLUTION ON STUDENT OUTCOMES IN A GENERAL EDUCATION BIOLOGY COURSE

Presented by EMILY MARIE WALTER

A candidate for the degree of

DOCTOR OF PHILOSOPHY OF LEARNING, TEACHING AND CURRICULUM - EMPHASIS IN SCIENCE EDUCATION

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

DR. PATRICIA J. FRIEDRICHSEN, CHAIR

DR. LLOYD BARROW

DR. DEBORAH HANUSCIN

DR. DAVID BERGIN

DR. GERALD SUMMERS

DEDICATION

This dissertation is dedicated to my daughters Lily and Charlotte and to my husband Clint. Your love, patience, humor, and bear hugs have been wonderful support for me throughout my doctorate program. I am grateful to share this achievement with you.

ACKNOWLEDGEMENTS

This dissertation is a result of five years of work in the MU Science Education Center. Throughout that time, many people have challenged and supported my thinking. I take the following pages to acknowledge these individuals.

Pat Friedrichsen, my advisor. Thank you for believing in me. You never once told me I might not graduate on time. This meant a lot to me, especially in moments of frustration and exhaustion. Thank you for your support, patience, and excellent feedback throughout this process. Thank you also for helping me look beyond the details and see the big picture. I could not have done this without you.

Lloyd Barrow, thank you for support. I appreciate that you are so in tune to the needs of graduate students. Thank you for your company at lunch and for your keen sense for asking the right question at the right time.

Debi Hanuscin, thank you for your support and insightful questions. It has been great working with you as a colleague. Your industrious yet gracious nature is something to strive for.

Dave Bergin, thank you for meeting with me to discuss quantitative patterns in the data prior to writing Chapter Four. Your insight helped me to have confidence in my results.

Gerry Summers, thank you for your insight and keen eye for detail. Thank you for your continued support of graduate students in Science Education to teach in the biological sciences. We greatly appreciate the experience.

Sandi Abell, thank you for the shaping the collaborative and hard working atmosphere at Mizzou. Writing this dissertation was often influenced by what "Sandi would say". I take great pride in holding myself to the "Sandi standard" and am grateful for the influence of your tough love. Thank you for making all of us go to NARST. Thank you for making us go to colloquium. Thank you for calling our blunders. Thank you for asking us how we were doing both professionally *and* personally. I hope I will find the same collaborative, friendly, and hard working atmosphere at my future institution. However, nothing will ever be quite the same as Mizzou.

To my graduate student colleagues:

Parker Stuart, thank you for always having a listening ear. I have consistently enjoyed our friendship and will miss seeing you on a regular basis.

Will Romine, thank you for your friendship and scholarly advice. You are a quantitative genius and I hope you can apply that knowledge to reach your career goals.

Aaron Sickel and Steve Witzig, thank you for your friendship and insightful questions. I learned so much from the both of you. You are such awesome amalgams of humor and intelligence. I hope that we can work together in the future.

To my faculty participant, Dr. Wallace. The implications of this study would be unknown without your willingness to participate in the study. I hope the findings of the study will be informative in your future teaching. A quick note on the choice of the name "Wallace" as your pseudonym. As you know, your name was purposefully selected to recognize the scholarly contributions of the often forgotten contemporary of Darwin and to recognize my college evolution instructor who happened to share the same surname.

To Greg and Cindy Mollman, my parents. Thank you for always believing in me and being my biggest fans. Thank you for your financial support throughout school and for providing me the loving home needed for a growing mind.

To Lily Walter, my incredible daughter. It's hard to believe you are almost 6 years old already. I love that you can read chapter books, do multiplication with Daddy's help, and glide so well on your scooter. You are awesome! Thank you for never complaining about me leaving to write my dissertation at 6 pm every night. I could have stayed and put you in bed at 8 pm, and you made a major sacrifice to let me go to campus and work instead. Thank you. I love you so much! You are a very intelligent girl. Never forget that intelligence is nothing without hard work. Put your smarts to work, my love, and you can do anything!

To Charlotte Walter, my sweet baby girl. I cannot believe you are already 14 months old. I love how you get excited when you see the kitty and how you love to sing along to songs. Thank you for making 6 am easier by doing a little dance when you see me. Your snuggles, giggles, and overall cuteness have made being really tired from this dissertation a lot easier. Thank you. I love you so much!

And finally, to my husband, Clint Walter. I save the best for last. You are my best friend, my cheerleader, and my soul mate. When we first starting dating in high school, I had pretty low self esteem. Thank you for helping me realize that I can be myself - nerdy, weird, anxious, grumpy, *whatever* - and you'll still love me. I love you more than anything, Kunbear. I look forward to all of our future adventures together.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This study investigated the influence of pedagogical content knowledge (PCK) for teaching macroevolution on non-science majors' knowledge of macroevolution and evolution acceptance. The nature and sources of an experienced faculty member's PCK and instruction as enacted PCK (Park & Oliver, 2008) were examined to consider the influence of these components on students' knowledge of macroevolution and evolution acceptance. The study used a mixed methods approach to understand how PCK influences student outcomes, and is one of the first to examine the influence of PCK on student outcomes at the post-secondary level. In addition, the study is one of few to document a significant relationship between knowledge of evolution and evolution acceptance, including how instruction influenced these outcomes.

The case selected for study was a general education biology class: 270 students and their instructor. To examine the nature and sources of the instructor's PCK for teaching macroevolution, the course was observed in its entirety, the instructor was interviewed before, during, and after the evolution unit, and artifacts were collected from the evolution unit. Interview and observational protocols for the instructor were developed based on the Magnussson, Kracjik, & Borko (1999) model of PCK. The instructor was found to have deep knowledge of learners, and this knowledge in turn informed the other components of her PCK. Her knowledge of learners was built through reflecting on student exam outcomes, referencing the pedagogical literature, interactions with students, and discussions with colleagues. These findings have implications for faculty professional development.

The influence of the course was examined both quantitatively and qualitatively. Students were surveyed using the Measure of Understanding of Macroevolution (Nadelson & Southerland, 2010a) the Measure of Acceptance of the Theory of Evolution (Rutledge & Warden, 1999, 2007). From pre- to post-test, students became significantly more accepting of evolution ($p < .0001$) and made significant gains in understanding macroevolution ($p < .0001$). Knowledge of macroevolution and evolution acceptance were also significantly correlated ($r[268]=.47$, $p<.01$). Twelve students initially scoring low on both instruments also interviewed to examine how the instruction influenced their responses on the instruments. Nine of the students became more accepting of evolution, which they attributed to learning about the volume of evidence for evolution (especially transitional fossils) and learning about the history of life. These findings have important implications for evolution education policy and practice at the post-secondary level.

CHAPTER ONE: INTRODUCTION

Introduction

Evolution is a central organizing principle of the biological sciences (American Association for the Advancement of Science [AAAS], 1993; Dobzhansky, 1973; Kagan, 1992; National Research Council [NRC], 1996). However, only 4 in 10 Americans agree that humans and higher apes share a common ancestor (Newport, 2009). Among Americans with some college education, 49% accept the theory of evolution for plants and non-human animals, while only 22% agree that humans evolved from earlier species (Lovely & Kondrick, 2008). Since evolution is a critical and foundational component of scientific literacy (AAAS, 2011; Bybee, 1997; National Association of Biology Teachers, 2010), and the general education biology course is one of the final opportunities to influence scientific literacy of college educated individuals, it is vital to understand what non-sciences majors know and how they learn about evolution in general education biology courses.

Rationale and Purpose for this Study

Biological Literacy and Evolution

The primary goal for current science education reform initiatives is to prepare and develop a society that is scientifically literate (AAAS, 1989, 1993; NRC, 1996, 2011, 2012), citizens responsible for scientifically informed decisions that affect the local and global community (Bell, Lederman, & Abd-El-Khalick, 2000; Smith & Scharmann, 1999). A scientifically literate society understands the nature of science as well as the core ideas from science disciplines - e.g. biology, chemistry, physics, and Earth science. The report *Vision and Change in Undergraduate Biology Education* (AAAS, 2011) defines core principles for biology, and among these is strong preparation in the theory of evolution. The frameworks (NRC, 2011) also highlight evolution as a unifying theme that serves as a framework for connecting biological concepts.

Evolution by natural selection is the central organizing principle that biologists use to explain natural phenomena. It accounts for three of the most fundamental features of the natural world: similarities among living things, the diversity of life, and many features of the physical world (i.e. fossils) (National Academy of Sciences [NAS], 1998). Furthermore, evolutionary explanations connecting evolution to greater, interdisciplinary scientific literacy by drawing on scientific results from physics, chemistry, geology, and biology (BSCS, 1993). It follows that biology instruction without evolution deprives students of a powerful concept that brings order and coherence to understanding the natural world (AAAS, 2011).

Evolution and Non-Science Majors

The population of non-science majors at 4-year institutions primarily includes students whose goals do not include a career in the biological sciences. Although these individuals will not be scientists, scientific literacy should be a goal for all students, not only those interested in science (AAAS, 1989). Scientific literacy for non-science majors allows them to take important principles of science and apply them in appropriate ways to real life situations (e.g. Alters, 2005; Demastes & Wandersee, 1992). In the case of evolution, practical phenomena such as antibiotic resistance, the artificial selection of domesticated animals and food plants, and the diversity and history of life can be explained by evolution (AAAS, 2011).

Unfortunately, few non-science majors have or develop meaningful understanding about evolution (e.g. Bishop & Anderson, 1990). Prior to instruction, non-science majors have few scientific understandings about evolution, regardless of previous instruction. As few as 4% of non-majors understand how new traits arise in a population, 7% understand how variation functions in a population, and 3% understand how the population changes over time (Demastes, Settlage, & Good, 1995). After instruction, students continue to think: (a) changes in traits are attributed to a need-driven adaptive process rather than random genetic mutation and sexual recombination, (b) variation of traits within a population is not linked to differences in reproductive success, and (c) traits are seen as gradually changing in all members of a population (Bishop & Anderson, 1990). Appendix A summarizes common alternative conceptions about natural selection for non-science majors, biology majors, and medical students.

Micro- and macroevolution. Teaching about evolution includes micro- and macro-evolutionary components. Macroevolution, in contrast, concerns the formation, radiation, and extinction of species and higher-order natural groups comprising a most recent common ancestor and all its descendants over long periods of time. In contrast, microevolution refers to changes in the genetic variation within a population (i.e. allele frequencies) due to natural selection (Campbell & Reece, 2005). Although both phenomena are well documented in the scientific literature, high school teachers often discuss natural selection without discussing examples of speciation on a long term, macroevolutionary scale (Berkman & Plutzer, 2011; Catley, 2006). For students to have a complete scientific understanding of evolution, students should learn examples of *both* micro- and macro-evolutionary biology (Catley, 2006).

Whereas past studies often focused on students' knowledge of natural selection, this study focuses on students' knowledge of macroevolution. In the context of this study, *selection* refers to: causes of phenotypic variation (e. g., mutation, recombination, sexual reproduction); (heritability of phenotypic variation; the over-reproductive capacity of individuals; limited environmental resources or carrying capacity; competition or limited survival potential; selective survival based on heritable traits; and changes in the frequency of individuals with certain heritable traits (Mayr, 1982, pp. 479-80). *Macroevolution* in this study refers to four biological tenets identified by Nadelson and Southerland (2010a). These tenets of macroevolution include phylogenetics, speciation, fossils, deep time. Nadelson and Southeland (2010a) also describe the nature of science (i.e. tentativeness, theory and law) as a tenet of macroevolution, but I consider this content to be conceptually different than macroevolution.

Knowledge of evolution and evolution acceptance. Several studies have hypothesized a potential link between scientific knowledge and acceptance of evolution. '*Acceptance'* in the case of these studies refers to personal recognition of evolution as representing the most powerful and most likely explanation for many natural phenomena. Interestingly, researchers have found little or no relationship between knowledge of natural selection and acceptance (Bishop & Anderson, 1990; Lord & Marino, 1993; Sinatra, Southerland, McConaughy, & Demastes, 2003). Science education researchers have also examined how teaching the nature of science promotes acceptance of evolution (e.g. Dagher & BouJaoude, 1997; Verhey, 2005; Cavallo & McCall, 2008). Providing students with an understanding of the nature of science allows students to perceive the boundaries of and distinguish between knowledge claims made by science and religion.

Although studies have found a link between knowledge of the nature of science and knowledge of natural selection, they have found little or no relationship between knowledge of the nature of science and acceptance (Butler, 2009).

Conversely, Nadelson and Southerland (2010b) reported that knowledge of macroevolution was correlated with acceptance of evolution for biology majors. This study promised to have major implications regarding inclusion of macroevolutionary concepts in biology curriculum. Considering the Nadelson and Southerland study and the importance of developing complete evolution curriculum for non-science majors, this study seeks to describe the relationship between non-science majors' knowledge of macroevolution and acceptance of evolution.

The importance of the teacher. A number of factors are important to consider in an investigation about how students learn evolution. This study will focus on the influence of the instructor, as teachers are cited as the most important factor in student learning (NRC, 1996) what students learn is greatly influenced by how they are taught (Brophy & Good, 1986).

Developing effective undergraduate instruction is complicated by teaching norms in university settings. Most general education classes are large-enrollment lecture courses taught in an auditorium and seventy to ninety percent of college instructors teach exclusively through lectures (Alters, 2005). Furthermore, instructors create lessons, select readings, and design assessments in the same way they always have (Wilson, 2010), calling on their experiences as learners to inform how they teach (Tobin, Tippins, & Gallard, 1994). This practice perpetuates ancient lecture norms and the assumption that teaching occurs by transmitting knowledge into empty minds. Even at Harvard

University, students from multiple disciplines (including science) have difficulty remembering fundamental science concepts (Schneps & Sadler, 1988). A primary reason for low scientific literacy among college graduates is poor teaching (Bok, 2006; Seymour & Hewitt, 1997), and behind the veil of poor teaching is a lack of pedagogical knowledge among faculty (DeHaan, 2005).

We cannot expect to improve teaching within the higher education community if we do not understand both the nature of pedagogical knowledge held by exemplary faculty members and how that knowledge informs instruction (Loughran, Berry, & Mulhall, 2006). Research into these areas can inform the goals and design of professional development programs that will in turn improve student outcomes (Abell, 2008).

Pedagogical content knowledge. The knowledge for teaching specific topics and within specific disciplines is described in the literature as pedagogical content knowledge (PCK, Shulman, 1986). Shulman (1987) identified PCK as a unique form of knowledge expressly for teaching. PCK in the context of this study is considered to be topic-specific (Hashweh, 1985; Magnusson, Krajcik, & Borko, 1999; van Driel, Verloop, & de Vos, 1998; Veal & MaKinster, 1999), in other words, the PCK necessary for teaching a specific topic in science (i.e. evolution, photosynthesis) would be unique to that topic. Teachers with rich topic-specific PCK know the most useful strategies for teaching a given topic, student learning difficulties and prior knowledge associated with that topic, the most effective assessment strategies to reveal students' understanding of the topic, how the topic relates within greater curriculum, and resources for curriculum.

We know little about the PCK of university faculty, including science faculty, as most literature describes the PCK of K-12 classroom teachers. The few studies of science faculty PCK have primarily focused on chemistry faculty and teaching assistants (e.g. Bond-Robinson, 2005; Padilla, Ponce-de-Leon, Rembado, & Garritz, 2008; Padilla & van Driel, 2011). More studies are needed on faculty from biology, physics (e.g. Jang, 2010), astronomy, and geology. Furthermore, past studies of faculty PCK focused on the instructors' knowledge of students and instructional strategies. These studies neglect other components of PCK in the Magnusson et al. (1999) PCK model - knowledge of assessment, curriculum, and orientations to teaching science (Figure 1). This study will focus holistically on investigating all components of PCK for the participant based on the Magnusson et al. (1999) model.

Summary of Objectives

The overall objectives of this study are to investigate (1) the nature and sources of an experienced biology professor's knowledge for teaching macroevolution, (2) how this knowledge influences the instructor's classroom practice, (3) how the instructor's classroom practice influences student knowledge of macroevolution and acceptance of evolution, and (4) to understand the relationship between acceptance of evolution and knowledge of macroevolution for non-biology majors. The results of the study will better inform goals for teaching evolution (Smith, 2009), refine standards for teaching evolution in grades 13-16 (Siebert & McIntosh, 2001), and inform the goals and design of professional development programs for faculty (Abell, 2008).

Conceptual Framework

Pedagogical Content Knowledge

Teaching is a complex cognitive activity that uses multiple knowledge domains.

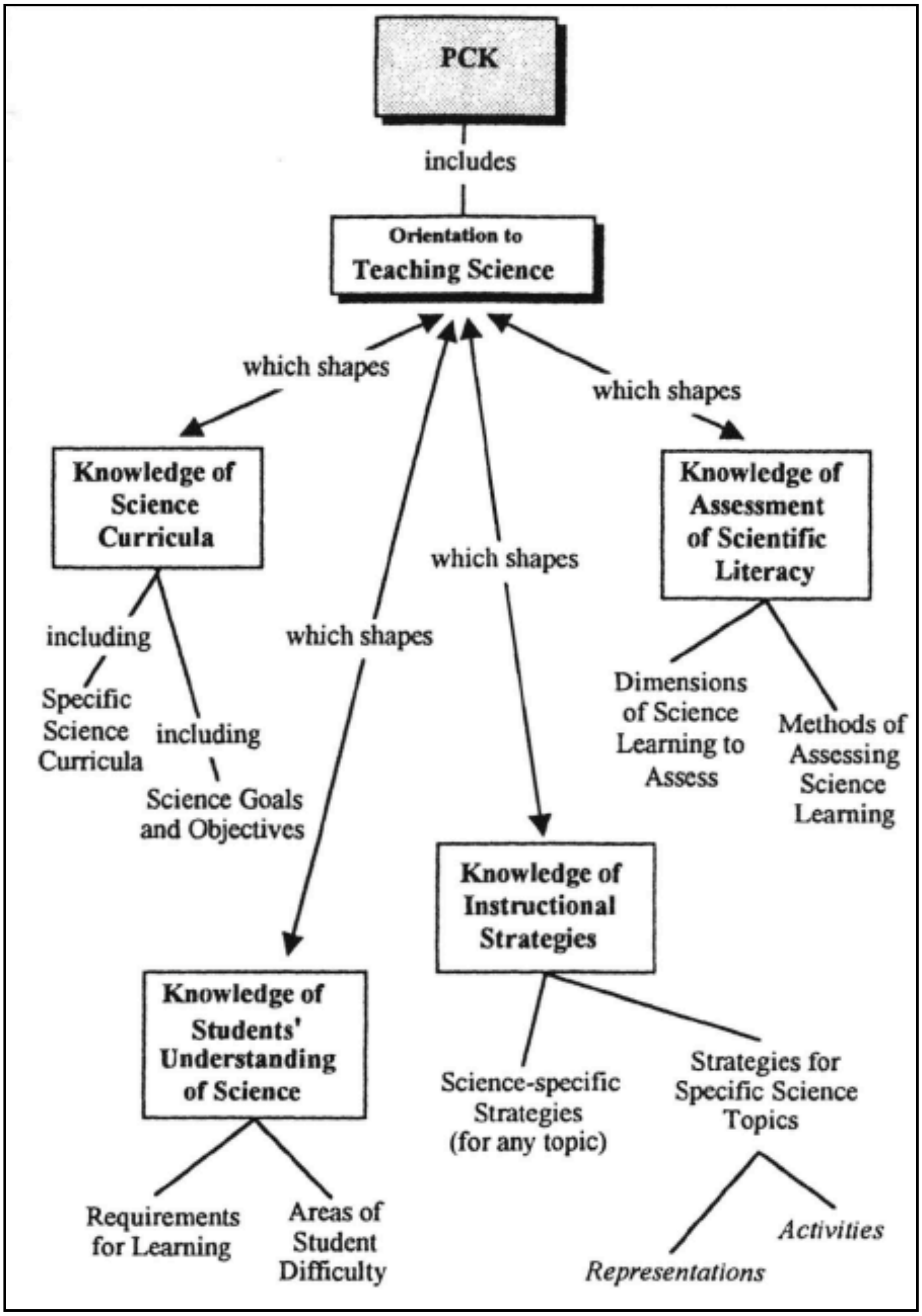


Figure 1. Components of pedagogical content knowledge for science teaching (Magnusson, Krajcik, & Borko, 1999, p. 99).

The knowledge for teaching specific topics and within specific disciplines is described in the literature as PCK. Shulman's (1986) model of PCK identified three general domains of teacher knowledge - content knowledge, PCK, and curricular knowledge. Content knowledge includes knowledge of substantive structures, the organization of basic principles, laws, and concepts within a discipline, and knowledge of how new knowledge is generated and validated (Schwab, 1978; Shulman, 1986). Curricular knowledge, also known as pedagogical knowledge (Grossman, 1990), includes knowledge of programs, resources, and instructional materials (such as textbooks) designed for teaching specific topics. PCK is a blend of several types knowledge at the intersection of content knowledge and pedagogical knowledge (Gess-Newsome, 1999). Teachers with rich PCK are described as knowing: "the most useful forms of representation… the most powerful analogies, illustrations, examples, explanations, and demonstrations -- in a word, the ways of representing and formulating the subject that makes it comprehensible for others" (Shulman, 1986, p. 9).

A framework for PCK. Grossman (1990) built on the work of Shulman (1986, 1987) by adding knowledge of context to the three main domains of teacher knowledge (knowledge of content, PCK, pedagogical knowledge). A popular theoretical model (Magnusson et al., 1999) breaks down the PCK construct into four component knowledge bases (Figure 1): *knowledge of students' understanding of science, knowledge of instructional strategies, knowledge of science curricula*, and *knowledge of assessment of scientific literacy* (p. 96). As knowledge components are drawn upon by the instructor, components shape and are shaped by a teacher's *orientation toward teaching science*. Magnusson et al. (1999) characterize *orientations* as the goals a teacher has for teaching science (e.g. to help students develop science process skills) and the nature of their instruction that accompanies such an orientation. Throughout this document I refer to the Magnusson et al. (1999) model as simply ‘the Magnusson model’ (see Figure 1).

- *Orientation to teaching:* Magnusson et al. (1999) describe orientation to teaching science as “the knowledge and beliefs possessed by teachers about the purposes and goals for teaching science at a particular grade level” (p. 97). The orientation that the teacher has for teaching science is a way of conceptualizing science teaching and learning. Teacher orientation acts as a “conceptual map” guiding decisions about learning objectives, implementation of curricular materials, and evaluation of students’ learning (Magnusson et al. 1999, p. 97)

- *Knowledge of science curricula:* Curricular knowledge references teacher understanding of the goals and objectives for student learning and the scope and sequence of the scientific concepts to be taught. Teacher knowledge of curriculum consists of two categories: (a) the mandated goals and objectives and (b) specific curricular programs, resources, and materials (Magnusson et al. 1999).

- *Knowledge of students’ understanding of science:* This component of PCK includes teacher knowledge of the requirements for student learning of specific scientific concepts and potential learning difficulties students may encounter when learning the concept(s) (Magnusson et al., 1999).

- *Knowledge of instructional strategies*: General teaching strategies such as the learning cycle, which have broad application in teaching within a scientific discipline (e.g., biology, chemistry, physics, etc.) are included in this component of PCK, as well as topic-specific strategies including ways to represent concepts (models, diagrams, pictures, tables, and/or graphs) and engage students with instructional strategies (investigations, experiments, demonstrations, simulations, problems or examples) to facilitate student learning of specific concepts in science (Magnusson et al. 1999).

- *Knowledge of assessment:* This component of PCK consists of (a) knowledge of the dimensions of science learning important to assess and (b) knowledge of assessment strategies and methods through which students’ learning can be assessed (Magnusson et al. 1999). Methods of effective assessment include informal, formative, and summative evaluations implemented to reveal student understanding implemented to assess students’ understanding of scientific concepts.

Although the Magnusson model does not graphically represent an interaction between the knowledge components - science curricula, assessment, student understanding and instructional strategies - these likely shape and inform one another

(Lankford, 2010; Verloop, van Driel, & Meijer, 2001) and are employed differently depending on context (Grossman, 1990). This study assumes that although PCK components likely interact with one another, they can be elicited separately through a methodological interview protocol (Appendix D) and focused observation, and can later be described as separate but not autonomous components.

PCK is topic-specific. I view PCK as topic-specific for the purposes of this study. Topic-specific PCK is described by Magnusson et al. (1999) as the knowledge, representations, and instructional strategies useful for teaching a specific topic in science, the knowledge of potential student learning difficulties and prior knowledge associated with the topic, knowledge of the most effective assessment strategies to reveal students' understanding of the topic, as well as knowledge of the science curriculum and curricular resources. In other words, the PCK for teaching macroevolution would look different than PCK for teaching a topic such as diffusion and osmosis. Each topic would require a different understanding of specific learner difficulties, pre- and alternative conceptions associated with the topic, specific knowledge of representations, instructional strategies, assessments, and curricular resources necessary to create meaningful learning opportunities.

How the Magnusson Framework Informs This Study

PCK is a useful organizing framework for understanding the major components of teacher knowledge for a given topic (Abell, 2008). In this study, I am investigate the nature and sources of the instructor's knowledge for teaching macroevolution and how this knowledge informs instruction. The Magnusson et al. (1999) model of PCK will inform my research questions, data collection, and analysis. The research questions specifically ask about the nature and sources of the instructor's PCK for teaching macroevolution and how this knowledge informs instruction. The pre-instruction interview, stimulated recall interviews, post-instruction interview and observation protocol (Appendix D) are designed around the five Magnusson et al. components of PCK. In coding the instructor interview, observation, and artifact data, I will use the Magnusson model components as initial coding categories. In the following section, I describe a framework for student learning that informed coding student interview data in a similar fashion.

Theoretical Framework: How Students Learn Science

Overview

Faculty in higher education are being asked to replace traditional methods of teaching with more learner-centered, student-engaged, interactive strategies informed by constructivist learning theory (Bransford, Brown, & Cocking, 2000). Bransford et al. (2000) frame student learning through a constructivist lens, wherein students learn by organizing new information around their existing knowledge and experiences. Bransford et al. provide a broad overview of how students learn and organize these ideas around a framework of three key findings about how students learn science (pp. 14-18): "(a) students have preconceptions about the natural world which must be engaged by the instructor; (b) students must develop rich factual knowledge nested in an easily accessible conceptual framework; and (c) students must be able to reflect on their own learning and monitor their own progress". The course selected for this study specifically fit these necessities for learning, and the student interview protocol (Appendix E) was likewise structured around the Bransford et al. (2000) framework.

Principle 1. Teachers Must Engage Students' Preconceptions

Students come to the classroom with preexisting ideas about the world. Teachers must recognize and engage with these previous understandings and experiences; without this engagement, students may not incorporate new concepts into their understanding or blindly memorize concepts for the test and later return to their prior conceptions (Bransford et al., 2000). One method for teachers to engage student preconceptions is through expanding the role of traditional assessment. The frequent use of formative assessment allows students' ideas to be clear to themselves (note *Principle 3)*, their peers, and the instructor throughout a course. These assessments also help teachers identify student preconceptions and alternative conceptions that can then be engaged, modified and refined as necessary. Furthermore, assessments provide the teacher the ability to perceive where students are in the "developmental corridor" from informal to more formal, structured thinking (note *Principle 2)*. In the course selected for this study, a personal student response system (clickers) is used for formative assessment. Clickers are radio-frequency, battery powered, hand-held devices that are part of an electronic polling system. In the context of this study, the students were polled with three multiple choice questions every class period. The predominant research about clicker use in science classrooms has found that clickers promote student discussion, increase engagement and feedback, and improve attitudes toward science (Draper & Brown, 2004; Duncan, 2005; Latessa & Mouw, 2005).

Principle 2. Students Must Develop Deep, Structured Understanding

To develop competence in an area of inquiry, students must (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application (Bransford et al., 2000). Teaching for deep understanding requires providing many examples of the same concept at work and a foundation of basic knowledge. In the case selected for this study, the instructor provides a number of macroevolution cases during the evolution unit to allow students to grasp defining concepts. Formative assessments (note *Principle 1)* informs which of these cases would be most meaningful for the students.

A key difference between the students and the instructor is the ability to organize information into a conceptual framework that can to be applied to new situations. The course instructor in this study has rich knowledge of evolutionary principles, which informs her instruction. This structured order of topics is likely informed by her knowledge of the growth and development of students' ideas over time.

Principle 3. Curriculum Should Be Structured for Metacognition

Metacognition, or thinking about one's own thinking (Metcalfe & Shimamura, 1994) often takes the form of internal dialogue. An emphasis on this type of thinking, which often goes unnoticed by the student, is important to make explicit during instruction. Strategies to encourage students to think about what they know and why they know it include formative assessments into instruction, such as the aforementioned clicker assessments.

How the Bransford framework informs this study. The course selected for this study fits the three principles required for learning science outlined by Bransford et al. (2000): the instructor accesses and engages student preconceptions, develops deep understanding and a conceptual framework for the students, and includes metacognitive tasks. The case therefore fits the theoretical framework, has the potential to support the development of macroevolution understanding, and could inform important outcomes. Understanding how and why macroevolution knowledge and acceptance are informed by instruction has the potential to inform the design of more effective evolution curriculum.

The Bransford et al. (2000) framework informed data collection of the study. The student interview protocol (Appendix E) was designed to elicit requirements for learning from the students based on the Bransford et al. (2000) principles. For example, students were asked to explain their understanding of macroevolution and evolution acceptance prior to and after instruction. Secondly, question on the student interview protocol focus around instructional instances that the students recall as helpful or memorable, as well as instances which the researcher believes could have influenced their learning. Lastly, the student interview questions were written to elicit why students changed their responses pre-instruction to post-instruction on the two quantitative instruments, the Measure of Acceptance of the Theory of Evolution (MATE; Rutledge & Warden, 1999; Appendix C) and the Measure of Understanding of Macroevolution (MUM; Nadelson & Southerland, 2010a; Appendix B). Qualitative data analysis of interview data using the Bransford framework as well as quantitative analysis of the pre- and post-instruction MATE/MUM data will elicit the nature of student understandings about macroevolution and evolution acceptance as well as the most meaningful instructional practices from the perspective of the students.

Significance

As science education researchers begin investigating the relationship among PCK, classroom practice, and student outcomes, it is most appropriate to examine PCK for a teaching a topic that is both central to a scientific discipline and conceptually challenging for students. Subsequently, this study explores an experienced biology professor's PCK for teaching macroevolution, how this knowledge informs instruction about macroevolution, and how the instruction influences students' knowledge of macroevolution and acceptance of evolution. This study was therefore guided by the overarching research question: *How does the nature of macroevolution instruction influence student understanding of macroevolution and student acceptance of evolution in a non-majors' biology course?*

Foremost, this study has significance as evolution is a foundational component of biological literacy (AAAS, 2011) and is difficult for students to comprehend (Bishop & Anderson, 1990; Demastes, Good, & Peebles, 1996; Moore et al., 2002). Within the discipline of evolution, curriculum that focuses macroevolution has been described as the "single most effective advance that can be made in educating the public about evolution" (Padian, 2010, p. 206). Since macroevolution is a critical and underappreciated component of biological literacy, and because the teacher is the most important factor in how students learn, this study examined how an experienced biology professor's PCK for teaching macroevolution influenced student learning outcomes.

This study is also significant as it examines how PCK influences student outcomes (Abell, 2008), in this case, knowledge of macroevolution and acceptance of evolution. Knowledge of macroevolution and evolution acceptance were chosen as student outcomes as these components are correlated for biology majors (Nadelson & Southerland, 2010b). Past studies which have found little relationship between components of biological knowledge (i.e. knowledge about the nature of science and knowledge of natural selection) and evolution acceptance. This study was therefore investigated the unknown relationship between knowledge of macroevolution and evolution acceptance for non-biology majors. Understanding the relationship between macroevolution and acceptance for this population may have transferrable implications for evolution literacy in the general public and also imply the need for macroevolution content in the general education biology course (i.e. *Vision and Change* [AAAS, 2011]).

Lastly, the student is significant as it addresses a gap in the literature for PCK faculty in the biological sciences and college faculty in general. Specifically, science education researchers know little about faculty knowledge of assessment, knowledge of curriculum, and general teaching orientations. The study holistically examines the PCK of an experienced biology professor through the lens of all components of the Magnusson et al. (1999) model - knowledge of students, instructional strategies, curriculum, assessment, and orientations toward teaching science, including the sources of that PCK. Understanding these components can inform goals for faculty professional development that will in turn improve student outcomes (Abell, 2008).

Organization of the Dissertation

The dissertation is organized into five chapters. Chapter One is an overview of the study including the rationale, research questions, conceptual and theoretical frameworks, and significance of the study. Chapter Two is a review of research on evolution education and a review of influential studies that examine the PCK of college faculty. This review describes relevant research regarding the two primary foci of the case study - undergraduate non-science majors' macroevolution knowledge and acceptance of evolution and the instructor's PCK for teaching macroevolution.

Chapter Three outlines the research questions for the study and the methods by which each research question will be addressed. This includes a description and rationale for the embedded single case study design and the choice of a sequential explanatory mixed methods approach. I also provide details on the context of the study, data collection strategies and data analysis methods. The chapter concludes with quantitative assumptions and a description of the trustworthiness of the design, validity and reliability measures, and implementation of the study.

Chapter Four describes the findings of the study with the purpose of answering the research questions. I first provide a rich description of the case, including a case profile for the instructor and a description of the course. I then describe the nature and sources of PCK for the faculty participant. This piece is then connected to student outcomes through a description of how the instruction influenced student learning outcomes. Lastly, I provide the results of quantitative and qualitative analyses related to students' knowledge of macroevolution and evolution from pre- and post-instruction.

Chapter Five is the final chapter; it begins with a summary of the findings in Chapter Four in relation to the research questions. This is followed by a discussion of the findings in relation to previous work which highlights my contributions to the literature. The chapter concludes with implications for practice, policy, and recommendations for future research.

CHAPTER TWO: LITERATURE REVIEW

This literature review includes two major sections, a review of research on evolution education and a review of influential studies which examine the pedagogical content knowledge of college faculty. The review describes relevant research regarding the two primary foci of the case study - undergraduate non-science majors' macroevolution knowledge and acceptance of evolution and the instructor's PCK for teaching macroevolution.

Review of Research on Evolution Education

The purpose of this portion of the literature review is to highlight major areas of research in evolution education and how these inform the dissertation study. The review focuses primarily on research conducted on the population of interest - undergraduate non-science majors. However, as some areas of evolution education are under-researched for this population, I also discuss relevant research on other populations (e.g. middle and high school students, biology majors, and K-12 teachers), with the understanding that the results of these studies may not be transferrable to non-science majors.

The first section reviews psychological constructs that influence how people think about evolution. The subsequent section is a synthesis of the research on students' knowledge of science content related to learning evolution, including knowledge of natural selection and knowledge of macroevolution. The final section explores studies that consider student acceptance of evolution, including those which consider a relationship between acceptance and knowledge of natural selection, macroevolution, and the nature of science.

Psychological Constructs that Influence Evolution Learning

Several studies examine psychological factors that may influence college students' evolution learning. These factors include cognitive biases (Evans, 2000, 2008; Gelman, 2003; Medin & Atran, 2004; Wellman & Gelman, 1998), intellectual development barriers (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000), dispositional and motivational barriers (Brem, Ramsey, & Schindel, 2003; Sinatra, Southerland, McConaughy, & Demastes, 2003), epistemological beliefs (Vosniadou & Brewer, 1992), and religious beliefs (Almquist & Cronin, 1988; Hokayem & BouJaoude, 2008; Sinclair, Pendarvis, & Baldwin, 1997). These factors are described in the section that follows as they provide practical insight into student learning of evolutionary concepts.

Cognitive biases. Humans have cognitive biases that are inherent to how we think, and these can have an effect on learning evolution. Three underlying cognitive biases exist as barriers to understanding evolutionary theory for college students, and this network of intuitive beliefs constrains human thinking (Evans, 2008). These essentialist, teleological, and intentional biases lead students to see their everyday world as unchanging, orderly, and commonsensical. Learning evolution may subsequently require students to think about the world in a different way than they normally would (Sinatra, Brem, & Evans, 2008). These biases are also partially responsible for why evolutionary ideas are inherently counterintuitive and not as 'contagious' as creationist ideas (i.e. Biblical literalism)(Evans, 2008).

Essentialist bias. The first of these cognitive biases is essentialism, the tendency to believe that all living things have a unique identity (Gelman, 2003). This "essence" of living things is perceived as absolute, i.e. one living thing cannot become another. It follows that species evolving into different lineages seems impossible. Essentialist biases are most common among children, but adults may also think this way when they encounter something unusual - like evolution (Evans, 2008).

Teleological bias. Another group of cognitive biases that influence evolution learning are teleological biases - assumptions that nature is directed toward a particular goal or that things are made for a purpose. Both children and adults find purpose-based accounts of living things as more plausible than those that are not (Sinatra et al., 2008). Even college-educated adults use teleological explanations (Kelemen & Rosset, 2009), a bias that may be correlated with personal belief in souls (Kelemen & Rosset). Naturalistic ideas, such as natural selection, contradict teleological assumptions. Natural selection is contingent on environmental pressures and is non-directional. Conversely, teleological biases are often behind Lamarckian misconceptions of evolution – e.g. thinking that giraffes have long necks for the purpose of eating treetop leaves.

Intentionality bias. Closely related to teleological assumptions are a final group of biases considered intentionality biases, the tendency to think that events are caused by an intentional agent. The intelligent design movement is based on the assumption that God intentionally planned the world (Evans, 2000). For this reason, creationist and intelligent design ideas are more easy to understand than scientific explanations because they reinforce how people intuitively think (Evans, 2008). One of the incorrect answers for Question 23 on the Measure of Understanding of Macroevolution (MUM, Nadelson & Southerland, 2010a) states that humans *want to* evolve and are a superior species. Selecting this answer would indicate an individual had an *intentionality* bias.

Intellectual development barriers. Beyond cognitive biases, meaningful learning of science concepts is also related with a cognitive operational stage. Piaget (1952) described the 'formal operational' level of conceptual development, achieved from age 12 and adult, as the pinnacle of learning. However, post-formal intellectual development during the college years (beyond Piaget's formal operational level) may be necessary for students to fully comprehend evolution (Evans, 2008).

Post-formal cognitive skills include the ability to understand entities that cannot be observed (Perry, 1970). As many as two thirds of introductory biology students lack post-formal level skills (Lawson et al., 2000). Since evolution, natural selection, convergent evolution, artificial selection, and fossils can only be observed over prolonged periods of time (relative to the species), these ideas are difficult for students to understand (Lawson et al., 2000). If college students are to completely comprehend evolution, instructors need to employ strategies that support intellectual development and use of post-formal thinking skills.

Dispositional and motivational barriers. Learning can be influenced by affective constructs (Strike & Posner, 1992) and can be in conscious control of the learner (Sinatra et al., 2003; Southerland & Sinatra, 2003). Psychological mechanisms and strategies toward thinking and learning may subsequently play an important role in how students learn evolution (Sinatra et al., 2003).

Students with particular dispositions are more likely than others to learn through conceptual change (Pintrich, Marx, & Boyle, 1993). Students with a mastery orientation have intentional goals of learning for learning's sake, matching their ideas to those of the instructor, and often use effective study strategies. These students are more likely to be open to learning about and accepting evolution (Sinatra et al., 2003). Their disposition toward open-minded thinking allows these students to consider and evaluate alternative perspectives, a necessary step in conceptual change learning. Students that are not open to new ideas (such as evolution) will seek evidence to confirm non-scientific alternatives (Hodson, 1998; Sinatra et al., 2003).

Evolution can be emotionally unpleasant to contemplate. Brem et al. (2003) noted that college educated adults perceived evolution as something that made people more racist, less able to accept spiritual ideas, and reduced one's sense of purpose and determination. Similarly, some high school teachers experience measurable stress when thinking about teaching evolution (Griffith & Brem, 2004). Emotions surrounding evolution can remove attention away from the task or decrease motivation and therefore may prohibit evolution learning. Instruction that directs attention and increases student motivation is thus more likely to support evolution learning.

Epistemological beliefs. Most students enter college with dualistic epistemologies (Perry, 1970), and these beliefs are important to consider when teaching evolution. Epistemological dualists view the world in terms of black/white or right/wrong. Students with dualistic worldviews are less comfortable with ambiguous data, and are often less knowledgeable and accepting of evolution (Sinatra et al., 2003). Dualistic students will also passively ignore information that is contradictory to their worldview.

Professors should be aware of this bias and use methods that encourage students to accept that uncertainty is real and unavoidable. These methods can help scaffold students to epistemological multiplicity (Perry, 1970). Most college graduates achieve multiplicity as an approach to complex problems (King & Kitchner, 1994). This may be one of the reasons why college educated adults are more likely to accept evolution than those that do not complete college (Newport, 2009). Unfortunately, individuals can temporarily regress into a dualistic worldview when confronted with new or challenging situations, such as learning evolution (Chi, Leeuw, Chiu, & Lavanchar, 1994; Chinn & Brewer, 1993).

Unfortunately, forced-choice traditional assessment methods, such as knowledge-level multiple choice exams reinforce dualistic epistemologies (Alters, 2005). Although the instruments selected to evaluate students' knowledge and acceptance of evolution in this dissertation do not address epistemology, themes related to students' epistemologies will be discussed as appropriate.

Religious factors. Cognitive biases, intellectual development requirements, dispositional, motivational and epistemological barriers must be surmountable as widespread acceptance of evolutionary theory exists in most of western Europe (>80% acceptance)(National Geographic, 2005). However, among Americans with some college education, 49% accept the theory of evolution for plants and non-human animals, and 22% agree that humans evolved from earlier species (Lovely & Kondrick, 2008). These low acceptance rates are due in part to perceived conflicts between religion and evolution. While there are certainly some religious ideas that explicitly contradict science (e.g., the belief that the Earth is 6,000 years old), many religious groups have no conflict with the theory of evolution (Pennock, 2001; University of California at Berkeley [UC Berkeley], 2008) and only 30.8% of Christian denominations in the United States have formal statements in opposition to evolution (Martin, 2010). Muslim students have also been known to have conflicted views about evolution (e.g. Hokayem & BouJaoude, 2008).

McKeachie, Lin, and Strayer (2002) examined the effects of creationist beliefs in American community college students learning evolution (N=60). Students rated themselves along a continuum from rejecting to accepting evolution. Individuals that rated themselves in the middle of the continuum between rejection and acceptance made the greatest shifts in their evolution acceptance after the course and did better in the course academically. Students who did not accept evolution relied more heavily on memorization than other students and did not perform as well in the course. The results of McKeachie et al. (2002) are contested by Smith (2002), noting that some of their questionnaire items were “double-barreled”. For example, one of the questionnaire options was “I accept evolution as a proven fact.” Although evolution is strongly supported by evidence, proof is not possible in science. A student could subsequently mark this statement false due to a strong understanding of the nature of science.

Perceived conflict between evolution and religion has also been studied in biology majors in Lebanon. Hokayem and BouJaoude (2008) noted that biology majors’ saw evolution theory as a theory deficient in trustworthy evidence, proof, or validity, different from other scientific theories, and as missing steps or not following ‘the scientific method’. The authors infer that these views may have been influenced by perceived conflict between literal Muslim beliefs and evidence for evolution.

Studies on Students' Knowledge of Evolution Content

This section of the literature review examines two sub-components of understanding science content related to evolution, (a.) student knowledge of natural selection and (b.) student knowledge of macroevolution (i.e. deep time, phylogenetics, speciation, fossils, and nature of science; Nadelson & Southerland, 2010a). I review the work on natural selection because early studies that focused on student understanding of evolution focused on the topic and provide important context to the study.

Student understandings about natural selection. Comprehension of evolution content includes understanding the individual concepts that comprise natural selection theory (Passmore & Stewart, 2000). The biological mechanisms of natural selection were described by Mayr (1982) as facts and inferences of the theory: "(1) causes of phenotypic variation (e. g., mutation, recombination, sexual reproduction); (2) heritability of phenotypic variation; (3) the over-reproductive capacity of individuals; (4) limited environmental resources or carrying capacity; (5) competition or limited survival potential; (6) selective survival based on heritable traits; and (7) changes in the frequency of individuals with certain heritable traits" (pp. 479-80). The scientific explanations of these seven key concepts are explained in Appendix A.

Mayr's key concepts are often used as guidelines to describe student knowledge of natural selection (Anderson, Fisher, & Norman, 2002; Bishop & Anderson, 1990; Nehm & Reilly, 2007; Nehm & Schonfeld, 2008). Herein, key conceptual ideas about evolutionary mechanisms are referred to as *natural selection knowledge*. Natural selection knowledge is influenced by prior knowledge that students bring to the classroom. Sometimes this knowledge matches scientific ideas and sometimes students have different, alternative conceptions. Alternative conceptions can make up a large portion of student knowledge of natural selection. These ideas are highly resistant to instruction (Bishop & Anderson, 1990; Demastes, Settlage, & Good, 1995; Nehm & Reilly, 2007). A plethora of alternative conceptions about natural selection have been documented for non-majors (Anderson et al., 2002; Bishop & Anderson, 1990; Demastes et al., 1995), first semester biology majors (Dagher & BouJaoude, 1997), second semester biology majors (Nehm & Reilly, 2007; Nehm & Schonfeld, 2008), and junior and senior majors (Dagher & BouJaoude, 2005; Hokayem & BouJaoude, 2008).

Instruments to measure of student understanding of natural selection. One measure of students' understanding of natural selection is the Conceptual Inventory of Natural Selection (Anderson et al., 2002). The CINS is a concept inventory developed in response to previous instruments (Bishop & Anderson, 1990; Settlage & Odom, 1995) because the authors found the old instruments to be overly simplistic and abstract. Their solution to this was to develop an instrument that used actual evolutionary examples (e.g. Galapagos finches, Venezuelan guppies *Poecilia reticulata*, and Canary Island lizards).

The 20-item CINS was therefore developed to measure non-science majors' understanding of natural selection. It was designed to have one correct answer and three distracter answers based on common alternative conceptions about natural selection (Table 1). The questions on the CINS target the seven key concepts of natural selection (Mayr, 1982) and two additional key concepts (origin of variation and origin of species). Two questions target each key concept to enhance reliability.

Other tools exist to assess knowledge of natural selection, including an open response instrument (ORI) developed by Nehm and Schonfeld (2008). The ORI was

Table 1

Descriptions of Common Alternative Conceptions of Evolution and the Studies that Document These Conceptions

Alternative conception	Examples	Population	Reference
Inheritance of acquired characteristics (Lamarckian)	• Traits acquired during an organism's lifetime will be inherited by offspring	Second semester freshman biology majors Medical students	Nehm and Schonfeld (2008) Brumby (1984)
Origin of species	• Organisms can intentionally become new species over time (an organism, tries, wants, or needs to become a new species)	Non-majors Second semester freshman biology majors	Anderson, Fisher and Norman (2002) Nehm and Schonfeld (2008)
Origin and role of variation	• Mutations are adaptive responses to specific environmental agents • Mutations are intentional: an organism tries, needs, or wants to change genetically • Genetic drift can cause variation • Dominant alleles are always selectively advantageous	Non-majors Second semester freshman biology majors	Bishop and Anderson (1990) Demastes, Settlage, and Good (1996) Anderson et al. (2002) Nehm and Reilly (2007)
Change in a population over time	• Changes in a population occur through gradual change in all members of a population • Learned behaviors are inherited • Mutations occur to meet the needs of the population	Non-majors Sophomore non-majors	Anderson et al. (2002) Greene (1990)
Use and disuse	• When a trait (organ) is no longer beneficial for survival, the offspring will not inherit the trait	2nd semester freshman biology majors	Nehm and Schonfeld (2008)

designed to measure undergraduate biology majors' knowledge about natural selection at differing levels of complexity. The five open-response questions on the instrument are ordered such that they began by requesting familiar concrete knowledge (e.g., ‘‘define natural selection’’) and end with unfamiliar abstract problem-solving questions (e.g., ‘‘how might a biologist try to speed up evolutionary change?’’). The CINS combined with the ORI may be a suitable replacement for time-consuming interviews with students about their knowledge of natural selection.

Non-science majors' knowledge of natural selection. Prior to instruction, non-science majors have few scientific understandings about evolution, regardless of previous instruction (Bishop & Anderson, 1990; Demastes et al., 1995). As few as 4% of non-majors understand how new traits arise in a population, 7% how variation functions in a population, and 3% understand how the population changes over time (Demastes et al., 1995).

After a unit specifically designed to address common alternative conceptions about natural selection, students still thought: (a) changes in traits were attributed to a need-driven adaptive process rather than random genetic mutation and sexual recombination, (b) variation of traits within a population were not linked to differences in reproductive success, and that (c) traits gradually change in all members of a population (Bishop & Anderson, 1990). However, students' use of scientific conceptions increased from less than 25% to just over 50%.

In a similar study of non-science majors using the CINS, students likewise had difficulties with natural selection after instruction. Students struggled with understanding the origin of phenotype variation (14.5% correct), origin of new species from existing ones (22.3% correct), and how populations change over time (18.2% correct)(Anderson et al., 2002). However, it is unclear if their difficulty on these particular topics was because questions on the CINS were too difficult or if these were genuine difficulties for the students (Nehm & Schonfeld, 2010).

Biology majors' knowledge of natural selection. Like non-science majors, biology majors enter the classroom without working knowledge of natural selection (Nehm & Reilly, 2007). In an open response instrument administered prior to a 12-week course, 27.4% of the second semester freshmen did not mention any key concepts of natural selection, 37.8% noted one key concept, and only 3.2% employed four or more key concepts. Surprisingly, these low percentages are for students that had completed one semester of introductory biology (genetics and phylogeny) and most (83%) had natural selection instruction in high school.

During the year-long course, one cohort of students (n=89) received active learning instruction with integrated evolution content throughout the semester, and the other group (n=100) had traditional, lecture-based instruction with a discrete evolution unit. Active learning activities included cooperative learning strategies, inquiry-based instruction, paired and group problem solving, and small group discussion (Nehm & Reilly, 2007). Due to its integrated nature, the active learning group discussed natural selection in 70 more classes than the traditional lecture group. The active learning group also had daily instruction on the nature of science.

After the course, the open response instrument was re-administered and semi-structured interviews were conducted. Seventy percent of the students in the active learning group employed more than four key concepts, significantly more than the 58%

that achieved this benchmark in the traditional methods group ($p<0.05$). The active-learning class was characterized by fewer misconceptions post course than the traditionally taught course (4.33 average key concepts used vs. 3.78), but these values were not statistically significant. Unfortunately, 70% of the active learning class and 86% percent of the traditionally taught class still employed one or more misconceptions after instruction. Furthermore, both classes exhibited an unsatisfactory understanding of natural selection after instruction as measured by a composite measure of key concepts and alternative conceptions. These findings confirm that active learning and integrated evolution content throughout a course may not fully promote conceptual change.

In a related study, Nehm and Schonfeld (2008) tested freshman biology majors for key concepts and alternative conceptions about natural selection after instructional units on evolution and natural selection. They did not discriminate results based on the type of instruction as Nehm and Reilly (2007). Data were gathered using the ORI, the CINS (Anderson et al., 2002), and an extended oral interview. Sample G participants (n=100) completed both the CINS and the ORI. Eighteen of Sample G participants also completed the oral interview. Sample N participants (n=82) completed only the ORI due to a time constraint. The three instruments captured key concepts and alternative conceptions at differing frequencies, but both instruments captured all seven key concepts of natural selection (Mayr, 1982). The most commonly understood key concept was the differential survival of offspring (91.5% Sample N, 74% Sample G). Overproduction of offspring was the least commonly used key concept in Sample N (18%) and competition/ limited survival potential was the least commonly used concept in Sample G (9%).

Interviews provided strong support for validity (these measure what they should) and reliability (similar results test after test) with the ORI and CINS.

Summary. Studies of natural selection education have indicated that students do not make substantive gains in knowledge with instruction and continue to hold a number of misconceptions. These low levels of evolutionary knowledge and high levels of evolutionary misconceptions are harbored by non-science majors (Bishop & Anderson, 1990), biology majors (Dagher & BouJaoude, 1997), and medical students (Brumby, 1984).

Student knowledge of macroevolution. Most research on students' understanding of evolution has been focused on their understanding of natural selection (e.g. Anderson, Fisher, & Norman, 2002; Nehm & Schonfeld, 2008). Since natural selection is only a portion of evolutionary knowledge, this study explored students' knowledge of macroevolution. In recent years, several authors have noted this imbalance, arguing that macroevolutionary concepts should be taught at the college level (e.g. Baum, Smith, & Donovan, 2005; Catley, 2006; Gregory, 2008). For example, Padian (2010, p. 206) argues that "a full and straightforward exposition of macroevolution in seventh-grade life-science texts, high school biology texts, freshman-level college biology texts, and upper division texts in evolution and related subjects is the single most effective advance that can be made in educating the public about evolution".

The purpose of this subsection is to discuss past research on students' understandings of macroevolution. The subsection is organized by the core concepts in Nadelson and Southerland (2010a): deep time, fossils, phylogenetics, speciation, and the nature of science. Due to the relatively under-researched of knowledge of these core concepts, I draw from studies of populations besides non-science majors. These studies provide baseline data for understanding the nature of macroevolution knowledge for college students and should not be assumed to be transferrable.

Deep time. Geologic time is often referred to in the literature as 'deep time'. Deep time is one of the most fundamental concepts in developing an understanding of evolution (Dodick, 2007; Dodick & Orion, 2003) because most speciation cannot be directly observed on human time scales (Libarkin, Anderson, Dahl, Beilfuss, & Boone, 2005). Knowledge of deep time has two primary components (Nadelson & Southerland, 2010a): (a) knowledge of specific events and the date of those events (i.e. the mass dinosaur extinction 65 million years ago) and (b) the sequence of such events (Novick & Catley, 2008). The history of life as an evolutionary sequence has been proposed as critical to scientific literacy as it provides a powerful predictive framework for understanding macroevolution (Catley & Novick, 2008; Novick & Catley, 2012).

Although students can usually sequence events in the correct order (Catley & Novick, 2008; Libarkin, Kurdziel, & Anderson, 2007), they usually have poor understanding of the actual date of these events (Libarkin et al., 2007). They may have extreme variability in their estimates of deep time (ranging over eight orders of magnitude). Students may also underestimate the amount of time that has passed since an evolutionary event (a phenomenon called forward telescoping) (Catley & Novick, 2009).

Hidalgo, Fernando, and Otero (2004) conducted a study of students' knowledge of both geological and evolutionary deep time. Their subjects were Spanish secondary

(16-year-olds) and post-secondary (19–20-year-olds) students who had completed several geology courses. Subjects sequenced four pictured scenarios of biological evolution and provided absolute time estimates for these scenarios: invertebrate marine taxa with a largely lifeless terrestrial background, a landscape containing dinosaurs, a landscape with birds and mammals, and a group of ‘‘hominids.’’ About 56% of the 16-year-olds and 83% of the 19–20-year-olds were able to correctly order the events, However, only 17% of the 16-year-olds and none of the 19–20-year-olds were able to provide correct time frames, even to an order of magnitude.

College students’ also struggle with estimating the amount of time between geologic events. When constructing timelines, they have difficulty estimating the amount of time between the formation of Earth, the time of the first life forms (prokaryotes) and the evolution of dinosaurs and humans (Libarkin et al., 2007). Similarly, Libarkin, Anderson, Dahl, Beilfuss, Boone & Kurdziel (2005) found that about 10% of college students consider the formation of Earth and the origin of life as the same event. These difficulties with deep time suggest that some (if not most) college students are without an effective conceptual framework to think about large time scales (Catley & Novick, 2009). Despite students’ difficulty with specific dates, they still have a concept of relative time. Trend (2001) noted that his participants (in-service teachers) perceived geologic events in relative time clusters: extremely ancient, moderately ancient, and less ancient. However, participants had difficulty sequencing events with each relative time cluster.

Learning about deep time is important as it may influence understanding macroevolution (Catley, Lehrer, & Reiser, 2004; Dodick, 2007). Learning about fossil and rock evidence during geology fieldwork influenced grade 12 students’ ability to construct a sequence of geological events over time (Dodick & Orion, 2003). Learning about fossil evidence in the general education biology course may similarly help students understand the sequence of biotic events over time (i.e. the history of life). Students with less than 0.5 semesters of biology coursework use more extreme high and low time estimates than students with an average of 3.2 semesters of biology and geology coursework (Catley & Novick, 2008). There may be an influence of one semester of biology coursework on students' ability to make approximations of deep time.

Fossils. Closely related to the understanding of deep time is the comprehension of the formation, location, discovery, and interpretation of fossils (Dodick & Orion, 2003). Fossils are a fundamental source of evidence to support macroevolution (Dodick & Orion, 2003; Gould, 2002) and general age of the Earth (Libarkin & Anderson, 2005). Knowledge of the formation of fossils is likewise important for understanding why there are gaps in the fossil record. An additional advantage to using the fossil record for illustrating evolution is that it establishes the concrete validity of the process (Dodick & Orion, 2003). Although fossils are an important aspect of macroevolution, fossil concepts are typically integrated into geological science courses, not biology courses (Libarkin & Anderson, 2005). The detection and retention of fossil misconceptions among students suggests that learners exiting high school biology courses have a limited understanding of fossils and their importance as evidence for macroevolution (Libarkin & Anderson, 2005).

Phylogenetics. Phylogenetics is the branch of biology that constructs and tests phylogenetic trees. Phylogenetic trees (also called cladograms) represent patterns of evolutionary relationships related to shared common ancestry. These trees have substantial visual conventions that are not necessarily intuitive, and can be difficult for novices to correctly interpret (Halverson, 2009). This is problematic as phylogenetic trees are included in biology textbooks, science museums, and other places frequented by the general public (Halverson, 2009). Poor content understanding, along with the non-intuitive nature of these trees can lead to students misinterpreting the meanings represented within the branching structures of the diagram. Misinterpreting how evolution explains change over time and relatedness could subsequently have a negative impact on students' acceptance of evolution.

Gregory (2008) highlighted ten common misconceptions that individuals have about interpreting phylogenetic trees. These were based in part by the work of Meir, Perry, Herron and Kingsolver (2007). These ten common tree thinking misconceptions include (1) higher and lower: the perception that organisms higher on a tree are more complex; (2) main lines and side tracks: the perception that the evolutionary tree culminates with the organism farthest away from the root; (3) reading across the tips: looking at the tips of the tree instead of the branching structure; (4) similarity versus relatedness: using similar features of organisms to determine relatedness of species instead of the branching structure; (5) sibling versus ancestor: a group is mistaken as descended from its sister group instead of the two sharing a common ancestor (i.e. humans evolving 'from' monkeys); (6) long branch no change: the length of the lines indicates a period of no evolutionary change; (7) modern species are assumed to be older lineages than those that have gone extinct; (8) backwards time axes: students interpret the location of the terminal nodes as indicative of time; (9) node counting: counting splits in the tree structure between species to determine relatedness and (10) change only at the nodes: species are only undergoing changes at the nodes (points of speciation) and not along the lines (time spent undergoing natural selection).

Speciation. All species of life on Earth are considered related as all have descended from a common ancestor (Gould, 2002), and the diversity of life on Earth has resulted from combination of mutations, natural selection, and chance (Futuyma, 2005). This is a challenging idea for learners to grasp, in part because of a lack of models to aid in the conceptualization of common ancestry. Examples of subtle differences that separate closely related species (i.e. Galapagos finches) are useful for explaining natural selection, but a focus on these concepts further supports a microevolutionary perspective of evolution (Catley, 2006). Little research has been done specifically on student knowledge of speciation, but we know that even after instruction that biology majors cannot correctly identify mechanisms of speciation (Sinclair et al., 1997).

Nature of science. The nature of science is the final tenet of understanding macroevolution per Nadelson and Southerland (2010a). Knowledge of NOS includes understanding of what constitutes scientific knowledge, how science differs from other types of knowledge, the nature of scientific theories and laws, and features of scientific evidence.

Alternative conceptions about NOS can result in misconceptions about evolution (Butler, 2009). For individuals to understand evolution, it is critical they should understand that science (a) is based on or derived from empirical observations of the natural world, (b) subject to change with new information, and students should understand (c) the diversity of scientific methods, (d) the nature of scientific theories, and (e) the process of forming scientific predictions (NAS, 1998). The assessment of macroevolution used for this study (the MUM; Nadelson & Southerland, 2010a) includes items that examine knowledge of NOS in the context of evolution.

There is limited research about what non-science majors know about tenets of the NOS (i.e., Abd-El-Khalick, 2006; Bezzi, 1999; Fleming, 1988; Gilbert, 1991; Ryder, Leach, & Driver, 1999). However, studies generally agree that college students do not have an informed understanding about NOS. For example, college students perceive ideas in science to be closed to interpretation from multiple perspectives and see scientists to be particularly objective (Bezzi, 1999; Abd-El-Khalick, 2006). In relation to tenets of NOS important for understanding evolution (NAS, 1998), the majority of undergrads (both science and non-science majors) think: there is a universal scientific method (Gilbert, 1991; Abd-El-Khalick, 2006), that science provides "proof" on empirical grounds (Abd-El-Khalick, 2006), that scientific ideas are not subject to change with new evidence (Abd-El-Khalick, 2006) and do not know that theories provide a predictive framework for research (Abd-El-Khalick, 2006). Furthermore, most students think theories are unsubstantiated and hold a lesser status than laws. Laws are perceived by students as 'proven' and theories as lacking evidence (Abd-El-Khalick, 2006; Sinclair et al., 1997). This fallacy is particularly concerning for the students learning about evolutionary theory, such as those selected for this study.

Dagher, Brickhouse and Shipman (2004) described non-science majors' representations of scientific theories, the criteria they use to distinguish theories from other ideas (i.e. laws), and the extent their representations of theories are consistent across different theories (e.g. the theory of natural selection; the big bang theory). They conducted semi-structured interviews with nine students in a large lecture astronomy course before and after instruction. The course was designed to have explicit instruction about the nature of science (Butler & Southerland, 2010; Khishfe & Abd-El-Khalick, 2002). Data from the interviews were triangulated with field notes of class observations and responses to an exam question. After instruction, 5 of 9 students moved from naïve definition of theory to understanding the empirical nature of theories. Students thought about evolution in a fashion similar to all other scientific theories, not distinguishing evolution as different from other theories (this contradicts the later results of Hokayem & BouJaoude, 2008). The most striking result was that even after instruction, students saw theories and laws as related to the amount of evidence each requires; laws were still seen as having more empirical evidence or 'proof' than theories.

In a similar study, Hokayem and BouJaoude (2008) explored biology majors' perceptions of the nature of evolution science at a primarily Muslim university in Lebanon. This included exploring students' thoughts on the status of evolutionary theory, how it compares to other scientific theories, and the criteria to determine a scientific explanation. Like Dagher et al. (2004), the majority of students (9 of 15) stated that evolution was a theory deficient in trustworthy evidence, proof, or validity. For example, one participant stated that evolution was a theory because it was not proven, otherwise it would be called a law. Another student stated that theories were "unscientific because they were tentative" (p. 384). Unlike students in the Dagher study, students differentiated between general scientific theories and evolutionary theory, stating that other theories were *tested* or *proven* (cell theory, kinetic theory, and gravity) but evolution was not. One third of the students also described scientific explanation to arise from experimentation, but not observation. Other students claimed that the theory of evolution was missing steps of the scientific method or did not follow ‘the scientific method’.

Butler (2009) examined two courses for non-biology majors, one that used explicit, reflective nature of science instruction, and the other that used traditional, implicit nature of science instruction. Explicit nature of science instruction specifically addresses tenets of the nature of science, such as tentativeness, theory and law, subjectivity, and the role of evidence. Data were collected on the participants’ acceptance of evolution (MATE, Rutledge & Warden, 1999), understanding of natural selection (CINS; Anderson, Fisher & Norman, 2002), and views of the nature of science (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). Data from the students’ written journal assignments were also examined. The explicit, reflective NOS approach to teaching evolution was statistically better than traditional instruction in improving understanding of both the nature of science and natural selection. However, understanding of natural selection was not correlated with acceptance of evolution.

Evolution Acceptance Studies

The relationship between knowledge of science content and acceptance of evolution has been a topic of debate in the literature. Does one preclude the other? Do students need to accept evolution as valid? Some authors note that rejection of evolution can serve as a barrier to developing knowledge about it (Coburn, 1994; Scharmann, 1990). Other research has shown that rejection of evolution does not affect the ability to learn about natural selection (Bishop & Anderson, 1990; Demastes et al. 1995; Sinatra, Southerland, McConaughy, & Demastes, 2003). This means that students can have an understanding of natural selection without accepting evolution, and conversely, students may accept the theory with poor understanding of it. This section explores studies which consider connections between understanding nature of science, natural selection, and macroevolution with acceptance of evolution.

Coursework and acceptance. Several studies document positive correlations between prior biology or evolution coursework and acceptance of evolution. Rutledge and Mitchell (2002) found significant associations between previous credit hours earned in biology and acceptance, with the largest percentage of accepters earning over 40 undergraduate or graduate biology credits. However, the variable of understanding only accounted for 3.3% of the variance in teachers' acceptance. Using different measures, Nehm et al. (2009) found a weak association between knowledge and beliefs regarding evolution, and argue that the two are distinct constructs. This supports the notion that improving students' knowledge of evolution may be unlikely to influence their acceptance.

Nature of science and acceptance. A better understanding of the nature of science allows students to remove themselves from dualistic thinking about religion and science (see *Epistemological beliefs*) to more carefully consider scientific explanations (Southerland & Sinatra, 2003). Some research has therefore focused on student ideas about NOS and how these conceptions relate to understanding and accepting evolution. Explicit, reflective teaching methods for the nature of science may be related to fostering knowledge of natural selection (Butler & Southerland, 2010; Khishfe & Abd-El-Khalick, 2002).

The relationship between knowledge of NOS, acceptance of evolution, and knowledge of evolution is evident in philosophical literature (Lawson & Weser, 1990;

Lederman, 2007; National Academy of Sciences, 1998; Smith & Siegel, 2004; Southerland, 2000), but is less documented in research of college students. A sophisticated understanding of NOS may be related to a learner‘s acceptance of evolutionary theory; one dissertation (Butler, 2009) has successfully documented a positive relationship between understanding NOS and understanding natural selection. Only two studies document a significant correlation between understanding NOS and accepting evolution for college students (Johnson & Peeples, 1987; Scharmann, 1990). Other studies document no relationship between knowledge of NOS and accepting evolution for (e.g. Butler, 2009). The majority of the studies about NOS and evolution document students' misconceptions about the nature of theory, and do not relate the construct to acceptance.

In contrast, some of the teacher literature indicates that teachers who possess sophisticated understandings of NOS are more likely to accept evolution. Rutledge and Warden (2000) reported a significant association between Indiana teachers' scores on a NOS subscale and acceptance subscale within the same instrument. Rutledge and Mitchell (2002) found a similarly positive correlation in a different Indiana teacher sample, revealing that teachers who had taken a NOS course were more likely to accept evolution.

Understanding natural selection and evolution acceptance. At least 50% of undergraduates accept evolution as personally true (Bishop & Anderson, 1990; Grose & Simpson, 1982; Lord & Marino, 1993). Previous studies have had mixed results regarding the relationship between knowledge of natural selection and acceptance for college student. Two have found no significant correlation (Bishop & Anderson, 1990;

Butler, 2009) and one has found a significant correlation (Robbins & Roy, 2007) between knowledge of natural selection and evolution acceptance. Robbins and Roy (2007) found significant gains in student acceptance after an inquiry-based teaching unit for evolution for non-science majors (N=141). The course yielded drastic improvements in college student explanations and acceptance of evolution. Before instruction, 59 percent of students reported they agreed 'unconditionally' with the theory of evolution. After instruction, 89 percent of the students mastered all conceptual aspects of evolution and 92 percent accepted evolution. Although these are promising results, the authors failed to address whether the surveys used were valid and reliable for measuring understanding and acceptance of evolution in college students.

Understanding macroevolution and evolution acceptance. Unlike the mixed results of research into student understanding of natural selection and acceptance, recent research indicates that knowledge of macroevolution *is correlated* to accepting evolution. Nadelson and Southerland (2010a, 2010b) investigated knowledge of macroevolution in 667 first year, first semester biology majors and 74 senior biology majors. They examined the relationship between knowledge of macroevolution and acceptance, the relationship between the amount of college biology coursework and acceptance, and if acceptance and knowledge of evolution could be changed over the course of a one-semester course. They created and validated the MUM, a 27-item multiple choice instrument with 1 short answer question, that spans five core tenets of macroevolution - deep time, fossils, phylogenetics, speciation and the nature of science. The results of the MUM were then compared to responses on the Measure of Acceptance of the Theory of Evolution (MATE; Rutledge & Warden, 1999). Despite past research that indicated little or no relationship between biology content knowledge and acceptance of evolution, acceptance of evolution was significantly correlated with knowledge of macroevolution (r=0.47, p<0.01). The number of biology courses was also significantly correlated to acceptance and knowledge of macroevolution (r=0.27, p<0.01). Furthermore, after a one semester course focused on macroevolution, there was a significant change in students' understanding of macroevolution [t (146) = 2.77; p<0.01] and acceptance of evolution [t(146)= 3.38; p<0.01]. These statistics are promising, as they indicate that properly structured curriculum could foster conceptual change for evolution knowledge and acceptance. However, these results cannot not be generalized for all college students as the instrument is valid for biology majors only.

Research on Faculty PCK

Like research on students' knowledge of macroevolutionary principles, few studies exist about pedagogical content knowledge for college science teaching. Teachers are cited as the most important factor in student learning (NRC, 1996) and what students learn is greatly influenced by how they are taught (Brophy & Good, 1986). On the college level, few researchers have focused on the instructor and his or her knowledge for teaching (Abell, 2007).

In this section, I review the few studies that examine PCK for college teaching: three studies on PCK for general college teaching (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994; Major & Palmer, 2002) and six on PCK for college science teaching (Counts, 1999; Padilla, Ponce-de-Leon, Rembado, & Garritz, 2008; Pareja, 2007; Rodriques & Bond-Robinson, 2006; Swami, 2002; Witzig, 2012). The purpose of this section is to illustrate what is known about the nature and sources of college science teacher PCK and to organize and synthesize these findings around the components of the Magnusson et al. (1999) model. The review also informed revisions to supplementary questions on a previously developed interview protocol (ReSMARRT), which was originally designed for interviewing novice secondary science teachers. These revisions allowed for the protocol to be appropriate for a university faculty member.

Goals for Teaching Science / Orientations

Teaching actions are highly influenced by knowledge and beliefs about the purposes and goals for teaching (Fernandez-Balboa & Stiehl, 1995). This construct is also referred to as *orientations for teaching science* (Magnusson et al., 1999), although few studies of faculty refer to it as such. Friedrichsen, van Driel, and Abell (2011) note the ambiguity of the term, and argue that studies use the orientations construct in different and unclear ways. In this study, I investigated orientations in terms of the purpose and goals the participant had for teaching macroevolution as well as her conceptions about teaching science in general.

In the research about K-12 teachers' PCK, it is common for individuals to be labeled with one of nine orientations (Friedrichsen et al., 2009). Some of these orientations are teacher-centered (i.e. didactic or academic rigor orientations) and others are more student-centered (i.e. conceptual change, activity-driven, discovery, inquiry/guided inquiry, and project-based science orientations) (Magnusson et al., 1999). This is likewise true in the faculty PCK literature. Trigwell, Prosser and Taylor (1994) labeled first year college physics and chemistry professors with one of five orientations toward teaching science, some teacher-centered (teacher-centered to transmit information, teacher-centered so students acquire concepts, and teacher-student interaction so students acquire concepts) and others learner-centered (student-centered so students develop concepts and student-centered aimed at students changing their conceptions).

Despite identification of various orientations toward science teaching, individuals may not always fall under a particular orientation. Beliefs and goals about teaching are simply too complex to be given one label (Friedrichsen et al., 2011). Furthermore, orientations may shift depending on the needs (Friedrichsen, 2002) or age (Magnusson, Krajcik, & Borko, 1999) of a particular group of students. For example, faculty know that course level, intended audience (majors or non-major) and course sequencing affect their choice of instructional strategies (Major & Palmer, 2002). The orientations construct is muddied further as an instructor with primarily one orientation may show elements of another (Friedrichsen et al., 2009). This was evident in Witzig (2012) as one his participants would teach protein synthesis with teacher- and student-centered instructional strategies, yet teach other topics exclusively in lecture format.

Teaching experience influences faculty orientations toward science teaching. Teacher-centered teaching may be more common than student-centered teaching for faculty in general (Padilla & van Driel, 2011), but may be especially common for faculty with less than 6 years of experience (Lenze & Dinham, 1994). This would place novice teaching faculty into a *teacher-centered so students acquire concepts* orientation (Trigwell et al., 1994). The purpose of teaching for more experienced faculty members shifts toward helping students learn “big idea” concepts and improving the lives of students through learning science (Fernandez-Balboa & Stiehl, 1995; Major & Palmer, 2002). Above other factors, experienced faculty want students to have improved lives after their courses. They want students to learn to love learning, be lifelong learners, develop values and ethics, become responsible members of society, and become consumers of science (Major & Palmer, 2002).

Epistemological and ontological beliefs also influence how faculty members make decisions in their teaching. Padilla et al. (2008) noted at least two opposing ways to think and teach the concept of 'moles' in chemistry, but used the Mortimer (1995) Conceptual Profile Model to describe the paradigms of the four participants. One faculty member had an *equivalentist* paradigm because they used exclusively macroscopic terms, such as mass, to describe the mole. This individual fit the conceptual profile of an *empiricist* (Mortimer, 1995), as she described the 'amount of substance' in a manner closer to the everyday, macroscopic perception. The faculty member with an *atomistic* (formal-rationalist) paradigm discussed the mole as something found by measuring nanoscopic entities through macroscopic mass and volume. This individual fit a formal-rationalist conceptual paradigm as it balances nanoscopic and macroscopic levels of explanation. The other two professors were between these two 'extreme' paradigms and had more heterogeneous ways of thinking.

Given the scattered nature of orientations literature for college faculty, few assumptions can be made about what to expect from the faculty member in this study. Similar to other college experienced faculty (Fernandez-Balboa & Stiehl, 1995; Major & Palmer, 2002), the instructor likely wishes for students to have real-life applications for course material and to gain skills as a learner, not just knowledge of science. It is also likely the instructor holds multiple views of how students learn science (Friedrichsen, 2002; Friedrichsen et al., 2011), and holds multiple orientations depending on the situation. Questions in the interview protocol specifically addressed these views to uncover the potentially contextual nature of the instructors' orientation toward science teaching.

Knowledge of Curriculum

Knowledge of curriculum includes knowledge of (a.) specific curriculum programs, resources, and materials, such as textbooks and online resources and (b.) mandated curriculum, goals and objectives (Magnusson et al., 1999, p.103). While this definition is helpful for primary and secondary teachers, it requires modification to describe college science teachers' knowledge of curriculum. College science teachers are not constricted to mandated goals and have freedom to develop their own curricular programs. The studies that discuss faculty knowledge of curriculum address the construct through the broader lens of college teaching and are not science nor topic specific (with the exception of Witzig, 2012).

Resources for curriculum materials for faculty can come from creating one's own curriculum materials, textbooks, videos, the internet, and from materials developed by others. Use of these resources is not uniform among faculty. Witzig (2012) found that two of his participants had become increasingly dissatisfied with textbooks. These individuals instead used curricular resources on the internet, such as Utah's genetics website and Berkeley's understanding science website (Witzig). Conversely, the participant with less pedagogical training relied heavily on the textbook to organize his curriculum, showing no dissatisfaction with this approach.

Outside of curricular resources, knowledge of curriculum includes goals and objectives for a given topic. College teachers acknowledge these goals and objectives despite a lack of formal standards documents. They understand that subject matter must be organized so that it is broadly applicable, meaningful and relevant to students' lives (Fernandez-Balboa & Stiehl, 1995; Major & Palmer, 2002). Faculty also understand that content must also be organized in a particular sequence, so that prerequisite topics are presented earlier in a course if critical to understanding topics later in a course (i.e. teaching protein synthesis before genetics and genetically modified organisms)(Witzig, 2012).

This study addresses a gap in the literature by examining the PCK specific to teaching macroevolution for an experienced biology instructor. Questions on the interview protocol address the instructor's knowledge of recommended evolution curriculum, goals, and objectives for the introductory biology course, knowledge of specific curriculum programs and materials, such as textbooks and online resources, instructional decisions based on course level, the intended non-science major audience, and rationale behind the overall course sequence.

Knowledge of Learners / Context

Magnusson et al. (1999) describe knowledge of student understandings as including knowledge of student difficulty areas, alternative conceptions, prerequisite student knowledge, and variations in student approaches to learning. Although we know faculty knowledge of student difficulties is linked to their content area (Linze & Dinham, 1994), faculty understanding of students' difficulties with science content is not well described in the literature but is described in an interdisciplinary context. Faculty know that students struggle with "ill-defined concepts, complex material, abstractions, and artificially constructed categories of information' and problems with 'rules, technical terminology, concepts, formal theories and organizing frameworks" (Lenze & Dinham, 1994, p. 11).

Faculty are also broadly aware of the pervasiveness of student difficulties (e.g., how long or how many students struggle with an idea) as well as student approaches necessary to overcome difficulties with content (Lenze & Dinham, 1994; Major & Palmer, 2002). When students request help with difficult material, faculty often recommend practicing, trying again, reading before and after class, doing homework, and listening instead of taking notes.

Faculty members indicate that students naturally vary in abilities and acknowledge that mid-level ability students may benefit most from new pedagogical approaches (Major & Palmer, 2002). They likewise note that individual learning styles vary among students. Conversely, graduate teaching assistants, especially international teaching assistants, may have unrealistic expectations of students. Graduate teaching assistants are more likely than faculty to label undergraduate students as "not wanting to learn" or "unintelligent" (Rodriques & Bond-Robinson, 2006).

The context of college teaching likewise plays a meaningful role in how students learn. Faculty are aware of the cultural influences of the generation, geographic region, and institutional culture that affect their teaching. For example, the sheltered, polite, and 'nice' culture of the southern United States region influenced teaching and learning for participants in the Major and Palmer (2002) study. The polite student culture made it difficult for faculty to use peer review activities in class, as students did not want to critique each other. Generational barriers also cause faculty to adjust their content and pedagogical techniques to facilitate learning, as faculty perceive 21st century students as having shorter attention spans and more reliance on technology than previous generations (Bond-Robinson & Rodriques, 2005; Fernandez-Balboa & Stiehl, 1995; Major & Palmer, 2002).

In the case of this study, questions on the interview protocol specifically address knowledge of student contexts relevant to macroevolution learning as well as knowledge of student difficulties, and how and why these factors influence instructional decisions for the instructor. Contextual factors may be particularly prevalent learning macroevolution due to religious identities of the students (note also *Psychological Constructs that Influence Evolution Learning*). Likewise, there are a number of student alternative conceptions about evolution in the literature, including naïve ideas about natural selection, macroevolution, and the nature of science. The instructor is likely aware of both contextual factors and student difficulties for teaching macroevolution and adjusts her instruction accordingly.

Knowledge of Assessment

Vague descriptions of college science teacher knowledge of assessment permeate the literature. Linze and Dinham (1994) note that college faculty new to teaching determine student difficulties through both formative and summative assessments. Formative assessments used by new faculty include asking questions to the class, giving feedback in-class, and responding to student body language. Summative assessments included tests, term papers, and end-of-course evaluations. Other faculty use these assessment strategies at different frequencies. Experienced college teachers employ formative assessments as they question students, but also note student body language and interpret students' facial expressions (Fernandez-Balboa & Stiehl, 1995). Furthermore, experienced faculty describe their assessment strategies in a more purposeful fashion than less experienced faculty (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994) and know how to use information from assessments to inform instruction.

The final interview with the instructor in this study followed the final exam for the students, including questions which elicited the instructor's rationale behind the exam and how her future instruction may be influenced based on the students' performance. Questions in the stimulated recall interview surrounded the rationale behind selection of formative assessments, such as clicker questions, in class activities, and questions on the fly, and how feedback from these assessments informed instruction. The findings illustrate the nature of the participant's macroevolution assessment knowledge, an area previously not described in the literature, and an area with the potential to inform other biology educators.

Knowledge of Instructional Strategies

Exemplary college teachers have rich repertoires of instructional strategies, informed by past experiences as students and teachers (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994). The list of instructional strategies that follows is diverse, yet were described similarly across faculty of different disciplines (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994). Participants used lecturing - on the blackboard, using lesson notes, and using recorded lectures, connecting students, content, and real world examples, teaching terminology first, questioning students, demonstrations, analogies, modeling thinking processes, role playing, motivational strategies, assigning tasks to students in and out of class, peer instruction, and organizing the students into groups to support student learning (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994; Witzig, 2012).

Most of these instructional strategies are not discipline or topic specific. This may be because professors construct their PCK in similar ways across disciplines (Fernandez-Balboa & Steihl, 1995). The surface-level description of these strategies more closely resembles general pedagogical knowledge, since little or no content knowledge is evident in the pedagogy. However, some studies shine more light on the topic-specific nature of instructional strategies for science faculty. Chemistry professors had instructional strategies that reflected PCK for teaching specific concepts (Padilla et al., 2008). This included strategies for teaching the concept of the ‘mole’ using analogies (e.g. “the chemist’s dozen”), demonstrations (e.g. using nails, nuts and screws), and other unique approaches (e.g. avoiding Avogadro’s constant in explaining chemical formulas).

Although college faculty may have similar repertoires of instructional strategies, experience may be a factor behind selection of teaching strategies. Experienced faculty demonstrate strong rationale behind how and why particular instructional strategies work under particular conditions (Fernandez-Balboa & Stiehl, 1995). New faculty members and graduate teaching assistants may use instructional strategies blindly, without knowing why or if they work (Linze & Dinham, 1994; Bond-Robinson & Rodriques, 2005). Furthermore, graduate assistants often lack instructional strategies to explain abstract phenomena or which link lecture to lab (Bond-Robinson & Rodriques, 2005).

Sources of PCK

Although science education researchers have examined the nature of PCK for science faculty, less is known about *what* informs their PCK. Grossman (1989) identifies various sources which influence how teachers acquire PCK: 1) apprenticeship of observation, 2) subject matter knowledge (SMK), 3) teacher education, and 4) classroom experience. Although PCK has been researched for over 30 years, researchers know little about the process of PCK development, especially for experienced K-12 teachers (Henze, van Driel, & Verloop, 2008) and college faculty. The literature indicates several potential sources of development of PCK applicable to faculty: apprenticeship of observation, science content courses and research, pedagogical training, teaching experience, and informal interactions with peers.

Apprenticeship of observation. Apprenticeship of observation suggests that teachers' draw from experiences from their own teachers in learning how to teach (Lortie, 1975). Apprenticeship of observation can occur when an individual recalls how concepts were taught to them and what worked for them as a learner. It follows that how and what most faculty teach is contingent on their experience as a student (Gess-Newsome, 1999). I would argue that apprenticeship of observation can also occur when faculty observe their colleagues teach. This was supported by Witzig (2012), as all three of his participants described learning to teach protein synthesis by watching others teach.

Subject matter knowledge. The general consensus is that coherent and thorough understanding of subject matter facilitates PCK development for K-12 teachers (Abell, 2007; van Driel, Verloop, & de Vos, 1998). Like K-12 teachers, faculty members learn foundational SMK through high school and undergraduate science courses (NSTA, 1998). Unlike their K-12 counterparts, faculty continue to build SMK in graduate coursework, research experiences, and through interactions with other scientists. The instructor investigated in this study has rich SMK for evolutionary biology and this may influence her PCK. However, the interview protocol used in the study was not designed to elicit the nature of SMK for the participant.

Pedagogical training. One distinct difference between most college faculty and K-12 teachers is the lack of formal pedagogical training among faculty (Dobson, 2001; Park & Ramos, 2002; Wulff, Austin, & Associates, 2004). Most faculty learn about pedagogy through informal experiences, such as (a.) discussion of best practice with others (Mintzes & Leonard, 2006; Witzig, 2012), (b.) structured programs of support for faculty (Lynd-Balta, Erklenz-Watts, & Freeman, 2006; Kahveci, Southerland, & Gilmer, 2006; Sirum, Madigan, & Klionsky, 2009; Witzig, 2012; Zhao, Witzig, Weaver, Adams, & Schmidt, 2012), and (c.) reading pedagogical literature (Mintzes & Leonard, 2006; Witzig, 2012). Mentorship may also play a major role in helping faculty develop their PCK (Major & Palmer, 2002), as colleagues advise each other on activities that work and difficulties to expect in classes they have taught before (Lenze & Dinham, 1994).

Teaching experience. The experience of teaching itself also fosters PCK (van Driel et al., 1998). Faculty with many years of teaching experience often have strong rationale behind instructional decisions, with an assortment of analogies, demonstrations, examples, and delivery methods (i.e. lecturing, video clips, etc.) (Fernandez-Balboa & Stiehl, 1995; Major & Palmer, 2002). Witzig (2012) found three main ways that teaching experienced to changes in instruction: (a) experiences with teaching too much content, (b) experiences with specific student difficulties, and (c) experiences with instructional technology. Faculty drew from their pedagogical knowledge to make changes in their instruction based on these disturbances, and through reflective thought and action, modified their instruction.

The influence of peers and reflection. Lastly, informal experiences contribute to PCK development for teachers. These experiences include collaboration with colleagues (Loughran et al., 2004; Witzig, 2012) and personal reflection (Loughran, Gunstone, Berry, Milroy, & Mulhall, 2000; Park & Oliver, 2008). For example, the use of Resource Folios (e.g. Loughran et al., 2006) has been advocated as a way to make teachers' tacit knowledge explicit. Explicating PCK and sharing the knowledge with colleagues in this fashion could be instrumental in PCK development for experienced science teachers (e.g. Wallace & Louden, 1992; Witzig, 2012).

Likewise, reflection plays a critical role in learning to be a teacher - it is through reflection of an experience in light of prior experiences that leads to learning (Dewey, 1938). For example, teachers who evaluated their use of analogies and metaphors in light of students' ideas and responses focused more on stimulating conceptual change than those that did not reflect (van Driel et al., 1998).

Although my study is not focused on *how* faculty learn how to teach, questions in the interview protocol examined sources behind the participant's PCK for teaching macroevolution. Understanding these sources (as well as the nature of the instructor's PCK) has implications for the goals and design of professional development programs for faculty, which can in turn improve student outcomes (Abell, 2008).

PCK and Student Learning

A number of studies have examined the nature of teachers' PCK and sources for that PCK. The question remains: does it matter if an instructor has rich PCK if this knowledge does not influence student learning? To answer this question (Abell, 2008), researchers have started to relate PCK with student outcomes. This work has been primarily quantitative in nature, wherein rubrics are used to quantify a teacher's PCK with the goal of correlating that PCK with student test scores (Alonzo, Kobarg, & Seidel, 2012; Anderson & Clark, 2012; Gardner & Gess-Newsome, 2011). Each of these studies was done at the K-12 level. No published work connects PCK to student outcomes at the college level, nor has PCK been related to student outcomes using qualitative *and* quantitative measures. As researchers begin to explore how PCK influences student outcomes, we should include student voices (and assessment outcomes) to qualify PCK (Nilsson, 2013). This study takes this approach.

Summary of Gaps in the Literature

There are several gaps in the evolution education and pedagogical content knowledge literature bases that this study addresses. Foremost, this study investigates the nature of macroevolution knowledge for non-science majors, a component of evolution knowledge not holistically examined by science education researchers. Little is likewise known about how non-science majors' knowledge of macroevolution may influence acceptance of evolution. This study examines the potential correlation between these two factors and qualitatively examines the nature of this relationship.

Also unlike previous studies (with the exception of Witzig, 2012), this study addresses *all* components of PCK of a college faculty member (i.e. knowledge of learners, assessment, curriculum, instructional strategies, and orientations toward teaching science; Magnusson et al., 1999). This also addresses the gap in the literature on PCK of faculty in the biological sciences as well as the gap on PCK of college faculty in general.

Lastly and perhaps most importantly, science education researchers know little about how the PCK of teachers influences student outcomes (Abell, 2008), and no such work has been done at the post-secondary level. This study specifically addresses the nature and sources of PCK of an experienced faculty member, how her PCK influences her instruction, and subsequently how her instruction influences student knowledge of macroevolution and evolution acceptance.

CHAPTER THREE: METHODOLOGICAL DESIGN

This chapter defines the research questions for the study and the methods by which each was addressed. The chapter begins with a description and rationale for the embedded single case study design and the sequential explanatory mixed methods approach. This is followed by details on the context of the study, data collection strategies, and data analysis methods. The chapter concludes with quantitative assumptions and a description of the trustworthiness of the design, validity and reliability measures, and a description of how the study was implemented.

Design of the Study

The design of the study centered around answering the overarching research question*: How does the nature of macroevolution instruction influence student understanding of macroevolution and student acceptance of evolution in a general education biology course?* Table 2 describes data sources and analyses related to the overarching research question and the six sub-research questions that support this central question.

The study uses sequential explanatory mixed methods approach (Hesse-Biber, 2010) to an embedded single case study design (Yin, 1994). The approach is considered *mixed* methods and not *multiple* methods as quantitative and qualitative approaches informed data collection and the research questions, not exclusively data analysis (Creswell, Plano Clark, Gutmann, & Hanson, 2003). The following sections describe the nature of the research tradition (embedded single-case study) as well as the nature of the mixed methods approach (sequential explanatory design), including rationale, strengths

Table 2

An Overview of the Research Questions and How each was Answered through Particular Data Sources and Analyses. Abbreviations: Measure of Acceptance of the Theory of Evolution (MATE), Measure of Understanding of Macroevolution (MUM)

Overarching Research Question:
How does the nature of macroevolution instruction influence student understanding of macroevolution and student acceptance of evolution in a general education biology course?

Sub-Research Questions	Data Sources	Analysis
What is the nature of a college instructor's pedagogical content knowledge for teaching macroevolution?	- Classroom observations (field notes and Tegrity recordings) - 3 instructor interviews (before, during, and after course) - Evolution unit exam (part of final exam, Appendix K)	Triangulation of themes across data sources for the participant based on Magnusson et al. (1999) model of PCK
What are the sources of a college instructors' pedagogical content knowledge for teaching macroevolution?	- 3 instructor interviews, one of which also included questions about the evolution unit exam	Triangulation of themes across data sources for the participant based on Magnusson et al. (1999) model of PCK
What do non-science majors understand about macroevolution before and after instruction?	Demographic data (N=270) Pre- and post-instruction scores on the MUM (Nadelson & Southerland, 2010a) (N=270) Student interview data (*n*=12)	- Descriptive and inferential statistics - Inductively code interview data and look for themes
To what extent do non-science majors' accept evolution before and after instruction?	Demographic data (N=270) Pre- and post-instruction scores on the MATE (Rutledge & Warden, 1999) (N=270) Student interview data (*n*=12)	- Descriptive and inferential statistics - Inductively code interview data and look for themes

Table 2 (Cont.)

An overview of the research questions and how each will be answered through particular data sources and analysis. Abbreviations: Measure of Acceptance of the Theory of Evolution (MATE), Measure of Understanding of Macroevolution (MUM)

Sub-Research Questions	**Data Sources**	**Analysis**
What is the relationship between understanding of macroevolution and acceptance of evolution by natural selection for non-science majors?	Pre- and Post-Instruction scores: - MATE (Rutledge & Warden, 1999) - MUM (Nadelson & Southerland, 2010a) Student interview data (*n*=12)	- Pearson's correlation analysis - Inductively code interview data and look for themes
How does instruction influence student knowledge of macro-evolution and acceptance of evolution by natural selection?	-- Pre- and Post-Instruction scores: - MATE (Rutledge & Warden, 1999) - MUM (Nadelson & Southerland, 2010a) - Student interview data (*n*=12) - Classroom observations (field notes and Tegrity recordings)	- Descriptive and inferential statistics - Inductively code interview data and look for themes

and limitations for these approaches, visual models, and details connecting the design of the study to the research questions, data collection, and analysis.

Research Tradition

Case Study

The case study tradition was a logical fit for this study. Case studies are a preferred method of investigation to answer “why” or “how” research questions, as well as when the investigator has little control over events or when the focus is a real-life context (Yin, 1994). These three features fit the nature of this study. The research questions pose the *influence* of instruction and the *influence* of PCK on instruction, and the study focused on a real-life course in which I was a non-participating observer.

Several authors describe foundational approaches to conducting case study research (e.g. Merriam, 1988; Stake, 2000; Yin, 1994). Although Merriam (1988) came from the perspective of higher education, I found Yin’s methodological approach to be the most useful. Yin (1994) provides a comprehensive and systematic outline for undertaking the design and implementation of a case study. His approach is written as a guide for investigators doing case study as a rigorous form of research (Yin, 1994). This was important to me as a researcher coming from the sciences, as qualitative research has been stereotyped as lacking sufficient quantification, objectivity, and rigor (Yin, 1994, p. xiii). Since scientific methodologies have influenced Yin’s approach to case study, his approach has parameters to build and maintain validity and rigor in data, as well as extensive documentation plans to strengthen the credibility and trustworthiness of the methodology.

Embedded single case study design. Yin (1994) describes four basic type of case study designs: (a) embedded single case designs, (b) holistic single case designs, (c) embedded multiple case designs and (d) holistic multiple case designs. This study used an embedded single case design. The unique context of this study, (i.e. a general education biology course with extensive focus on macroevolution) qualified it as an appropriate single case to explore (Yin, 1994). An embedded design was most appropriate as the case had unique subsets of participants within the greater case (e.g. surveyed students, interviewed and surveyed students, the instructor, etc).

Each subset of participants served as a unit of analysis. These subunits were analyzed in and of themselves and compared to other units of analysis, and to the entire case (Yin). These subunits added opportunities for extensive analysis, enhancing the insights into the single case. The overall unit of analysis was the case as a whole, and the embedded subunits of analysis within this case were the instructor (n=1), surveyed students (N=270), interviewed and surveyed students (*n*=12), and sub-groups of interviewed and surveyed students grouped by pre- to post-instruction gains on the surveys (four groups of *n*=3) (Figure 2).

Although the data were collected and analyzed using the scheme represented in Figure 2, I found few similarities among the three participants within the smallest subunits of analysis. It was not possible develop unique themes within groups of students with and without particular gains on the MATE and MUM (Groups C, D, E, F in Figure 2). I subsequently present student-related themes in Chapter Four at a higher subunit of analysis (among the 12 interviewed students, Group B in Figure 2) and do not discuss themes among each 3-person subunit (Groups C, D, E, and F). These subunits remain in the visual model of the case since the students were selected for interview based on these

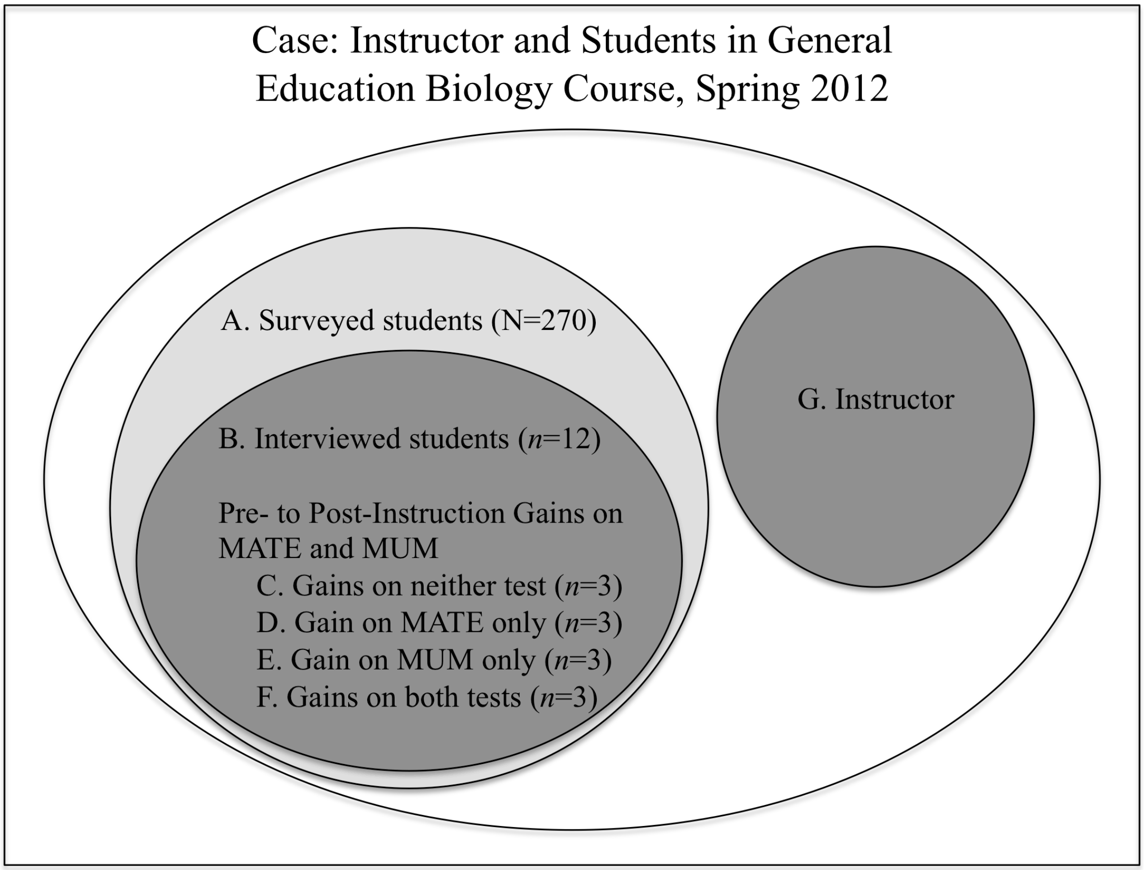


Figure 2. Visual model of the case, including embedded sub-units of analysis (Letters A-G) within the embedded single case study design (Yin, 1994). Dark gray shading = Qualitative Data; Light gray shading = Quantitative Data. Abbreviations. MATE = Measure of Acceptance of the Theory of Evolution (Rutledge & Warden, 1999), MUM = Measure of Understanding of Macroevolution (Nadelson & Southerland, 2010a)

parameters (see *Student Interviews*).

Limitations of an embedded single case design. The single case nature of this study presents limitations. A potential weakness of a single case approach is that the initially determined case may not be the case the investigator anticipated (Yin, 1994). Yin warns that single case designs therefore require careful investigation of the potential case prior to data collection. This minimizes the chance of misrepresenting the case and maximizes the access to sufficient data for the case. Prior to the study I investigated several instructors' syllabi to find an individual incorporating extensive macroevolution content into their course. This instructor was the only individual among several who taught the general education biology course who included extensive macroevolution instruction. Since I was familiar with the course, knew the instructor, and understood the nature of student evolution thinking prior to the study, the case was well documented during data collection. Another limitation of a single case is that it only examines one instructor and therefore may be so unique that it is not transferrable to other contexts. However, steps were taken to remedy this trustworthiness issue (see *Measures of Verification*).

The embedded nature of the case likewise had potential pitfalls. One potential problem was that the case study would focus only on the embedded subunits and fail to return to the larger unit of analysis (Yin, 1994). However, since the several research questions required data from multiple sub-units of analysis (e.g. How does instruction influence student knowledge of macroevolution and acceptance of evolution?), I believe the whole case was described as well as its parts.

Description of the Case

A case study by definition is an exploration of a "bounded system" of a case over time, through detailed, in-depth data collection of multiple sources of information and rich context (Merriam, 1988; Creswell & Maitta, 2002). This study presents an in-depth perspective of one such bounded case - an instructor and her students during a 15-week general education biology course during spring 2012 (Figure 2).

Description of course. This study was conducted at a research intensive university with undergraduate students enrolled in a 15-week general education biology course. The course was designed for students not majoring in the biological sciences with the goal to discuss general themes and fundamental concepts within the field of biology and how these apply to students' everyday lives. The course also explored the connections among science, technology and society. The course was selected for the study because the majority of the students taking the course were non-biology majors, the instructor was highly experienced teaching the course and evolutionary content, and the instructor spent extensive class time on macroevolution content.

Description of the participants.

Instructor. The course instructor spent nine 50-minute lecture periods on macroevolution (13 in the evolution unit) out of 45 total lectures in a 15-week semester. She was known to use multiple speciation examples and emphasize the evidence for a common ancestor from which all life diverged. She was a non-tenure track professor in the Division of Biological Sciences with a professional research focus on the behavior of katydids and tree frogs. She concurrently taught a course called Evolution for Everyone during data collection in spring 2012. The instructor did not receive monetary compensation for her time. A more detailed description of the instructor and the course is found in Chapter Four.

Students. Of the over 400 people in the general education biology course, 310 students participated in the pre-test surveys, 290 in the post-test surveys, and 270 on both the pre- and post-test surveys. Participants were primarily freshmen from the State of Missouri. They had to be 18 years of age and not majoring in biological sciences to be eligible to participate in the study. The students completed two instruments before and after the evolution unit: the Measure of Acceptance of the Theory of Evolution (MATE; Rutledge & Warden, 1999) and the Measure of Understanding of Macroevolution (MUM, Nadelson & Southerland, 2010a). The instruments were completed electronically outside of class. Students were given normal homework points for completion of the pre- and post-instruction MATE and MUM surveys, regardless of performance on the instruments. Participation in the study had no effect on students' course grade. Although participation in the study was voluntary, completion of the instruments was required for the class.

Post-instruction interviews with 12 purposefully selected students were then conducted to elicit how instruction influenced student answers on the quantitative instruments (see *Student Interviews* for selection criteria). Students that completed an interview received a $10 gift card for their time.

Methodological Approach

Mixed Methodology Overview

Mixed methods research provides more comprehensive evidence for studying a research problem than either quantitative or qualitative research alone, taking advantage of the strengths and avoiding the weaknesses of each (Green, Caracelli, & Graham, 1989). For example, quantitative research is valuable in providing statistical trends and generalizations, but weak in understanding the context or setting of the participants (Creswell & Plano Clark, 2006). Conversely, qualitative research focuses on in-depth knowledge of participants' perspectives, but the data require the personal interpretation of the researcher and are thus difficult to generalize to a large group (Creswell & Plano Clark, 2006).

Mixed method approaches are also considered superior to single method approaches as they can answer research questions that other methodologies cannot and thus provide stronger inferences (Tashakkori & Teddlie, 2003). In this dissertation, the overarching question - *how the nature of macroevolution PCK influences student knowledge of macroevolution and acceptance* - could not be answered without quantitative data from students' survey results and qualitative data describing the nature of the instructors' PCK. Likewise, questions about what the students learned about macroevolution and to what extent they accepted evolution are best answered through examining both quantitative and qualitative data.

One limitation to a mixed methods approach can occur when the quantitative and qualitative components lead to contradicting conclusions (Tashakkori & Teddlie, 2003). This issue is not necessarily problematic. Divergent findings are valuable as they sometimes can only be found through use of a mixed methods approach. Such findings can then lead to subsequent re-examination of the research questions and methodology and result in more informative iterations of the study (Tashakkori & Teddlie, 2003).

Sequential Explanatory Mixed Methods Design

There are about forty mixed-methods research designs reported in the literature (Tashakkori & Teddlie, 2003). Creswell, Plano Clark, Gutmann, and Hanson (2003) describe the six most frequently used designs - three concurrent and three sequential designs. Concurrent designs simultaneously collect quantitative and qualitative data, whereas sequential designs have one approach followed by the other. This study uses a sequential *explanatory* design, which required collecting and analyzing quantitative data and then using the quantitative data to inform qualitative data collection (Figure 3). The purpose of this sequence was to use qualitative data to *explain* quantitative trends.

The strengths and limitations of a sequential explanatory mixed methods design have been widely discussed in the literature (Creswell, 2002; Creswell, Goodchild, & Turner, 1996). Advantages of this design include: (a) it is easy to implement for a single researcher, as it proceeds from one stage to another in sequence; (b) it is useful for exploring quantitative results in more detail; and (c) it is useful when unexpected results arise from quantitative data (Morse, 1991). The limitations of this design include: (a) as any mixed methods design, it requires lengthy time to complete; (b) it requires feasibility of resources to collect and analyze both types of data; (c) quantitative results may not fall into expected patterns and therefore criteria for interview selection may have to be revised. I encountered this latter limitation, and details of this issue are discussed in the *Limitations* section of Chapter Five.

Methodological Issues

As with any mixed methods design, this study dealt with the issues of *priority, implementation,* and *integration* of the quantitative and qualitative approaches in refining

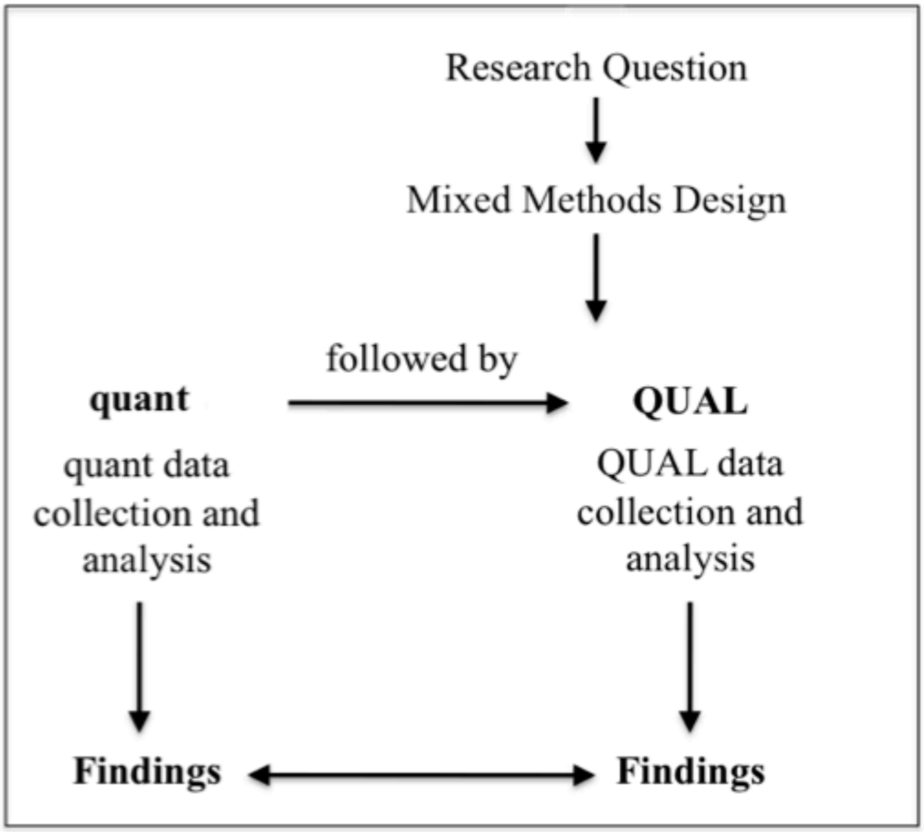


Figure 3. Sequential explanatory mixed methods design with quantitative methods informing qualitative methods. (Hesse-Biber, 2010, p. 73).

the methodological approach (Ivankova, Creswell, & Stick, 2006).

Priority. Priority refers to which approach, qualitative or quantitative, a researcher gives more weight throughout data collection and analysis (Creswell, 2003). Priority is often given to the quantitative approach (Creswell & Plano-Clark, 2011), as quantitative data come first in the sequential explanatory sequence and may therefore represent a major aspect of the data (Ivankova et al., 2006). However, given the nature of my study design and scope of my research questions, I gave priority to the qualitative data. I chose to do this for two reasons. Foremost, I have qualitative data from both student and faculty participants but have quantitative data from only the students. Second, the most meaningful research questions of the study (i.e. *how* does evolution instruction influence student knowledge of macroevolution and acceptance of evolution) can only be answered by qualitative analysis.

Implementation. Implementation refers to whether the quantitative and qualitative data collection and analysis come in sequence, one following another, or concurrently (Creswell et al., 2003). In a sequential explanatory design, the data are collected over the period of time in two consecutive phases with qualitative following quantitative data collection. The researcher first collects and analyzes the quantitative data and qualitative data are collected in the second phase based on the outcomes from the quantitative phase. In the case of this study, quantitative statistics narrowed the pool of 270 potential interviewees by focusing on individuals with below average MATE scores (<70.21) and/or MUM scores (<14.32) prior to instruction. Interviewing individuals who already accepted evolution and understood macroevolution had less potential to be influenced by the instruction than their lower scoring peers. Among potential interviewees with below average MATE and MUM scores, potential interviewees were selected from among students with at least 75% class attendance (see *Student Interviews* for more information about selection criteria).

Integration. Integration refers to the phases of the research process where quantitative and qualitative approaches inform each other (Creswell et al., 2003). I have integrated qualitative and quantitative approaches from the onset of this study: in formulating the purpose of the study, introducing both quantitative and qualitative research questions, and through integrating quantitative and qualitative findings at the interpretation stage. Most importantly, as this is a mixed methods sequential design, the two approaches were implemented at the data collection phase as results from the quantitative data informed selection of the student interviewees.

Quantitative Methodology

The quantitative portion of the study addressed what non-science majors understand about macroevolution and to what extent they accept evolution, as measured by pre- and post-instruction scores on the MATE and MUM. The MATE and MUM scores were analyzed using t-tests and normalized gain scores to compare the pre- and post-instruction data, as well as analyzed for Pearson's correlations between the MATE and MUM. The quantitative data also served to inform purposeful selection of students for interviews (see *Student Interviews*).

Additional Analyses

Some researchers question the value of independent t-tests. Concerns are primarily related to the effects of extraneous variables, including the Hawthorne effect (awareness of being tested affects the test results), the halo effect (tendency to respond positively or negatively to an instructor), and the practice effect (improving on a post-test due to taking the pre-test) (Colt, Davoudi, Murgu, & Zamanian Rohani, 2011). I therefore included normalized gain scores for the pre- to post-test MATE and MUM scores to provide an additional metric of difference.

Since normalized gain scores (g) take into account the mean score as well as individual student gains, they provide an objective and informative means to document learner performance (Hake, 1998). The normalized gain ranges between 0 and 1 is calculated by taking the *average increase* in students' scores on the instrument divided by the average increase that *would* have resulted if all students had perfect scores on the post-instruction test. The metric was developed out of work with the Force Concept Inventory cohort.

Hake (2008) argues that the normalized gain could be a measure of effective instruction. He found that introductory physics courses that can be characterized as traditional in teaching style had normalized gains of 0.23 ± 0.04. By contrast, the normalized gains for courses with interactive engagement were 0.48 ± 0.14, significantly higher. After examining a number of explanations, Hake concluded that the different teaching methods employed in the courses attributed to these results (Hake, 1998). It is not a directive of the study to evaluate the instructor. The normalized gain scores provided herein are intended to provide an additional measure of student performance only, and should not imply effectiveness of the instruction.

Methodological Assumptions

The quantitative portion of this study made four assumptions about the data: normality, linearity, homoscedasticity (homogeneity of variance), and independence of observations. These assumptions are required to confirm that the data were parametric - i.e. the data were not in an odd distribution pattern that would require special statistical analyses.

Normality. The assumption of normality requires that the distribution of both variables (MATE and MUM scores) approximates the normal distribution and is not skewed in a positive or negative direction. Normality of both the variables was examined by graphical representations, including histograms with normal curve overlay and Q-Q plots. Q-Q plots compare the quantiles of a data distribution with the quantiles of a standardized theoretical distribution from a specified family of distributions (in this case, normal distribution). Normality should not be based on plots alone, but also descriptive statistics such as skewness and kurtosis. Skewness value measures the degree of asymmetry in a distribution. Some authors suggest that abnormal skewness statistics are within ±1 (Chan, 2003). The kurtosis statistic demonstrated how peaked the data were. A kurtosis statistic ±3 indicates that the data are not normal.

Based on these guidelines, both MATE and MUM data had normal distributions upon investigation of kurtosis, skewness, and histogram with normal curve overlay. The hypothesis of normality was rejected using a Komolgorov-Smirnov one-sample test, but considering other three measures of support for normality, I assumed the data to be normal.

Linearity. Linearity assumes that the data follow a linear pattern, that is, y = (a + bx) + e. The data were assumed to be linear since the points on Q-Q plot were found all along the scale.

Homoscedasticity. Homoscedasticity refers to the assumption that the one variable exhibits similar amounts of variance across the range of values for the other variable. Since the errors on the Q-Q plots had an equal number of points below and above the line, the data were considered mostly homoskedastic.

Independence of observations. In the case of this study, the scores for one student on the MATE and the MUM would not have influenced the scores of another student, because the students took the surveys electronically outside of class. The data were therefore assumed to have independence of observations.

Qualitative Methodology

The qualitative phase of the study addresses the nature of the instructor's PCK for teaching macroevolution, how this informs her instruction, and how the instruction influences student knowledge of macroevolution and acceptance of evolution through a case study research tradition.

Paradigm

The qualitative portion of the dissertation assumes a constructivist paradigm. Constructivism has emerged as a paradigm for science education research in the last thirty years, following a global shift away from positivism as the philosophy of science. A constructivist paradigm assumes that a separate reality is constructed for every individual, based on his or her unique experiences, knowledge, and beliefs (Hatch, 2002; von Glasersfeld, 1984). Knowledge is not perceived as a direct representation of an external, objective reality, but rather knowledge is perceived as a personal representation of the world, actively constructed by the knower. In the case of this study, both the knowledge of the instructor and the learning experiences of the students are uniquely constructed realities.

Ontological Assumptions

A constructivist paradigm assumes that students are able to take knowledge learned in class and use it with existing ideas to understand experiences. Although I see individuals as interacting within a single reality, individuals have unique interpretations of that reality with respect to his or her experiences. The biology course was a single shared reality among the students and their teacher. However, what a student perceived from class differed based on his or her experiences. I therefore believe that knowledge is subjective and the lens of human perception creates infinite interpretations of reality. Patton (2002) refers to this as *ontological relativity:* "all tenable statements about existence depend on a worldview, and no worldview is uniquely determined by empirical or sense data about the world" (p. 97). Thus, "the world of human perception is not real in an absolute sense, as the Sun is real, but is 'made up' and shaped by cultural and linguistic constructs" (Patton, 2002, p. 96).

Epistemological Assumptions

A constructivist paradigm assumes that learners construct knowledge through interacting with their environment and others. Subsequently, understanding teacher knowledge and likewise student learning can only be done through the experiences of the teacher or learner. The epistemological assumption of constructivism implies that knowledge is dependent upon information and context available when constructing assertions about reality or truth (Guba & Lincoln, 1989).

Methodological Assumptions

Hermeneutic-dialecticism is also a constructivist methodological assumption (Guba & Lincoln, 1989). This assumption presumes that it is the responsibility of the researcher to investigate and reconcile the realities of both the researcher and the participants. This interaction involves communication among individuals with different perceptions and is negotiated by the researcher to make sense of the individual realities. Initially, the researcher attempts to assess the constructed reality of the participants, then the researcher and the participant(s) engage in a dialogue to co-construct the meaning of the experience. This methodological assumption leads to the use of persistent observation, member checks, and other methods to ensure trustworthiness.

Data Collection

Data were collected throughout the 15-week general education biology course, including prior to, during, and following the evolution unit (13 50-minute class periods, Figure 4). I attended each lecture to observe instruction and record field notes. The instructor was interviewed once prior to the evolution unit, once during the unit, and after the evolution unit exam (which was also the final exam). Students were assessed prior to and after the evolution unit, and select students were then interviewed after the post-test (see *Student Interviews* for selection criteria).

Student Measures

Students were assessed during the second week of the course (late January 2012) as a pre-test and immediately following the evolution unit as a post-test (mid-April 2012). The MATE and MUM pre- and post-tests were given electronically outside of class.

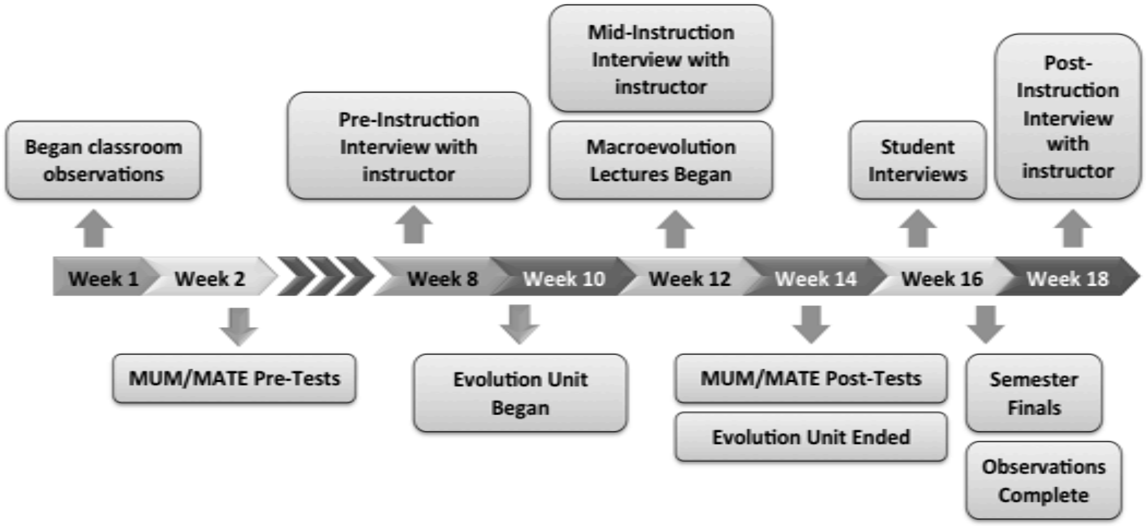


Figure 4. *Timeline for study including observations, interviews with the instructor and students, and schedule for the evolution unit.*

Twelve of the surveyed students were then purposefully selected to be interviewed in May 2012 before the end of the semester (see *Student Interviews* for selection criteria).

Measure of Acceptance of the Theory of Evolution (MATE). The MATE is a 20-item, 5-point Likert scale instrument (Appendix C) that measures students' acceptance of evolution. It is considered valid and reliable (α= 0.86) for use with undergraduate students (Rutledge & Sadler, 2007).

Measure of Understanding of Macroevolution (MUM). Students' understanding of macroevolution was evaluated using the Measure of Understanding of Macroevolution, or MUM (Nadelson & Southerland, 2010b). The MUM is a 27-item multiple choice instrument with 1 short answer question (Appendix B). It reportedly measures five core tenets of macroevolution: deep time, fossils, phylogenetics, speciation, and the nature of science.

Student interviews. Twelve students were interviewed about the influence of instruction on their answers on the quantitative MATE and MUM instruments. Interviews were semi-structured around principles of how people learn (Bransford et al., 2000)(Appendix E).

All interviewees scored below class average on the MATE and/or MUM before instruction. After instruction, pre-to post-instruction gains determined eligibility for interview. To be selected for an interview, the student had to be (a) willing and available for an interview, (b) have at least 75% attendance during the evolution unit (determined by clicker grade), (c) have a low pre-instruction score on the MATE and/or MUM, and (d) have a sufficient increase on MATE and/or MUM score on the post-test. A low pre-instruction score on the MUM was below the average class score of 14.43 (of 27), and a low pre-instruction score on the MATE was below the average class score of 70.67 (scale 20 to 100). Originally, I had planned to interview students with at least 90% attendance, but had to relax this requirement to 75% due to difficulty recruiting participants (see *Limitations*).

Table 3 illustrates the sub-groups of students selected for interviews. All interviewees had below average MATE and/or MUM scores pre-instruction. From this group, three students from each of the following sub-groups were interviewed: students with (a) increase in MATE but not MUM , (b) increase on MUM but not MATE, (c) increases on both MUM and MATE and (d) no increases on either instrument. Students with the greatest increase pre- to post-instruction were contacted for interviews prior to individuals with lesser gains.

The minimum and maximum scores within each sub-group were determined by the nature of interviewee MATE and MUM scores. For example, among the six individuals recruited for an increased MATE score, the individual with the smallest gain increased her score by 9 points (scale 20 to 100). Five others increased their score by more than 9 points. Conversely, among the six individuals recruited for "no change or decreased MATE score", the highest gain on the MATE was only 3 points. This placed in the minimum value (among interviewees) for a MATE "increase" at 9 points and the maximum value for "no change or decrease" at 3 points. No interviewees had MATE increases between 4 and 8 points. The same process was used to determine the minimum and maximum values for the MUM sub-groups (see Table 3).

Table 3

Sub-Groups of Students Selected for Interview. All Interviewees Scored Below Class Average on the MATE and/or MUM Before Instruction. Pre-to Post-Instruction Gains Determined eligibility for Interview in any given Sub-Group. Abbreviations: MATE: Measure of Acceptance of the Theory of Evolution, MUM: Measure of Understanding of Macroevolution

MUM Increase $\Delta \geq$ *7 points*	Increase on MUM but not MATE post-instruction Below average MUM score pre-instruction (3 students selected for interview)	Increase on MUM and MATE post-instruction Below average MATE and MUM score pre-instruction (3 students selected for interview)
MUM Decrease or No Change $\Delta \leq$ *2 points*	Increase on neither MATE nor MUM post-instruction Below average MATE and MUM score pre-instruction (3 students selected for interview)	Increase on MATE but not MUM post-instruction Below average MATE score pre-instruction (3 students selected for interview)
	MATE Decrease or No Change $\Delta \leq$ *3 points*	MATE Increase $\Delta \geq$ *9 points*

Instructor Measures

PCK is an external and internal construct (Baxter & Lederman, 1999; Nilsson & Loughran, 2010), and consists of what a teacher knows, what a teacher does, and the reasons for the teacher's actions (Baxter & Lederman, p. 158). The teacher's pedagogical content knowledge was examined three specific ways: observations of lessons, three instructor interviews (before, during and after instruction), and by examination of artifacts from the class (tests and in-class activity materials).

Instructor interviews. Three interviews with the instructor focused on her plans for the macroevolution unit, events from class, reflections related to the major areas of the Magnusson model of PCK, and how she predicted students to perform on the MUM based on the course curriculum. I interviewed the instructor once before the evolution unit and once during the evolution unit about her pedagogical decisions by using a semi-structured interview protocol (Appendix D). After the evolution unit exam (which happened to be the final exam), I interviewed the instructor again about her pedagogical decisions during the evolution unit (for instances that occurred after the second interview) and discussed how she designed the evolution unit exam.

Classroom observations. Including classroom observations is an important factor in understanding how teachers use their knowledge for teaching. Park and Oliver (2008) note that PCK can only be expressed *during* teaching as teachers transform subject matter to make content understandable for students. It follows that any interviews and qualitative artifacts should be triangulated with observations of PCK in action. I attended each lecture of the class, including those outside the evolution unit, with observations documented through field notes and Tegrity lecture capture. Analysis focused primarily on the evolution unit within the course, with a particular focus on macroevolution instruction.

Artifacts. The instructor included macroevolution content on one in-class activity related to phylogenetic trees (Appendix J) and on the final exam (Appendix K). These artifacts were coded for components of the instructor's PCK per the Magnusson et al. (1999) model and are included in the Appendices.

Quantitative Measures of Verification

Validity and Reliability

In quantitative research, reliability and validity of instruments is important for reducing errors from measurement problems. Reliability refers to the instrument generating similar results test after test (Thorndike, 1997) and is typically measured using Cronbach's alpha (α). Validity refers to the degree to which an instrument accurately assesses a specific concept or construct (Thorndike). Content, face, and construct validity of a survey instrument must be established. Content validity establishes that questions on an instrument accurately measure all dimensions within a given parameter. For example, the claimed dimensions of macroevolution (knowledge of fossils, speciation, phylogenetics, deep time and nature of science) should be accurately measured using the MUM. Face validity confirms that the questions make sense to the intended audience, in this case non-biology majors. Construct validity confirms that the questions on the test actually measure what they should, for example, questions about knowledge of fossils measure only that parameter and not also knowledge of deep time.

Verification of the Measure of Acceptance of the Theory of Evolution (MATE)

The MATE had already been found valid and reliable for non-science majors and therefore did not require further revisions to be used in this study (Rutledge & Sadler, 2007). The MATE achieved a Cronbach's alpha of 0.94 (maximum value = 1), indicating that the items of the instrument were highly related and therefore measure the construct (evolution acceptance) and had a test-retest reliability (Pearson Product Moment correlation = 0.92).

Verification of the Measure of Understanding of Macroevolution (MUM)

The original MUM was found valid and reliable for biology majors (α= 0.86). The MUM (Nadelson & Southerland, 2010a) could therefore not be considered valid and reliable for a population of non-science majors. Additional reliability tests were therefore conducted in a pilot study prior to the dissertation. This pilot study was done on a similar population of non-biology majors in a general education biology class in Fall 2011. Dr. Wallace was not the instructor for the pilot study course.

Reliability. In the pilot study (analyses in Appendix F), Cronbach's alpha for the MUM was 0.534. This indicates 53.4% consistency in scores. Since this value did not meet the desirable 0.7 value for reliability (Nunnally, 1978), I considered removal of individual MUM questions. However, no individual questions were more difficult than others, and so I did not remove items from the instrument. Despite lower (but not dismissive) reliability, I determined that the MUM could be retained in its original form in the dissertation study. The only revision to the test was to add numerical values to answers on the deep time questions (Q3, Q21, Q27). This revision was made at the suggestion of a student during the pilot study. For example, answers that previously read

“5 million years” read “5 million years (5,000,000)” on the version used in the dissertation.

Face validity. Face validity was another concern with the original MUM instrument. In other words, some questions may have been confusing to students. Q3, Q6, Q14, and Q27 had around 30 and 40% of students answering correctly (Nadelson & Southerland, 2010a), even among junior and senior biology majors. These low averages should have highlighted the need for revision or removal of these questions or removal to improve face validity. The authors instead attributed low values to poor student understanding on the items in question and did not attribute the values to the nature of the questions themselves.

Content validity. The content validity of the entire MUM instrument is questionable without a factor analysis to determine which of the test items pooled together. For example, if the students did not understand deep time, they should have done poorly on all questions related to deep time, and not solely Question 3. This brings into question whether the test items accurately measure the content they claim to. Unfortunately, there is no way to determine if the original MUM accurately measured the five tenets of macroevolution that it claimed (deep time, nature of science, phylogenetics, speciation and fossils) without a factor analysis of Nadelson and Southerland’s (2010a) data.

Content validity was also a concern in the MUM’s nature of science questions. The MUM instrument reportedly addresses alternative conceptions about the tenets of NOS. This is only somewhat true. The MUM does not address all alternative conceptions about the nature of science deemed critical to understand evolution by the National

Academy of Sciences. Questions cover the empirical nature of science (Q5, Q11, Q23), tentativeness in science (Q5), and the nature of theories in science (Q5, Q26). The instrument also elicits alternative conceptions about subjectivity in science (Q23) - an important tenet of understanding the nature of science a whole (National Research Council, 1996) - but not a tenet identified as critical to understanding evolution (NAS, 1998). However, the instrument does not address ideas about "the" universal scientific method nor ideas about the predictive value of scientific theories.

Construct validity. Validity was compromised further as some MUM questions clearly assessed more than one parameter, and thereby affecting construct validity. For example, question 22 reportedly assessed only knowledge of fossils. However, it has answers geared toward misconceptions about the nature of science (answer A) and phylogenetics (answer D).

> Question 22. The fossil record for early humans is very sparse compared to many other organisms. In the context of the Great Ape tree this means:
>
> > A. Much of the evolutionary relationships of humans and the other Great Apes is opinion and based on guess.
> >
> > B. Analysis of genetic codes and anatomy are used to derive such relationships.*
> >
> > C. The evolutionary relationships of humans are relative easy to determine based on the wide variety of humans alive today.
> >
> > D. Humans have not undergone many evolutionary changes and remain at the top of the tree.
> >
> > (Nadelson & Southerland, 2010a, p. 182).

MUM validity measures. In the pilot study of the MUM (Appendix F), an exploratory factor analysis revealed three factors (not five) explained most of the variance. Although questions did not cluster into the named components described by

Nadelson and Southerland, the three factors for non-science majors' thinking about evolution came out of the Principle Components Analysis - (a.) evidence (b.) change over time and (c.) common ancestry (Appendix F). In the subsequent MUM factor analyses (pre- and post-test), the same questions did not cluster within three factors. Only one factor emerged with a high Eigenvalue for each test, and there was little similarity among which questions clustered within this factor between the pilot, pre-test and post-test MUM. Since the questions did not factor together as Nadelson and Southerland (2010a) would predict, these questions do not validly assess knowledge of fossils, phylogenetics, speciation, deep time, and nature of science.

Reflections on the MUM. I came to realize that the MUM instrument was imperfect. It had minor issues with reliability (Cronbach's alpha = 0.534) and several potential problems with validity. However, the MUM was the only test available that reportedly measures (at least in some capacity) students' knowledge of macroevolution. This combined with the potential for correlation between acceptance and knowledge of macroevolution as measured by the MUM was cause for me to use the instrument and proceed with the dissertation study.

Qualitative Measures of Verification

Trustworthiness

The criteria for judging qualitative data differ from quantitative research. In qualitative design, the researcher seeks believability, based on coherence, insight, and instrumental utility (Eisner, 1991) and trustworthiness (Lincoln & Guba, 1985) through a process of verification rather than through traditional validity and reliability measures. Although the findings were limited by context, several steps were taken to ensure trustworthiness. The four aspects of trustworthiness (Lincoln & Guba) are credibility, transferability, dependability and confirmability. A trustworthy qualitative study gives confidence in its findings because of quality in methods and analysis. Since I was the qualitative research instrument, interpretations of the data had to be adequately representative of participant's constructions of reality (Lincoln & Guba). Specific details on how each aspect of trustworthiness were addressed throughout methods and analysis are in Table 4.

Credibility. Lincoln and Guba (1985) define credibility in qualitative research as data analysis that accurately matches reality. This study is at least credible as matching reality (Merriam, 1998) on minimal grounds as it involved prolonged engagement with the instructor, classroom observation for the entire 15-week course, and triangulation among multiple data sources (interviews, field notes, artifacts, and pre/post tests).

Dependability. Lincoln & Guba (1985) state that there is no credibility without dependability, an assessment of the quality of the integrated processes of data collection, data analysis, and theory generation. In other words, a study should demonstrate that the findings are consistent and could be repeated. This study was dependable by design dissertation appendices include several data analysis documents used to generate answers to the research questions for dependability purposes. Furthermore, the complete set of data analysis documents is on file and available upon request. Access to this "paper trail" gives other researchers the ability to transfer the conclusions of this study to other contexts as they see fit, or closely repeat the procedures of the project. Likewise, the interview protocols for both the instructor and the students are available for researchers desiring to conduct a similar study (Appendices D and E).

Table 4

Corresponding Criteria, Concerns, and Methods for Trustworthiness (format adapted from Baker, 1995 with considerations from Creswell, 1998 and Lincoln and Guba, 1985)

Criteria	Concerns	Methods
Credibility	Data analysis must be an accurate representation of "reality"	- Triangulation of themes among student participants - Triangulation of themes among the interviews with the instructor and the various data sources (interviews, field notes, Tegrity recordings, pre/post tests)
Transferability	Results are applicable beyond the context of the study	-- The choice of a broad participant group (undergraduate non-science majors) and commonly taught general education class -- Thick description of instructor PCK, how this influences instruction, and themes that influence student understanding of macroevolution/ evolution acceptance
Dependability	Methodological shifts; Redundancy in data	-- Systematic interview protocols -- Easily accessible paper trail, including analysis samples in the dissertation appendices
Confirmability	Theory grounded in data; logical inferences; strong rationale for themes in data	-- Peer and expert debriefing -- Member checking with instructor

Confirmability. Lincoln and Guba (1985) define confirmability as the extent to which the findings of a study are shaped by the respondents and not researcher bias, motivation, or interest. Confirmability in findings was generated by having individuals unfamiliar with the intricacies of the data evaluate the findings – including the faculty participant (member checking) and colleagues (peer and expert debriefing). Confirmability was also established as I debriefed data patterns to both colleagues (peers) and my advisor (expert). This reduced my internal bias as sole researcher and to verify accurate descriptions of the data. Furthermore, during the analysis portion of the study, the instructor was allowed to comment on the accuracy of the identified categories and themes related to her PCK. She was allowed to suggest add, delete or modify information if she desired, but made no revisions.

Transferability. Transferability is the degree to which the findings of the study are relevant in other contexts (Lincoln & Guba, 1985). Since the participants were not biology majors and the general education biology class is typically a high enrollment class across the United States, the results of the study could be broadly applied to similar courses. The study is also transferable by design as the numerous data sources (interviews with instructor and students, field notes, artifacts, and pre/post tests) created rich descriptions that provide detailed answers to each research question. Describing each phenomenon in sufficient detail should allow the reader to evaluate the extent to which the conclusions drawn are transferable to other times, settings, situations, and people (Lincoln & Guba, 1985).

Additional Limitations

Evolution acceptance as measured by the MATE. Although Rutledge and Warden (1999) assert that the MATE assesses student acceptance of the theory's validity from a scientific perspective, some statements in the instrument seem to assess the view of the theory as personally true (i.e. "Q7. the age of the Earth is less than 20,000 years old", rate from strongly agree to strongly disagree, "Q11. The age of the Earth is at least 4 billion years). The instrument elicits personal acceptance of evolution. This is a disconnect between my personal definition of acceptance and how the MATE measures acceptance. I assert that individuals should accept evolution as scientifically valid, but do not see it necessary for individuals to accept evolution as their worldview.

Despite this disparity, the MATE was selected as the tool to investigate students' views of evolution. Scores on the MATE were significantly correlated with knowledge of macroevolution (as measured by the MUM) in a recent study of biology majors (Nadelson & Southerland, 2010b). The potential for a similar relationship between knowledge of macroevolution and acceptance for non-science majors implied the need to select the MATE over other acceptance instruments available (i.e. Alters, 2005; Hawley, Short, McCune, Osman, & Little, 2010).

Recruitment. Not all of the interviewed students had MATE and MUM scores below class average. This was due to (a.) a low number of students who had >75% class attendance but did not make gains on the instruments and (b) interviews were rescheduled to the week before semester finals due to a delayed start to the evolution unit. This caused many students to be unavailable for an interview.

Despite this, all students within their sub-group (Table 3) met the necessary requirements to be categorized in that group. For example, although Adam had an above average MUM score pre-instruction (16), his pre-instruction MATE score was below average (44). After instruction, his score on the MUM remained about the same (15), but his MATE score increased substantially (70). He therefore met the criteria to be in the "increase on MATE but not MUM" sub-group.

CHAPTER FOUR: FINDINGS

In this chapter, I provide evidence to each research question of the study. The chapter is divided into three sections. I begin the chapter by discussing the nature and sources of PCK for the instructor. This includes a description of the faculty participant and instruction during the course. This description provides context for the second section of Chapter Four, which focuses on the pre- and post-instruction knowledge of macroevolution and evolution acceptance for the student participants. The final section of Chapter Four describes how the instruction influenced students' knowledge and acceptance of evolution, including data that support a relationship between these two components.

What is the nature of a college instructors' pedagogical content knowledge for teaching macroevolution?

In this section of Chapter Four, I provide a case profile for the course instructor, Dr. Wallace. The purpose of the case is to provide an in-depth profile surrounding the themes in Dr. Wallace's PCK for teaching macroevolution, the experiences (sources) which have influenced her PCK, and how her PCK informed her instructional practice. The case profile begins with a vignette: a moment in Dr. Wallace's instruction presented in story form. In the vignette, I attempt to capture the essential elements of her practice during a moment in her instruction that student interviewees described as particularly memorable.

The case profile begins with this vignette and continues on to a description of Dr. Wallace's background, teaching context, and a summary of her evolution unit. The major themes in her PCK are then discussed around the components of the Magnusson et al.

(1999) model of PCK. The discussion of Dr. Wallace's PCK begins with her orientations toward science teaching and knowledge of learners, as these were components particularly influenced other PCK components and were particularly evident in her instructional practice.

Instructional Vignette: *Archaeopteryx* Comes to Class

"This was a Valentine's present from my husband a few years ago. It's better than the six pack of Sam Adams he usually gives me," remarked Dr. Wallace.

Students turned their heads and laughed to themselves as she walked a plaster slab up and down the center aisle of the lecture hall. Dr. Wallace was carrying a fossil replica of *Archaeopteryx*, a transitional life form between reptiles and birds (Figure 5). This was the fourth of what would be six transitional fossil examples presented to the class. She returned to the front of the classroom and projected a PowerPoint slide with a picture of a dinosaur and a pigeon.

"By the way, many dinosaurs were small like this pigeon. Some of them had similar features to this pigeon as well."

She projected the *Archaeopteryx* fossil on the ELMO.

"Note that it isn't very big. *Archaeopteryx* has characteristics of both dinosaurs and birds. It's a beautiful example that shows both reptilian features and feathers. 150 million years old."

She pointed to features on the fossil.

"There are several ways we can tell that this is a transitional fossil between reptiles and birds. The pelvis shows that it stood up like a bird, it has elongated fingers

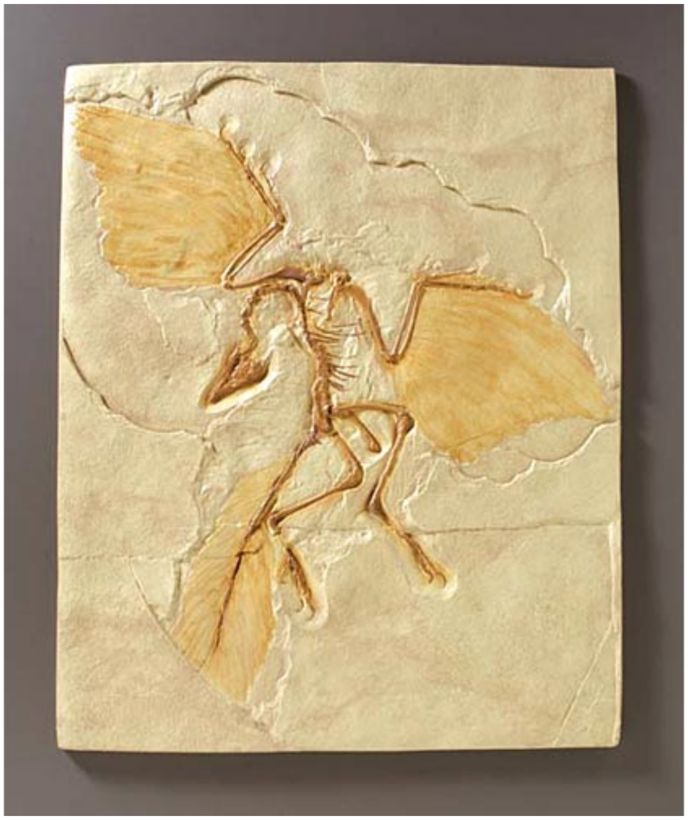


Figure 5. A photograph of the fossil replica of *Archaeopteryx* similar to the one used in class. Source: http://sciencekit.com/images/250/1760-54WebF.jpg

for wings, but it has a long reptile tail, little reptile teeth, reptile like claws, and a heavy reptile-like bone structure."

Dr. Wallace switched the projection back to PowerPoint notes, a list of transitional features she just described.

"If anybody wants to see this up close, please come up afterwards. It will be kept in my office too. By the way, there was a similar species of feathered dinosaur found in China last Monday. It is the size of a bus and had downy feathers like a chick."

Case Background and Context

Dr. Wallace, a woman in her forties, holds an undergraduate degree in biology and a PhD in behavioral ecology. She is a non-tenure track faculty member at a large research-intensive university in the Midwest United States. This was her sixteenth time teaching the general education biology course. She also taught three other courses, including upper-level community biology, senior-level animal communication, and an "Evolution for Everyone" course - a non-science majors course on the applications of evolutionary theory to modern human affairs.

The majority of the undergraduate student population at the university was 80.9% white, non-Hispanic, 7.7% Black/African American, and 11.4% other, with a total enrollment of 26,024 undergraduate students (University of Missouri, 2011). Dr. Wallace's general education biology course had an enrollment of 403 students in spring 2012. Her lecture space had auditorium style seating, with about 18 rows of 20 seats each, divided into two sections by a center aisle and flanked by aisles on the left and right sides of the room. There was a large projection screen and a chalkboard in front of the room, and a data projector extended from the ceiling for PowerPoint slides, DVD, or projections from the ELMO.

Summary of the evolution unit

Dr. Wallace spent thirteen 50-minute lecture periods on evolution from March 19 though April 25, 2012. Table 5 highlights the sequence of the instruction and specific topics taught. The evolution unit began by introducing evolution as “a change in allele frequencies over time,” followed by five class periods related to mutations as sources of new alleles and followed by a discussion of the mechanisms of selection, including natural, sexual, and artificial selection. Her instruction then transitioned into explaining how selection can lead to speciation (macroevolution). This was followed by two class periods on the evidence for evolution, with a particular emphasis on transitional fossils (as described in her *Vignette*), and vestigial traits.

Dr. Wallace administered Exam Four, which assessed natural selection concepts but not macroevolution. The day following the exam was a 50-minute in-class activity interpreting phylogenetic trees. Dr. Wallace ended the macroevolution unit by returning to the fossil intermediates as evidence for major transitions in the history of life on Earth, including the evolution of humans.

Overview of the Nature of Dr. Wallace’s PCK

Dr. Wallace’s PCK for teaching macroevolution was highly influenced by her knowledge of students and her orientations toward teaching science. These components are well integrated with her knowledge of instructional strategies, assessment, and curriculum. This section therefore begins with Dr. Wallace’s orientations for science teaching, followed by a description of her knowledge of learners. The last three sections

Table 5

Summary of Topics Taught in Dr. Wallace's Evolution Unit during spring 2012 by Date and Nature of Macroevolutionary Content.

Date	Topic	Contained macroevolution content
19-Mar	Intro to Natural Selection; What is evolution?	
21-Mar	Natural Selection through Darwin's observations	
23-Mar	Mutations, alleles through Sexual Selection	
2-Apr	Horned lizards natural selection activity	
4-Apr	Sexual selection, genetic drift, migration, genetics & evolution	X
6-Apr	Speciation and start of evidence for evolution, ends with *Archaeopteryx*	X
9-Apr	*Archaeopteryx* fossil in class, Evidence for Evolution, PBS Great Transformations video	X
11-Apr	Exam IV	
13-Apr	Tree Thinking In Class Activity	X
16-Apr	Evidence for Evolution	X
18-Apr	Misconceptions about Accepting Evolution History of Life on Earth	X
20-Apr	Endosymbiosis; History of Life on Earth	X
23-Apr	Human evolution	X
25-Apr	History of life on Earth, more on fossil age	X

describe Dr. Wallace's knowledge of instructional strategies, curriculum, and assessment for teaching macroevolution, highlighting the meaningful connections between Dr. Wallace's knowledge of learners and orientations for teaching science in each of these components.

Orientations Toward Science Teaching

Dr. Wallace's instruction had elements of a didactic orientation; she primarily taught using lecture and multiple choice assessments. However, Dr. Wallace had a student-centered orientation toward science teaching as her use of didactic strategies was primarily an artifact of her context. Dr. Wallace had over 400 students and did not have a grader for the course to help with scoring assessments. She lamented that if she had more time and fewer students, that she would incorporate small group work and more writing into the class. Despite these contextual barriers to teaching student centered ways, when Dr. Wallace discussed her goals for the course and her role as an instructor, she consistently discussed students' interests and needs. For this reason, I labeled her as having a student-centered orientation.

Three central goals guided Dr. Wallace's instructional decisions in the course as a whole and evolution unit. Foremost, she wanted the students to find the course material interesting and saw it as her role to engage students' interest. Secondly, Dr. Wallace wanted students to think critically about the material and saw it as her responsibility to offer opportunities for them to do so. Lastly, she wanted students to be scientifically literate. She wanted students to leave the class with knowledge of the practical applications of evolution, including understanding phylogenetic trees and the predictive power of theories.

Goal 1. Make biology interesting

"I want them to see that the material is interesting, that's important to me, that they find the material interesting. So I see that also as part of my job." (Interview 3, p. 13). Dr. Wallace wanted students to find the course interesting and therefore designed the biology course to engage students in unique and relatable examples. This goal guided Dr. Wallace to learn more about her students interests over the years through post-course surveys (see *Knowledge of Learners*). The results of these surveys in turn informed changes to her curriculum. Over time she has eliminated content she thought was boring or unsatisfying for students, including the origins of life and specific modes of speciation. In a reciprocal fashion, Dr. Wallace has increased class time on evolution topics (see *Knowledge of Curriculum*) which were more interesting for students, including human evolution, tree thinking, and vestigial traits (see *Knowledge of Learners*). For example, she described wanting to 'wow' students with interesting examples, like the small leg bones found in some whale species.

> [Whale leg bones] are an example something that might make them say - wow that's cool - and that wow that's a cool factor - and that is important to me. And so I love vestigial structures and I want to share with them and so I used a variety of examples in that. (Interview 2, p. 17)

Goal 2. Provide opportunities for critical thinking

> The role of the professor is to provide the background information that they need and the stimulation to think about it. And whatever tools they need to get them to think about it. Prompts for the questions that force them to think about the

> material. So I guess it's the combination of the two things, the background knowledge and the stimulation to think about it. (Interview 3, p. 14)

Dr. Wallace's PCK was highly influenced by her desire to engage the students in critically thinking about the material. This was particularly evident in her knowledge of instructional strategies and assessment. Throughout the course, Dr. Wallace wanted students to have multiple opportunities to think critically about their misconceptions. She did this by including multiple discrepant examples and activities which challenged students' misconceptions. One such strategy was an in-class activity about phylogenetic trees, which addressed not only students misconceptions about how to interpret trees, but also targeted misconceptions about human evolution and speciation (see *Knowledge of Instructional strategies*).

Dr. Wallace also wrote formative and summative assessment items to elicit critical thinking skills. When writing a new test item, she described drawing from about five different question formats, most of which required higher level thinking skills.

> Overall for the course, I want them to be developing their thinking skills, so how to abstract and apply information, so I try to write and not all my questions are successful in this regard, but I try to write questions that require them to use information that they are learning (Interview 3, p. 13).

Dr. Wallace wanted students to go beyond rote memorization of the content and be able to abstract and apply information. The format of her assessment items reflect this goal. Students had to critically read the question as incorrect answer options would be scientifically correct but did not answer the question. Questions also required students to use their knowledge to interpret new phenomena, determine true/false relationships among statements, or synthesize knowledge from different areas of the course. (see *Knowledge of Assessment)*

Goal 3. Scientific literacy

Dr. Wallace wanted students to develop scientific literacy during the evolution unit and course as a whole. Dr. Wallace described two primary components for teaching evolution through the lens of scientific literacy. The first component of this goal for scientific literacy was the practical use of evolution for the layperson. She frequently questioned if a topic was important for students' everyday lives. For example, since phylogenetic trees appear in popular scientific articles, newspapers, and magazines, Dr. Wallace saw practical use in developing students' abilities to interpret phylogenetic trees: "I think including the trees helps students to become more science literate as they can read articles about evolution and interpret a tree correctly" (Interview 1, p. 3). Similarly, she wanted students to understand that the terms *theory* and *law* in science meant something different in science than in everyday language (See *Knowledge of Curriculum* for additional examples).

Dr. Wallace also wanted students to see the predictive power of theories. She frequently discussed how she wanted students to see the significance and logic behind why scientists knew evolution is occurring: "I want them to be able to pull together and see the significance of it and see how inevitable evolutionary change really is when selection is occurring" (Interview 1, p. 2). Dr. Wallace described that many observations of the natural world were difficult to explain without evolution, and therefore wanted students to see the value of evolutionary theory for both predicting and explaining natural phenomena.

> I think that vestigial structures are very difficult to explain otherwise. *Why* do whales have leg bones in them if they didn't evolve from four legged animals? I find them very convincing. They may not predict that they would see [vestigial structures], but it makes sense to the students for these to exist if animals evolved from a common ancestor. (Member check interview)

Since the evidence was exactly what scientists would predict if evolution was occurring, and because this evidence was so extensive and diverse, Dr. Wallace believed that students would see that evolution was "inevitable" and therefore understand why it is not a controversial issue for scientists. This goal of evolution predicting and explaining natural phenomena was most evident in her synthesis of the evidence for evolution as related to the nature of scientific theories (see *Knowledge of Instructional Strategies*).

Knowledge of Learners

Dr. Wallace had deep knowledge of her students. In tandem with her student-centered orientation toward science teaching, Dr. Wallace's knowledge of learners was the most influential component in informing her other areas of PCK and her instructional practice. She knew students were interested in learning evolution, in part because many had little evolution education in high school. Dr. Wallace therefore chose examples which focused around student interests. She knew students brought a number of incoming ideas and misconceptions about evolution, and therefore developed instruction and assessments that gave students the opportunity to critically about the content and have multiple opportunities to address their misconceptions. This sub-section describes the nature of Dr. Wallace's knowledge of learners in context with her instruction.

How students develop understanding. Dr. Wallace's PCK was informed by the guiding principles that (a) students need explicit instruction and (b) should have their incoming ideas and misconceptions engaged throughout the course.

Students need explicit instruction. Dr. Wallace believed students need explicit instruction to develop understanding. This was most evident in her reflective practice over assessment outcomes (see *Sources of PCK*). When she reviewed how students did on the exam, her first inclination was often to question whether her instruction was clear. Dr. Wallace knew that PowerPoint slides were critical to college learners. If text was missing from a slide, the text was not in their notebooks, and therefore may not be available as study material.

One example of this reflective process happened during my third interview with Dr. Wallace when she hypothesized why only 24% of the class answered Q27 correctly on the final exam. As she reflected on the possible reasons for this, she realized the content needed to understand the question was unclear in her PowerPoint slides. She remarked that she would have to go back and make revisions before asking a similar question in the future. Other examples of how Dr. Wallace used her knowledge that students need clear instructional materials follow in later sections.

> The notes for mammalogy, although I gave examples between forelimbs. . . it's not in their PowerPoint slides and therefore are probably not in their notebooks . . . what makes it hard is that the notes that are on their PowerPoint slide, a lot of this stuff is alluded to, but it's not explicit. (Interview 3, p. 1)

Students' incoming knowledge. Dr. Wallace focused on students' incoming ideas throughout her instruction. She knew that many of the students had little prior evolution instruction and knew relatively little about the topic. Although she had not compiled the data for her past students, a colleague had done a survey of his undergraduates' evolution learning experiences. He learned that many of his students, especially those from rural areas, had not learned evolution in high school biology. Dr. Wallace inferred that her class probably had similar demographics.

Dr. Wallace knew that even if students had past evolution instruction, they may not understand evolution or know anything about the selection mechanisms behind evolution. She also recognized that another reason for low incoming knowledge of the topic could be because it had been several years since the students last learned evolution.

> That's not going to be a black and white thing of course, and just because they got evolution, that doesn't always mean the same thing. . . I'm sure there are a lot of them that haven't had it and so, and even if they have had it, it had been several years. (Interview 1, p. 9)

Students' misconceptions.

> If they didn't have a good high school biology class, they simply don't know much. I think they are coming into the evolution unit with ideas of things that they think they know about it. But then in many cases are incorrect and it's just stuff that they've picked up and they are just common misconceptions that people have. (Interview 1, p. 4)

Dr. Wallace used her knowledge of student misconceptions to inform other areas of her PCK and much of her practice (see *Knowledge of instructional strategies* and *Knowledge of Assessment*). She knew her students often had little past evolution instruction and had few scientific understandings, and therefore brought misconceptions to the class. This subsection highlights Dr. Wallace's knowledge of these misconceptions, written in the order in which they relate to the instruction. Other PCK subsections describe how Dr. Wallace used these misconceptions to inform her instructional practice.

Difficulties connecting genetics to evolution. Dr. Wallace explained that many of her students had a difficult time conceptualizing the connection between genetics and evolution. She related this to poor high school preparation in evolution and genetics.

> I think that the ones that have not gotten a strong background of evolution in their high school biology are coming in without any understanding of the relationship between genetics and evolution. They don't make a connection between those two fields. (Interview 1, p. 13)

She described that because of this difficulty, students had difficulty conceptualizing the understanding how mutations relate to natural selection, the connection between the universal DNA code and evolution, and the importance of both genetic divergence and reproductive isolation in speciation.

> I think they can memorize these are the steps for speciation and reproductive isolation and genetic divergence of the two populations and then they can no longer reproduce with each other, but I'm not sure they all get why the reproductive isolation is necessary. (Interview 1, p. 19)

Phylogenetic tree misconceptions. Dr. Wallace knew the students had a number of misconceptions about phylogenetic trees. This was one of the reasons she chose to do the tree thinking in class activity (see *Knowledge of instructional strategies*). "I think I had a growing realization that a lot of people don't interpret [phylogenetic trees] correctly. And there's an awful lot of misconceptions" (Interview 1, p. 3). There were three primary misconceptions about phyogenetic trees that Dr. Wallace mentioned during her interviews. First, she knew students would count nodes to determine the relatedness of organisms on trees. She learned about this misconception after reflecting on student performance on the exam of another biology faculty member (see *Sources of PCK*).

> Well with tree thinking, with interpreting the trees there are some misconceptions people have that are really hard to get over. So this idea that you can determine how closely related species are by counting the number of nodes in the tree, and so even if they have been told you can't do that, I expect that's something they would still have trouble with. (Interview 1, p. 19)

Dr. Wallace also knew that students had difficulty with reading trees at the tips. That is, they did not know arrangement of the tips of the tree are inconsequential. Every internal node on the tree can be rotated without any implications for relatedness. Students are unaware that patterns of relatedness can be depicted in slightly different ways, depending on how the tree is rotated. The final misconception students Dr. Wallace described students having about trees was to use their background knowledge organisms to determine relatedness rather than the structure of the tree itself. Dr. Wallace described that "for many students it's hard to get them past in interpreting the tree based on what they know about organisms." (Interview 1, p. 19)

Misconceptions about evolution as a science. Dr. Wallace had knowledge of learners' misconceptions about evolution as a science - topics which she saw as tied to the evolution acceptance. She knew some students may have learned in church or Sunday school that evolution was a controversial field in science and may also have learned that that accepting evolution required abandonment of their faith: "[Some students think that] evolution makes you an atheist, you cannot accept evolution and be religious" (Interview 1, p. 5).

> They come in with the idea that humans evolved from chimps, that biologists are in disagreement about evolution, that it's a controversial field, they believe in that misconception, that it's a controversial field within science. I think many of them are coming in with the misconception that if you accept evolution, you have to give up your faith, that accepting evolution makes you an atheist. (Interview 1, p. 6)

Misconceptions about human evolution. The final set of misconceptions Dr. Wallace discussed were students' misconceptions about human evolution. She recognized two primary misconceptions in this area - foremost, she knew students thought that humans evolved from chimpanzees. Secondly, Dr. Wallace knew some students thought humans were superior to other organisms and therefore at the pinnacle of complexity (line of progression). She did not think that students appreciated the extent to which humans were inconsequential on the tree of life. "I don't know whether they really fully appreciate the extent to which humans are statistically just a tiny dot and they're embedded within life. But that's probably something that if you think about it, is an eye opener to them." (Interview 2, p. 2)

Knowledge of Learners' Interest in Evolution

Dr. Wallace came to the Midwest from New York state. She described that she had concerns about moving to the "Bible Belt" because she thought students there would be predominantly Creationist and therefore resistant to learning about evolution.

> I knew I was moving to a very Christian, conservative part of the world and so yeah I thought that my students would for the most part be creationist and would be resentful about having to learn about evolution. I have to admit I was very nervous. (Interview 1, p. 7)

After a few years teaching the course, Dr. Wallace started to do an end-of-course survey to determine what topics the students found most interesting. To her surprise, students were most interested in evolution. In semesters she had actually counted the responses for each topic, she was amazed that 37% of students wrote something about the evolution unit. Dr. Wallace describes this as a critical moment in her attitude toward teaching evolution. She realized that students shared her interest in evolution and found evolution more interesting than other topics in the course. After this point, Dr. Wallace knew her students were less resistant to learning evolution than she previously thought, and were actually interested in learning about evolution.

> That was such an eye opener to me that the students actually, that they actually liked that unit. And that they do find it interesting. That for so many of them, and this is competing with biotechnology and cancer and viruses and all the other things that they do and I find interesting. It was a huge eye opener to me that they are interested in the topic and that really helped enormously in my attitude toward it. I was like, oh they do like this. I'm not pulling teeth. (Interview 1, p. 9)

Knowledge of specific areas of student interest in evolution. As Dr. Wallace has taught the course, she has realized that students were interested in particular evolution topics. These interests have guided her other pedagogical decisions, particularly in curriculum, but also in her use of particular instructional strategies and assessments. Dr.

Wallace described student interest in animal and human examples of evolution, vestigial traits, and in phylogenetic trees. She saw students as less interested in modes of speciation (allopatric/sympatric) and the origins of life. Representative quotes for these areas of student interest are couched within other subsections to provide the context in which student interest informs Dr. Wallace's pedagogical decisions.

Knowledge of Instructional Strategies

Dr. Wallace knew that students needed clear, easy to understand instruction and saw it as her role to provide the opportunities for students to learn in this manner. Dr. Wallace's knowledge of instructional strategies related to this goals, and in turn her knowledge of learners, in three ways. Foremost, she wanted to provide multiple examples for the same topic. Furthermore, she wanted to directly address student misconceptions. Lastly, she wanted to provide visual representations of how species have changed over time. This sub-section describes these three components of the nature of Dr. Wallace's knowledge of instructional strategies using examples and figures from classroom observations.

Instructional Strategy: Use multiple examples and multiple formats. Dr. Wallace wanted students to have clear, easy to understand instruction. This manifested in Dr. Wallace's use of multiple examples for each evolution concept. Her rationale behind this approach was that including more opportunities for students to confront a misconception provided more opportunities for them to overcome that misconception.

> The more times that you address a particular misconception in class, the better. And addressing it simply by lecturing might help some students get over it but

> addressing it by getting them to confront their misconception by answering a [clicker] question might help more get over it. (Interview 1, p. 19)

Dr. Wallace used a multiple example approach throughout her course, but in particular during her explanations of the evidence for evolution. She used seven different lines of evidence for evolution - artificially selected organisms, transitional fossils (a concept returned to during the history of life lectures), vestigial structures, homology, universality of the genetic code, biogeography, and cases of observable "natural selection in action" (Table 6). For each of these seven areas, she included as many as twelve different examples of evidence for evolution (see *Knowledge of curriculum* regarding scope).

A moment of synthesis. At the end of her two-period discussion about the seven lines of evidence for evolution (and 30 examples), Dr. Wallace appealed to the students' logic as she synthesized the evidence with a discussion of the nature of science, a topic not discussed explicitly since the first week of the semester (10 weeks earlier). Dr. Wallace reminded students of the essential features of a scientific theory: a general explanatory idea (but a big idea), broad ranging, testable, open to revision, and deal with natural phenomena. She then fit the evidence for evolution into these principles. A theory had to be broad ranging, as seen by the diverse range of evidence for evolution, these are all *explained* by evolution (Tegrity recording, April 18, 2012). A theory has to be testable, which she supported by discussion how fossil hunting can be predictive, as seen in the story of Dr. Neil Shubin and *Tiktaalik*. "Fossil hunting is predictive and paleontologists are experts at a given period of time. If I find rocks that are 380 million

Table 6

The Seven Lines of Evidence for Evolution used by Dr. Wallace in Class with Corresponding Examples and Count of Those Examples

Line of Evidence	Number of Examples	Specific Examples
Artificial selection (we can control how organisms change)	3	Dogs Wild mustard plant Lab mice
Transitional fossils	6	Consistent historical sequence in rock layers Humanoid skulls Horses *Archaeopteryx* Mesonychids to modern whales *Tiktaalik*
Vestigial structures	12	Snake leg bones Whale hip, leg, and feet bones Manatee toenails, hip bone, wrist and fingers Vampire bat molars Cave salamander eyes Blind mole rat eyes Dandelion pollen Humans - Goosebumps Appendix Wisdom teeth Muscles for turning ears (non-functional) Nipples along milkline (occasionally)
Homology	5	Vertebrate forelimbs Mammalian body form Manatee and elephant hip bones/molars Mammalian appendix (cecum) Insect ovipositor and bee stinger
Universality of genetic code	1	Hemoglobin across organisms
Biogeography	2	Florida butterflies Galapagos Islands
Natural selection “in action” (evolution is observable)	5	Finch body size as related to food source Drug resistant bacteria and viruses Tuberculosis Strep Human Immunodeficiency Virus (HIV) Herbicide resistant weeds

years old, I expect to find transitional traits between fish and amphibians. And here they were in Canada, and they have the proper transition" (Tegrity recording, April 18, 2012).

Instructional Strategy: Engage Students' Misconceptions

Dr. Wallace continued to use a multiple example instructional approach as she employed another instructional strategy: directly addressing student misconceptions. Most of her explanations in lecture, activities in class, and supplemental videos were designed to directly target students' misconceptions. This subsection describes how she addressed students' evolution misconceptions throughout her instruction.

Addressing students' misconceptions about speciation. Dr. Wallace knew that students had difficulty understanding how one species diverged into two, in particular understanding that both reproductive isolation and genetic divergence were necessary conditions for speciation. "I think seeing examples of how speciation occurs, I think that that's something that if [students] haven't learned about evolution in the past, how you can go from one species to two is a bit mysterious" (Interview 1, p. 6).

Dr. Wallace employed both a strategy of multiple examples and an approach of confronting misconceptions to address this area of difficulty. She included several examples of organisms undergoing speciation, including a hypothetic example with mice separated by a river, and real-life examples of snapping shrimp, squirrels at the Grand Canyon, and aquatic organisms on either side of the isthmus of Panama. As she gave each example, she reiterated the required steps for speciation: two populations become reproductively isolated from each other, then genetic difference may arise, and once the genetic differences are great enough to prevent reproduction, the groups are considered different species. Dr. Wallace also discussed requirements for speciation when she described the symbolic meaning of tree nodes during the tree thinking in class activity.

Addressing students' tree thinking misconceptions. The tree thinking activity was an important case of Dr. Wallace's instruction because it addressed several student misconceptions. The 50-minute worksheet addressed students' tree thinking misconceptions about nodes, rotation around nodes, misconceptions about human evolution, and reiterated principles of speciation (Appendix J).

The first portion of the worksheet had a phylogenetic tree with 14 ape species, including humans. Dr. Wallace chose this particular tree for the activity because she wanted to communicate the ordinary nature of humans on a phylogenetic tree. She described a similar desire to "treat humans like every other species". Dr. Wallace took the same approach of including humans in a phylogenetic tree with ape species when teaching the history of life.

> I like having the humans mixed in among the apes for example rather than trying to couch anything about human evolution and referring from saying anything about humans. So I prefer to just treat humans like every other species. (Interview 2, p. 5)

The activity asked students to interpret various portions of the tree, requiring students to interpret points of ancestry as indicated by symbols on the tree (Figure 6). Students were required to indicate what the asterisk node symbolized, find the common ancestor of humans and chimps, and to answer several questions about which organisms were more related to one another. This allowed students to apply their understanding of nodes as points of common ancestry, see that a strategy of "counting" nodes did not work

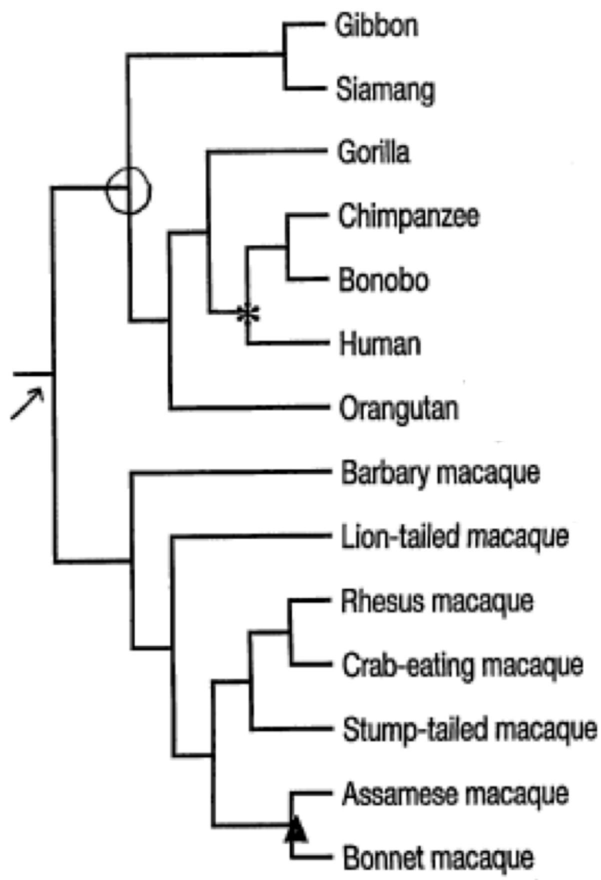


Figure 6. Ape phylogenetic tree from Tree Thinking in class activity (Appendix J). Symbols (arrow, triangle, circle, asterisk) represent various nodes of interest.

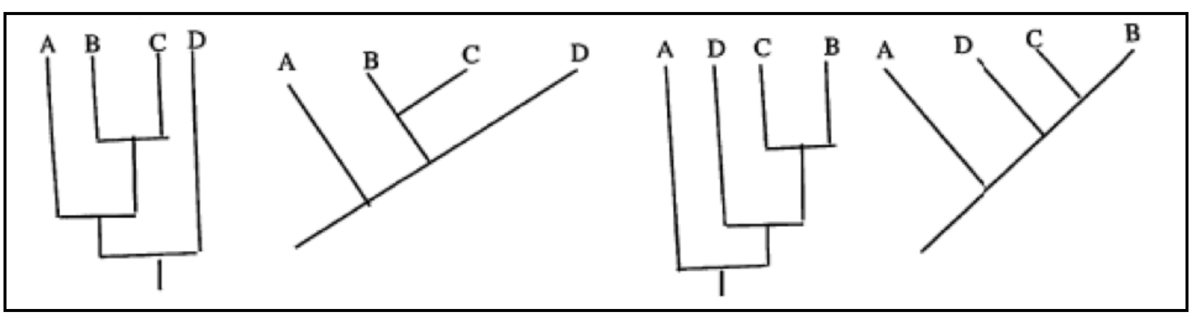


Figure 7. Phylogenetic trees lacking specific species from the tree thinking in class activity (Appendix J). Used for students to think about the structure of the tree without considering the physical features of the organisms.

to answer questions, and to see a visual representation of that demonstrates humans did not evolve from chimpanzees.

The second half of the tree thinking activity required interpretation of some trees that did not have specific species on them (Figure 7). Dr. Wallace purposefully included trees without species because she wanted students to consider the relationships of the organisms based on the structure of the tree and not the physical features of the organisms (a common misconception). This also provided the students the opportunity to consider which trees were similar and different by mentally rotating the trees at nodal points.

> So when I teach trees like the sites that I used I specifically use the letters to represent species rather than putting up say donkeys, whales, camels, birds goats or something because I want them to be thinking about the structure of the tree as suppose to what they know about those species and why those animals are grouped together. (Interview 2, p. 5)

Dr. Wallace ended the tree thinking class period with a BlackBoard animation. This animation addressed the misconception that the relationships of species on trees could be determined by looking at the tips of the trees (see *Knowledge of learners*). Dr. Wallace could click on any node, and the tree would spin around that node. Species at the tips would swap places, but the relationships among species remained the same. For example, species B swapped with species C (Figure 7) and this did not change relationship between the two species.

Addressing acceptance-related misconceptions. Dr. Wallace spent a portion of a class period talking about misconceptions about accepting evolution. She described these to the class as ‘evolution misconceptions’ although two concepts she spoke about were in direct relationship to ideas she had learned from reading creationist literature (see *Sources of PCK*). Dr. Wallace listed the misconceptions as bullet points on her PowerPoint slides and provided evidence to why each was not true.

The first of these misconceptions was that “evolution is controversial for scientists”. Dr. Wallace explained that this was simply not true. She commented that people with graduate degrees in biology (who were the most qualified to comment on the validity of evolution) had an evolution acceptance rate near 99.8%. She reminded students that although a part of being a scientist was being skeptical, and scientists do argue about details of evolution, they are *not* arguing about whether it is occurring or is still occurring (Classroom observations, April 18, 2012).

The second of the acceptance misconceptions Dr. Wallace refuted was that “accepting evolution requires giving up your faith”. Dr. Wallace explained to the students that this was not true that millions of people worldwide were devoutly religious but still accept evolution as the best explanation of diversity of life. She then went to the website for the Clergy Letter project, an online repository of letters confirming acceptance of evolution signed by Christian clergy. She showed students that 12,806 had signed as of the day of the lecture, including 284 from the state they were in. She reiterated the idea that there was no need for a dichotomy between evolution and faith in God and encouraged students that if they felt conflicted, they should learn more about this project.

> There is no necessary dichotomy between having faith in God and accepting evolution. If anybody tells you that this requires you give up your faith, they are misguided. I encourage you to take a look at this project. There are similar

> projects for other faiths around the world. (Dr. Wallace, Tegrity recording, April 18, 2012)

The last of these, although not given as a “misconceptions” slide, Dr. Wallace reminded the students about the differences between theory and law in science.

Addressing misconceptions about human evolution.

During the human evolution portion of the history of life lectures, Dr. Wallace took time to directly address misconceptions the students may have about the evolution of humans that they are superior to other organisms and that they come from chimps.

Humans are not superior to other organisms. Dr. Wallace addressed the human superiority concerns by noting that humans were an “infinitesimal speck” on the tree of life. Dr. Wallace thought that this principle would be eye opening for students - humans do not have even have their own branch on the tree of life (Figure 8).

> I do present these trees which I try to make this point. Oh and here's humans embedded within the animals and this little tiny branch up here and that I suspect that might be an eye-opener to many of them to see this tree that is showing the three domains and where humans are not even listed, not even mammals are listed. (Interview 3, p. 20)

Humans did not evolve from chimps. Dr. Wallace placed a giant X over the 1970’s picture “The March of Progression” to refute the misconception that humans came from apes (Figure 9a). She followed with slide of a phylogenetic tree with humans and chimps and indicated the most recent common ancestor for humans and chimps at 6 million years ago (Figure 9b). Dr. Wallace indicated that after this shared ancestry point, one line evolves into chimps, the other line evolved into humans (Figure 9b). In tandem with these

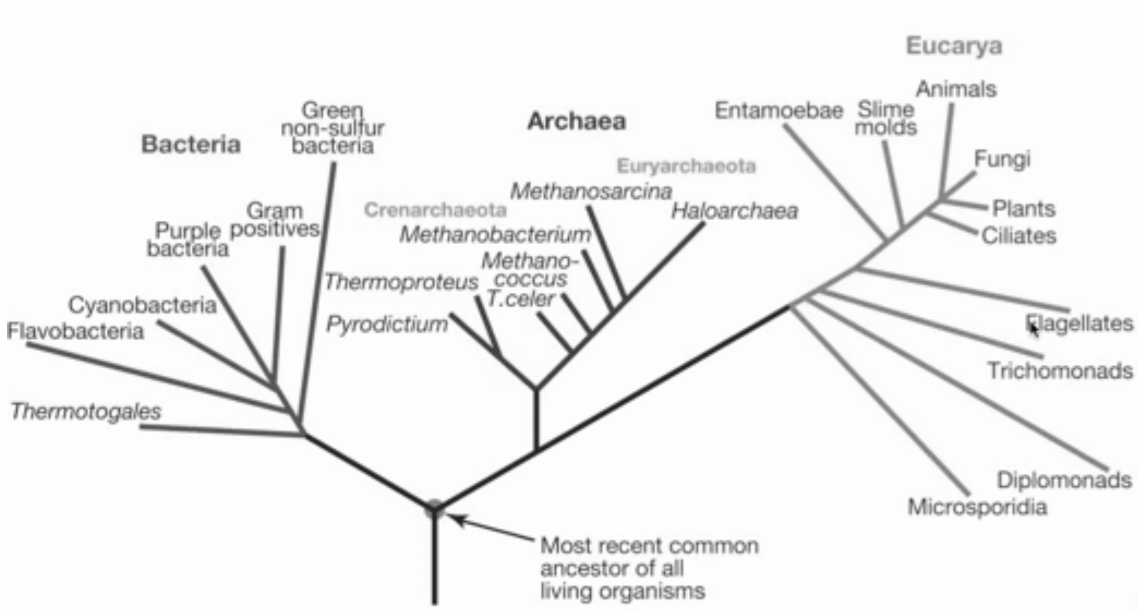
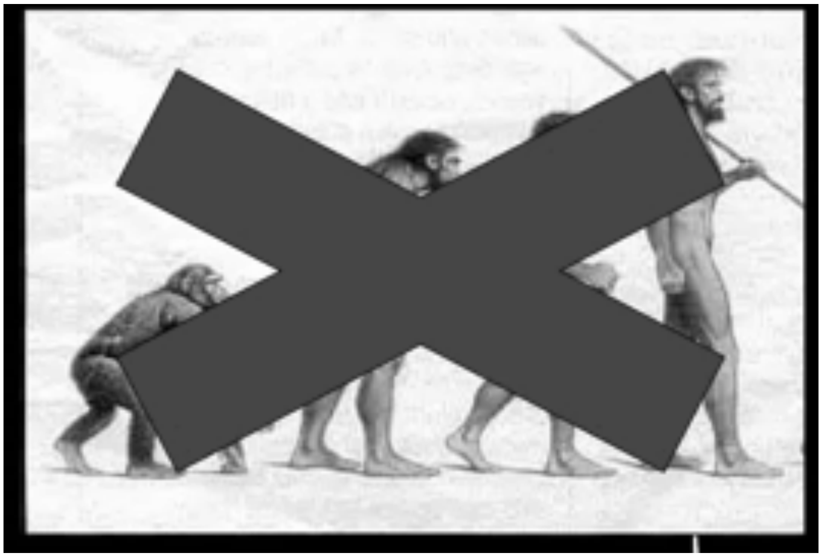


Figure 8. "Humans aren't even on the chart": Tree of life figure presented in lecture in the context of human evolution.

a) 

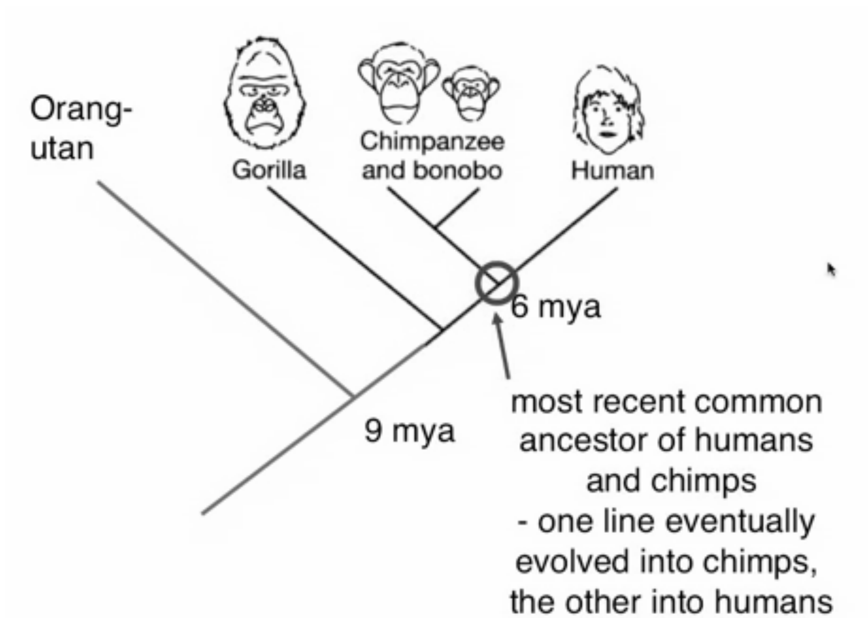
(b) 

Figure 9. Figures used in class to refute the misconception that humans came from apes. (a) Giant "X" over the March of Progression, (b) Phylogenetic tree indicating shared common ancestor between humans and chimps at 6 million years ago (Tegrity recording, April 23, 2012).

slides, Dr. Wallace reiterated an analogy which explains common ancestry is not the same idea as “coming from” another organism: “Humans do not come from chimps, they share a common ancestor. Just like you did not come from your cousin. You and your cousin share a common ancestor: your grandmother” (Tegrity recording, April 23, 2012).

Instructional Strategy: Visualizing transitional life forms

The last instructional strategy Dr. Wallace used to create explicit instruction was the use of transitional life forms to demonstrate how organisms have changed over time, including sequences of fossil intermediates and transitional species. She used these both in her discussion of the evidence for evolution and when discussing transitional fossils as evidence for evolution and for discussing major transitions in the history of life.

PBS *Great Transformations* video and the evolution of whales. Dr. Wallace used six different examples of transitional fossils when discussing evidence for evolution. One of these examples was the mesonychid to modern whale transition. She presented this example using the PBS *Great Transformations* video series. Dr. Wallace explained that this video told a fascinating story that would be new to students and therefore engaging students’ interest (see also *Orientations toward science teaching*). “I love the whale video for a number of reasons. One is I just, I think it's a fascinating story that a lot of students just don't know about” (Interview 1, p. 14).

The video presented several forms of evidence for whale evolution from the mesonychids, a land-dwelling wolf-life creature. After the video, Dr. Wallace followed with verbal questions to the students to check for their understanding - “What was the clue linking the wolf-like animal to the whales? How do scientists know that this animal was the ancestor to modern whales? How did the blow hole on the top of the head evolve?" (Tegrity recording, April 9, 2012)

She then displayed a sequence of skull fossils that demonstrated the blowhole of whales gradually migrated to the top of the head. Dr. Wallace then displayed a picture of a live blue whale blowhole and posed the question - "What does this look like? It looks like a nose! A blow hole is just a nostril on top of a head!" (Tegrity recording, April 9, 2012).

Replica *Archaeopteryx* fossil. At the beginning of the lecture on the day she discussed fossil evidence for evolution, Dr. Wallace brought in a 14"x18" replica fossils of *Archaeopteryx*, a transitional fossil between reptiles and birds, and walked students through which features of the fossil that were reptilian and which were bird like (see *Instructional vignette)*.

***Tiktaalik* and Dr. Shubin.** As she discussed the nature of transitional fossils, Dr. Wallace described how evolution allowed for scientists to predict about what they expect to find in the fossil record. That is, if scientists go to the rocks of the right age and the right type, they should find transitions between two major forms of life. She told the story of paleontologist Neil Shubin and how he was searching for the transitional fish-amphibian fossil by looking in the proper age rocks (370-380 million years ago [mya]). After telling the story of the *Tikaalik* discovery in the Canadian high Arctic, Dr. Wallace explained how this "fishopod" represented a transitional fossil in a similar fashion to how she described *Archaeopteryx*. She pointed out how *Tiktaalik* had scales like a fish, a hinge between its head and spine (neck) which was amphibian-like, and that it has legs but not fingers - an important distinction because leg bones represent a major difference between fish and amphibians (Figure 10).

History of life summary of transitional life forms. Dr. Wallace reiterated the importance of fossils of mesonychids, *Archaeopteryx*, and *Tiktaalik* into her discussions about the history of life. As she discussed transitional points in animal phyla, she added pictures of supporting transitional fossils one by one a chart depicting the historical diversity of vertebrate phyla. Figure 11 shows the final iteration of this slide, which including the first amphibian (as related to *Tiktaalik*), *Archaeopteryx*, and a mesonychid placed at the points of transition along the chart.

Knowledge of Curriculum

This sub-section describes themes in the sequence, scope, and specific examples used in Dr. Wallace's evolution curriculum discussed in context to how her curriculum has changed over time as informed by her knowledge of students and orientations toward science teaching. Over time, Dr. Wallace's evolution curriculum has changed. She has sequenced her evolution unit and made changes to the scope of content to address areas of interest and difficulty for her students. Dr. Wallace described these curriculum changes as amazing because her current instruction was so dramatically different to how she first approached teaching the course:

> It's amazing when I think back to the syllabus my first couple of years teaching and how much I covered then that I don't cover now. And part of me thinks, well where did all the time go? And I feel like I cover so little of what I used to. (Interview 1, p. 13)

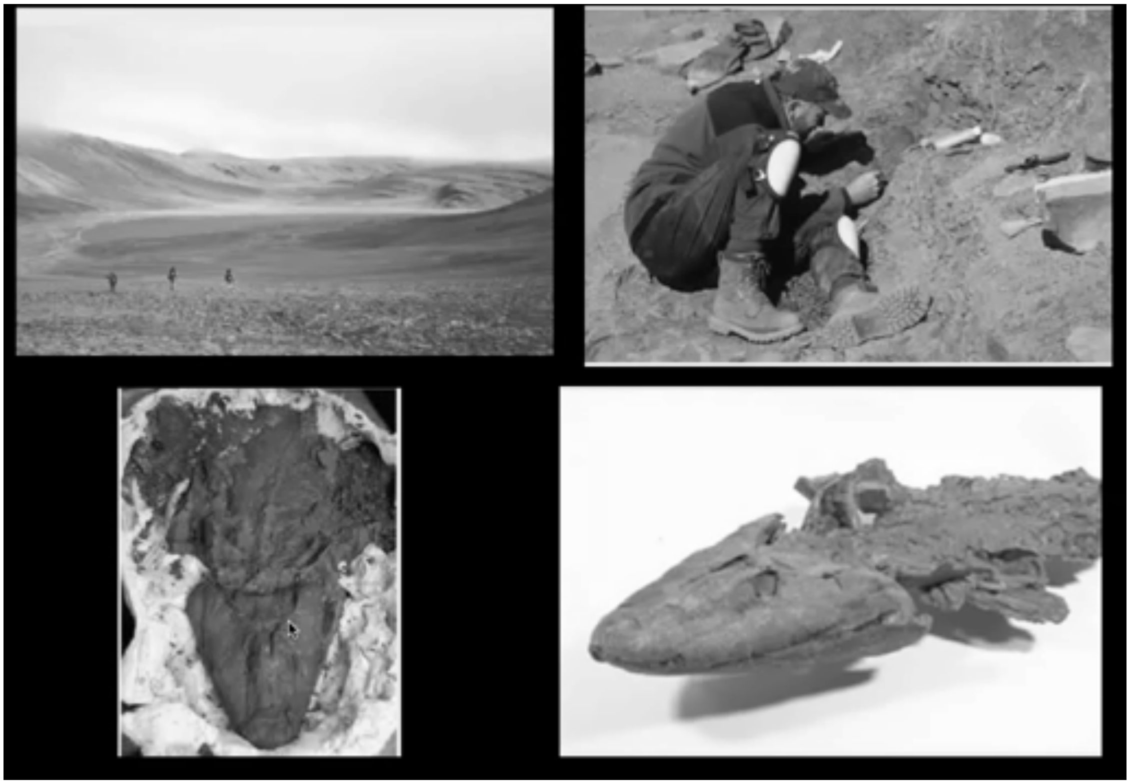


Figure 10. PowerPoint slide used in telling the story of the *Tiktaalik* discovery in the Canadian Arctic by Dr. Neil Shubin and his paleontological team

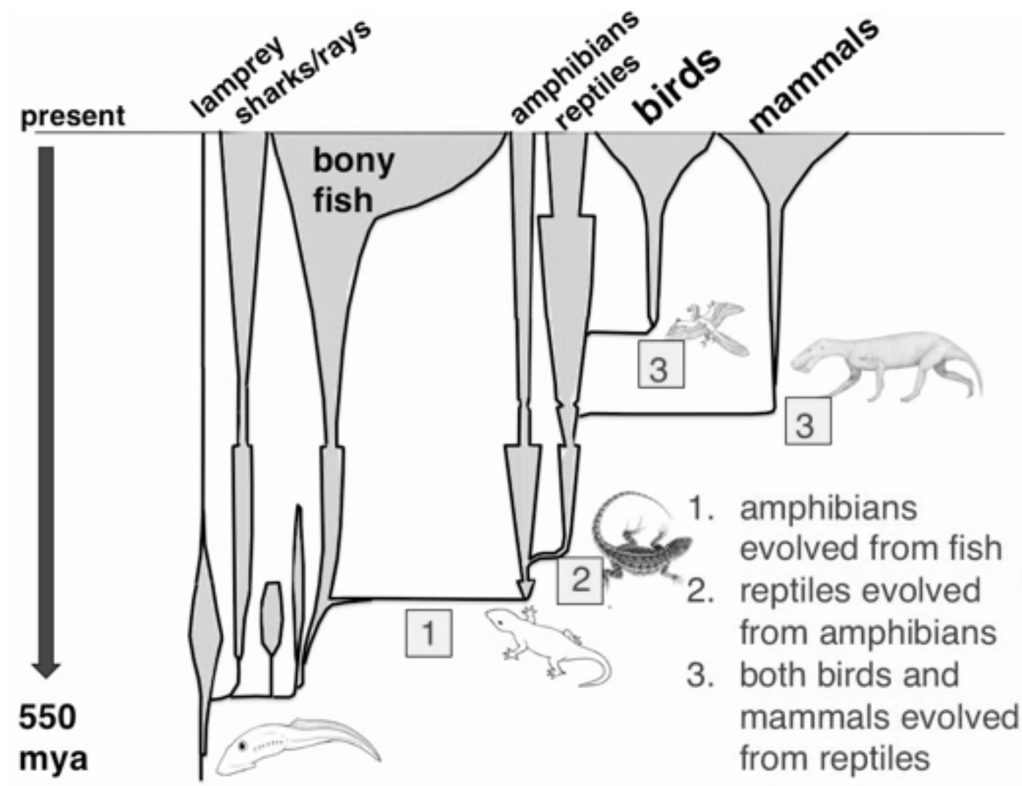


Figure 11. Phylogenetic tree with radiation patterns of major vertebrate phyla, including the first amphibian, a mesonychid, and *Archaeopteryx*.

Dr. Wallace informed her curriculum through a pragmatic lens, while also considerate of student interests and her goals to challenge students' misconceptions. This meant changing her instruction from her first years teaching, Dr. Wallace realized how much the course had changed over the years.

Sequence of the Evolution Unit

The first two lectures in the evolution unit (which define evolution and discuss selection mechanisms) focus around students' incoming ideas about evolution. Dr. Wallace knew recognized that many students did not know the actual definition of evolution (see *Knowledge of Learners*) and commented that students never relate evolution to changes in allele frequencies over time.

> I want them to understand [what evolution is], because a lot of students have never heard the actual definition of evolution and then they come out and they say well I never, that's not how I thought of it, I never realized that evolution. It makes sense once they understand what evolution actually is. (Interview 1, p. 2)

After explaining evolution, Dr. Wallace spends four lectures on mechanisms of selection (natural selection, sexual selection, artificial selection) to build students' knowledge of evolutionary mechanisms. She chose to do this because she thought students needed to understand how evolution explained natural phenomena (*goal)* or they would have difficulty understanding speciation (*Knowledge of Learners)*.

> I start with the mechanisms because to me you can't, if you don't yet understand the mechanisms, I feel like you can't understand how it is that, if you look at the history of life, how it is or why it is you see the changes you see. (Interview 1, p. 12)

Another reason Dr. Wallace began the unit with a definition of evolution and selection was to build students' appreciation of evolution science. This relates to her pragmatic orientation to help the students see the logic in evolution. She knew that many students came in without an understanding of what evolution, especially students that came from rural parts of the state. Dr. Wallace therefore felt that only *after* they understood how evolutionary biologists define evolution could students develop an appreciation of the evidence for evolution.

> My reason for waiting and presenting evidence afterwards is that I feel like they don't understand yet what evolution is. So I feel like they can't appreciate the evidence and especially given that a lot of the evidence involves understanding of natural selection in particular. (Interview 1, p. 1)

This approach of engaging incoming knowledge and building prerequisite knowledge informed the sequence Dr. Wallace's entire evolution unit. Each topic was a prerequisite to understanding the following topic. She noted that she did not think this was the only sequence to teach the unit, but saw the most logical way to teach the unit as based on what students know and need to know.

Dr. Wallace thought about curriculum in the evolution unit similar to how she viewed the course as a whole. Most of her curriculum sequence was based on what she knew about students' incoming knowledge and what was most interesting for students. In an ideal course, Dr. Wallace wished she could spend no time talking about topics that the students knew from previous biology classes (i.e. organic molecules, cellular respiration) and instead focus only on the interesting and meaningful examples.

> I would like to get to be able to get rid of some of the stuff that we cover at the beginning of the semester that they've had in the past and some of the cellular stuff from molecular stuff, of organic molecules and cellular respiration and stuff that I know they've learned about before or should have learned. That I know it was covered before in their classes. (Interview 3, pp. 15-16)

Scope of Evolution Unit

> It's amazing when I think back to the syllabus my first couple of years teaching and how much I covered then that I don't cover now. And part of me thinks, well where did all the time go? And I feel like I cover so little of what I used to. (Interview 1, p. 13)

Depth over breadth. Dr. Wallace was amazed that she used to cover so much material in her course to talking about fewer topics in more depth. Over time, her approach gone from "mostly using my textbooks for references" and covering nearly every topic in the book to more focused on students' areas of interest, prior knowledge, and evolution misconceptions. This focus on fewer concepts in depth was likewise evident in her instructional strategies as she focused on multiple examples of each topic. Dr. Wallace described this change from breath to depth as related to her realizing that students were not understanding the material. She therefore began to revise her course to address those problems (see *Sources of PCK*).

> The more and more you recognize what it is the students are having trouble with and then you end up spending more and more time explaining those particular concepts so even something that I taught the same to the same level of depth in all

> the years I've been teaching, I might spend a lot more time on it now than I did in the past. (Interview 1, p. 2)

Finding time for depth. As Dr. Wallace expanded some topics, she needed to reduce or eliminate others. Her determination of which topics to reduce were made based on students' interests in the topic (*Goal 1*) and the significance of the topic to scientific literacy *(Goal 3).* This resulted in the elimination allopatric and sympatric speciation, founder effects, and bottleneck effects (boring and unessential), and origins of life (unessential). Dr. Wallace has in turn increased class time on evolution topics which she believed were more interesting, including human evolution, tree thinking, and examples of vestigial traits (see *Knowledge of learners* for representative quotes).

> I've always covered [abiogenesis] because it's a question that always arisen as well where did that come from in. And but I always feel like that material is unsatisfying to the students and I don't feel like they understand it very well. (Interview 2, p. 1)

Knowledge of Assessment

There is an iterative, reflective relationship between Dr. Wallace's knowledge of learners' and orientations for teaching science and her knowledge of assessment (see *Sources of PCK*). Dr. Wallace chose what topics she would assess based on what she knew students had the most difficulty and how she asked by her goal to engage students in critical thinking (see *Orientations*). This approach to assessment was employed throughout her assessments, including clicker questions, online homework, and course exams. This sub-section explores themes in Dr. Wallace's knowledge of assessment as informed primarily by knowledge of learners and her orientation to engage the students in critical thinking.

A focus on misconceptions. Dr. Wallace focused many of her clicker questions, online homework questions, and exam questions on students' misconceptions. This assessment approach relates well to her orientation to engage students in critical thinking, her instructional strategy to have students confront their misconceptions as many times as possible, and of course her knowledge of learners. Dr. Wallace described writing and selecting quiz questions with a bias toward questions that addressed misconceptions:

> I'll go to my blackboard quiz pool and on that topic and then read through them and pick one. I would say in general I try to pick ones that address misconceptions that I think the, the more times that you address a particular misconception in class the better and addressing it simply by lecturing might help some students get over it. I would say I'm a little bit biased about picking questions for use in class that deal with misconceptions that students have. (Interview 1, p. 16)

Using clicker questions to elicit and refute misconceptions. Dr. Wallace wanted students to realize when they did not understand a topic, and therefore created clicker questions focused specifically on students' misconceptions and structured to require higher order thinking skills (see *Knowledge of Assessment)*.

Dr. Wallace knew which clicker questions would be problematic for students and chose many of her clicker questions to be questions which would cause a portion of the class to get the question wrong. When a large proportion of the students answered a clicker question incorrectly, Dr. Wallace would take time to explain why popular incorrect answers did not answer the question.

One example of this formative assessment practice was a clicker question about significance of a universal DNA code among all living creatures.(Note that the use of this question demonstrates Dr. Wallace's knowledge that students have difficulty with the genetic components of evolution, her orientation that to provide opportunities for students to address their misconceptions, and her goal to help students see the relevance of evolutionary observations. The question read as follows: *What is the importance of the fact that the genetic code is identical among nearly all organisms?* Most of the students (75%) answered the question correctly - that the genetic code is identical among nearly all organisms because all living organisms are descended from the same ancestor (Observation notes, April 18, 2012). However, 25% of students answered incorrectly - that this was because the sequence of DNA bases in nearly the same in the chromosomes of all organisms.

These discrepant results spurred Dr. Wallace to explain to the students why the first answer was correct and the second answer was not. She told the students that the first answer demonstrated that all organisms are using the same system for translating their DNA into a protein from a sequence of DNA. This did not imply that all organisms had the same DNA. Dr. Wallace went on to provide rationale for this idea. She reminded the students that their genetic sequence was different than other students in the class, and also different from an oak tree or a parrot or a slime mold. She then used an analogy to help students think about what it meant for DNA to code for proteins. "Think about the secret letters to a friend you wrote as a kid. Remember how A was 1 and B was 2, etc? Every organism on Earth uses the same code." (Tegrity recording, April 18, 2012)

Dr. Wallace concluded her explanation of the incorrect answer by focusing on a novel example to reiterate the significance of the observation that all organisms of have the same DNA coding rules. She explained that one of first questions scientists would ask if they found life on Mars was whether the organism used the same universal code. If the organism used a different code, it would imply multiple origins of life.

Reusing clicker questions as test items. Another way Dr. Wallace would provide opportunity for students to address their misconceptions was by rewording clicker questions as exam items. She explained that she would do this primarily for questions that students had difficulty answering during class.

> It's not uncommon for me to reuse clicker questions from class, especially those students struggle on, on the final exam. One of the reasons for this is that I want students to learn from the clicker questions in class. (Interview 3, p. 8)

One such example of this approach used a question about how the fossil record provided evidence for evolution (*Observation notes, April 9, 2012*). Many of the students (69%) answered this question correctly during class - that the fossil record provided evidence for evolution because the sequence in which organisms appear in the fossil record is consistent throughout the planet. However, 21% of the students answered that the fossil record provided evidence for evolution because "fossils are the remains of plants and animals that lived long ago". This answer was scientifically correct, but did not explain how fossils provided evidence for evolution. After seeing the difficulty students had with answering this question in class, Dr. Wallace posed a similar question (but not the same question) on the final exam, asking how fossils provided evidence for evolution (Question 2, see *Appendix K*). This time, 96% of the class answered correctly.

Final exam questions informed by misconceptions. Dr. Wallace's knowledge of learners' misconceptions informed her assessment practices were the final exam questions about phylogenetic trees (*Appendix K*). During the first interview, Dr. Wallace explained that students had difficulty determining the relatedness of organisms on a tree, and would attempt to do this by counting nodes, using the physical features of the organisms, or by looking at the arrangement of organisms on the tips of the tree.

On the final exam, Dr. Wallace provided students with a phylogenetic tree not used before in class (Figure 13). She added symbols to the tree to highlight nodes of interest in the same fashion as the tree thinking in class activity. The final exam questions about this tree aligned with Dr. Wallace's knowledge of learners' misconceptions about phylogenetic trees. Students had to find the most recent common ancestor of giraffes and peccaries. Similarly, students had to select among five pairs of species which pair had greatest similarity in their sequence of genetic bases. Both of these questions require students' knowledge of the proper strategy to determine relatedness (no node counting, use of physical features, or orientation of organisms at the tips). Students also had to interpret the symbolic meaning behind the arrow, which required knowledge that nodes were symbolic points of ancestry.

Eliciting critical thinking through assessment. Dr. Wallace develops her assessments around students' misconceptions with the goal of engaging the students in critical thinking. Her goal was to write most of her assessment questions to require abstraction or interpretation of the same phenomenon in a new context.

> An overall for the course is that I want them to be developing their thinking skills, so how to abstract and apply information. I try to write questions that require

> them to use information that they are learning and their homework questions are very heavy on it. (Interview 3, p. 13)

Critical thinking through answer formats. One example Dr. Wallace engaging students' critical thinking was in how she wrote incorrect options on multiple choice test items. Should would list options that were scientifically correct but did not answer the question. This required students to select an answer that was both correct and answered the question at hand. This approach was demonstrated in the aforementioned clicker question how fossils were evidence for evolution.

Critical thinking through question formats. Dr. Wallace's critical thinking approach to assessment was also evident in the way she wrote questions. She explained there was "system of about five or six question formats I use for writing questions" (Interview 3, p. 2), including (a) basic definition or function, (b) explain the phenomenon, (c) correctness and relationship of two statements, (d) all true statements "except" one, and (e) 'what would be a useful question to ask?' questions.

Most of these question formats required students to apply their knowledge of the concept to a new situation, find the relationship between two concepts, or to synthesize knowledge from different but related topics. Dr. Wallace described the process of creating such questions as somewhat difficult: "it can be kind of challenging to come up with ways to test them that isn't just did you memorize this fact?" (Interview 3, p. 3). One example of applying ideas from class to a new context was found on the final exam. Dr. Wallace asked students to use their knowledge of vestigial traits to interpret why there is dewclaw on the hind leg of dogs (Question 14, Appendix J).

Dr. Wallace did not speak in great detail about methodological use of different question formats for particular evolution concepts. She instead focused on the students' role as critical thinkers and explained how complex question formats would sometimes bring students to office hours to complain. Dr. Wallace's response to these complaints was to tell students that the questions were designed to make them think and take it upon themselves to think.

> I've had students in the past that when they come in with a homework question and they say that they are having trouble with it and I say "well, this question is designed to make you think", and the student responds "but that's not fair!". . . I think that it's the students' responsibility to be willing to think and not to regard it as unfair if they are being asked to think. (Interview 3, p. 15)

Nature of PCK Summary

Dr. Wallace had a primarily student-centered teaching orientation that was reflected in her deep knowledge of learners. Although she frequently taught using lecture, this was primarily an artifact of her context. She remarked that her instruction was driven not by the goal of conveying information, but by engaging learners' interests and incoming ideas, meeting students' needs for learning, and challenging students' misconceptions.

The nature of her PCK was integrated, with knowledge of learners central to informing other components of her PCK. She knew students had little prior scientific knowledge of evolution and therefore sequenced topics by which topic was prerequisite to the next. She selected curriculum based on students' interests (i.e. human evolution) and removed less interesting curriculum (i.e. bottleneck effects). Dr. Wallace's knowledge of learners was evident in her knowledge of instructional strategies. She knew students needed clear, explicit instruction to understand a concept and that students had a number of misconceptions, including those about phylogenetic trees, the connection between genetics and evolution, mechanisms of speciation, and the nature of science. Dr. Wallace gave multiple examples of each concept in the course so that students would have several opportunities for critical thinking. Dr. Wallace's knowledge of learners was also evident her assessments. Formative and summative assessment items focused on students' misconceptions and were designed to elicit critical thinking.

What are the sources of a college instructors' pedagogical content knowledge for teaching macroevolution?

In this section of Chapter Four, I highlight the sources of PCK for Dr. Wallace. This section is divided into two parts. First, I describe three challenges Dr. Wallace has experienced as an instructor and how resolving these issues has led to her PCK development: the burden of her expertise in identifying areas of student difficulty, anxiety about student resistance to learning evolution, and working through problematic test items with colleagues. The major theme among these stories is that Dr. Wallace is focused on areas of students' difficulty and seeking solutions for these difficulties. When Dr. Wallace does not know or is unsure of student difficulties, she will consult resources such as the misconception literature or colleagues to learn more about students and potentially solve the problem.

The second portion of this section is an analysis of Dr. Wallace's reflective process for understanding difficult questions. Dr. Wallace is methodical in troubleshooting reasons why students get certain test questions wrong. She hypothesizes solutions for student difficulties after she identifies the problem (i.e. lack of clarity in instruction, student difficulty with the topic, or wording with the question) and this process in turn informs changes in future instruction.

Challenges in Teaching Evolution: Experiences Influencing PCK

Learning about student difficulties when content is intuitive. Dr. Wallace found teaching evolution more challenging than teaching other topics in the course, such as photosynthesis or cellular respiration. Her expertise in evolutionary biology made it difficult to recognize areas of student difficulty and to determine what content was most relevant to teach.

> It is a topic that I know a lot more about than I know about other topics that I cover in the class and that can make it harder for me to recognize what is important and also what is difficult. (Interview 1, p. 17)

Part of the reason for this constraint was that she did not recall having difficulty learning evolution as a student. It was therefore challenging to recognize which concepts were troublesome for students because she did not recall which (if any) evolution topics were difficult for her: "And so I don't remember that I used to think that way and so I need to learn about what their misconceptions are from other . . . it's not obvious, it's not as obvious to me what they are not getting or what they are likely to have trouble with compared with other units in the course." (Interview 1, p. 17). She elaborated:

> When I teach something like protein synthesis or cellular respiration or photosynthesis, I don't know very much about those topics and I had to relearn those topics in order to teach them. I'm much closer to the students level of understanding about those topics and that makes it easier for me to identify what are the important things that they need to get out of this and it also makes it easier

> for me to recognize what's difficult here. (Interview 1, p. 17)

Dr. Wallace had to relearn topics outside of her area of expertise before teaching them. This process of putting herself in the place of the learner helped her realize the important facets of the concept and what was difficult to learn. This was not the case for preparing to teach evolution. Dr. Wallace realized that she was not familiar with students' ideas about evolution and chose to find resources to learn about students' difficulties with evolution. She listened to students during office hours, monitoring mistakes on exams, speaking with colleagues, and reading education literature to learn more about students.

> And so I don't remember that I used to think that way [about evolution] and so I need to learn about what their misconceptions are from other resources, either from listening to the students explain what they are not getting during office hours or exams and so forth and pay attention to what mistakes they are making, because that's instructive to me. Or I need to use educational resources and things to figure out what are the common misconceptions. (Interview 2, p. 3)

Concerns about student resistance. Dr. Wallace described that she was anxious about teaching evolution when she moved to the "Bible Belt" from New York state. She thought students would be predominantly Creationist and therefore resentful about learning about evolution and might even challenge her during class.

> I have to admit when I first started teaching here, my first few years I dreaded the evolution unit even though it's my field and I hated teaching it for a couple of reasons. One was I thought, oh, this is [the Midwest], they are all creationists they don't want to hear about it. They are all going to be resentful. And I assumed that

> many of them were. (Interview 1, p. 7)

Two events changed Dr. Wallace's attitude toward teaching evolution. The first occurred after a few years of teaching when a student challenged the evidence for evolution during class. "What I had always been dreading actually happened, where in the evidence for evolution lecture, there was a student who after everything I said would raise his hand and say well, what about this?" (Interview 1, p. 8). Dr. Wallace described that although she felt panicked, she remained calm and answered each question as scientifically as she possibly could as the student asked about dating the Earth, missing fossils, and the possibility of a global flood.

> I was kind of panicking on the inside, on the outside I stayed calm and I answered each question that he had calmly and scientifically. 'Well, the rate at which these atoms change from one form to another is the same whether its in water or in air so that doesn't make a difference.' And I always had time while they were writing down notes to think about my next piece because I knew I would have another question. (Interview 1, p. 9)

Eventually the questions from the student stopped. However, the event is memorable for Dr. Wallace as it gave her the confidence that she could successfully defend evolution in class. She attributed her success to reading enough creationist literature before the incident to know how to counter its common arguments.

> That event made me realize that I could handle it and it was true that by that time that I had probably read enough creationist websites and things that I was more familiar when I first arrived to what types of things they might say. . . But that event was important to me because it gave me the confidence that I could handle

> whatever came to pass. And I don't know if I will handle everything well as it comes up in class, but I at least don't worry about it anymore. (Interview 1, p. 8)

Lessons from an end-of-course survey. The other experience which improved Dr. Wallace's attitude toward teaching evolution likewise occurred a few years into teaching the course. Dr. Wallace started to do an end-of-course survey to determine what topics the students found most interesting. To her surprise, students were most interested in evolution.

> The other thing that I think is more interesting for me is that at one point, before we had clickers . . . I had students write down one interesting thing that they learned in this class this semester . . . And to my astonishment, enormous numbers of them wrote something from the evolution unit. (Interview 1, p. 9)

In semesters Dr. Wallace counted the responses for each topic, she was amazed to find that 37% of students down wrote something from the evolution unit. Dr. Wallace described this as a critical moment in her attitude toward teaching evolution. She realized that students shared her interest in evolution and found evolution more interesting than other topics in the course. After this point, Dr. Wallace knew that many of her students were not resistant to learning evolution and were interested in learning about it.

Learning about Students from Colleagues

Dr. Wallace would frequently speak to other faculty to discuss teaching. She often referenced how colleagues would help her make decisions to drop exam questions or determine why students were struggling with a topic. Her colleagues had a reciprocal relationship of asking for guidance from Dr. Wallace. These experiences have added to Dr. Wallace's PCK, in particular, her knowledge of students. The story that follows is one such example.

Dr. Kline (pseudonym), an evolutionary biologist and close colleague of Dr. Wallace, gave his biology majors' evolution class a tree thinking question on a test. He made two different versions of the test in order to prevent cheating. One version of the test the statement read something similar to "Species A is more closely related to species B or C, true or false" or the other version said "Species A is equally related to species B and C, true or false." One of these statements was true and the other was false.

Surprisingly, students answered correctly on one version of the exam but did poorly on the other version. Dr. Kline came to her to discuss this perplexing issue.

And both Dr. Kline and I, when we read [the question], couldn't understand what makes this version so much harder than that version, to us it was assessing the same concept from the tree. And it seemed obvious to us, we couldn't understand why the students, you know, were they not understanding the wording of the question, what was it? (Interview 2, p. 17)

Next, Dr. Kline and Dr. Wallace then gave the question to another colleague, Dr. McCarty (pseudonym). Dr. McCarty did not have a background in evolutionary biology. She explained that she chose the (incorrect) answer she did because she was "counting splits on the tree". This was a revelation to Dr. Wallace (and Dr. Kline) to learn that students used a node counting strategy to interpret phylogenetic trees.

> We couldn't figure it out and then we showed it to Dr. McCarty and asked her how she would answer these questions. And she did what the students did. She said, well there are more split this way and I'm like oh splits of course people are counting splits and it made it if you have that misconception that influenced how

you answered the question. (Interview 2, p. 17)

After talking with Dr. McCarty, the three colleagues took the question to the graduate students in Dr. Kline's lab. They gave the question to four students, three of them had expertise in animal behavior or neurobiology and one had expertise in phylogeny. Only the student doing phylogenetic work answered the question right and the other three answered the question with the same errors as others.

Dr. Wallace learned from this experience that her way of thinking about phylogeny was different from those not in the practice of thinking about phylogenetic trees. Since only experts of phylogeny could get the question right, she realized that "it's whether you are in the habit of thinking about trees or how they actually work and how they represent relatedness that you put that into practice and think about it." (Interview 2, p. 11). Individuals without such expertise did not have the opportunity to challenge their misconceptions about node counting:

> And so if you used to reading trees you get over that misconception and those two questions seem to be identical in what they're asking but if you're not used to reading trees it's very likely you've got even if you've learned in the past like these grad students probably did. (Interview 2, p. 11)

After this point, Dr. Wallace realized that she did not know about every student misconception about phylogenetic trees. In response, and in the same way that she built her knowledge of common antievolution arguments, Dr. Wallace read educational literature about tree thinking misconceptions to learn more about her students.

Reflecting on Student Outcomes to Inform PCK

Dr. Wallace methodically reflects on student exam outcomes. She questions why students struggle on particular questions: Was it the question? Was her instruction clear? Which incorrect answer did they think was correct? Did the students lack background knowledge they needed to answer the question? As she asks herself these questions, she tacitly calls upon and deepens her PCK, resolving to make changes to her instruction in the future. What follows is a description of Dr. Wallace's reflection process her reflections regarding the spring 2012 final exam (Appendix K).

Relating exam outcomes to instruction. Dr. Wallace related problematic exam items outcomes to learners' needs for explicit instruction. In essence, these questions are opportunities for her to hypothesize revisions to her instruction. "I would say is that the questions that required more detailed knowledge from the lecture, especially things that were not explicitly stated in the PowerPoint itself, were difficult for students" (Interview 3, p. 3).

This section describes Dr. Wallace's reflections on problematic final exam questions as related to implicit instruction, and conversely, reflections on successful exam questions as related to explicit instruction. For example, only half of the students could correctly answer Question 15, which asked students why human toenails and dog claws were both made of keratin (Appendix K). Students who answered tended to answer (incorrectly) that "humans and dogs evolved their toenails/claws independently of each other". Dr. Wallace realized the reason the students were answering this way was because she did not talk about the difference between homology (the same trait in related animals has similar form and function) and analogy (trait that appears similar in two unrelated organisms). She referred to the most popular incorrect answer as she hypothesized reasons for student difficulty:

> They chose humans and dogs evolved their toenails or claws. Yes, something that I didn't talk about in class, I talk about homology but I didn't talk about analogy. And the distinction between them, so they might not even have understood what that means, that they evolved their toenails and claws independently of each other…That might have been the problem with that question. (Interview 3, p. 7)

Dr. Wallace also related implicit instruction to low student performance (25% correct) on Question 27, which asked students how to determine if an intermediate fossil between reptiles and mammals was more reptile-like or bird-like (Appendix K). The correct answer was "How many different types of teeth did it have in its mouth?". Dr. Wallace related students' difficulty with this question to unclear instruction about the differences between mammal and reptilian teeth.

> There's a reference in the PowerPoint slide to the teeth structure but they would have had to remember. To me this is something very memorable, but maybe not to them that reptiles have all the same teeth and mammals have a variety of different teeth. (Interview 3, p. 1)

Another example of Dr. Wallace considering the role of explicit instruction was related to Question 33, which asked students the following: "A scientist interested in the evolution of the first bony jaws would look for what type of fossils?" Dr. Wallace related students' low performance on this question (46% correct) to a particular slide in her instruction. She knew immediately that the slide did not have the necessary text about internal skeletons for the evolutionary transition between jawless fish (lampreys) and bony fish.

> I realized thinking back about it, that when I talk about those evolutionary

> transitions, jaws comes under the heading of, the important transition there is internal skeleton and I talk about fish and I show the lamprey and I explain the evolution of the jaw and we go through how fish breathe and what happens to those bones and everything. But it doesn't explicitly say that fish means internal skeleton. (Interview 3, p. 2)

Dr. Wallace hypothesized that in the future, she would make changes to her instruction that would resolve the implicit instruction for students: “So I will change the PowerPoint when I say as one of the important evolutionary transitions is the origin of the internal skeleton and I will add the word fish to that slide for example” (Interview 3, p. 12).

Dr. Wallace thought that her instruction was not clear enough for students to do well on questions 15, 27 and 33. In a reciprocal manner, she related good student performance to clear instruction in class. On Question 26 (91% correct): “Which of the following statements best describes the evolutionary pattern of life on Earth?”, Dr. Wallace recalled that she gave students a good summary slide, and that the final bullet point about how evolution explains the diversity of life. Since these concepts were in the PowerPoint and therefore in the students’ notes, Dr. Wallace knew that students had the tools they needed to answer the exam question.

> I have never asked a broad question about the evolutionary pattern of life on Earth, I do think that my summary that I gave them on the PowerPoint of what they needed to know about that figure, the final bullet point for #4 or whatever it was, was something to this effect so if they studied their notes, they would have come across that. (Interview 3, p. 3)

Knowledge of learners' difficulties and exam outcomes. There were several moments in our interviews that Dr. Wallace was surprised when students did poorly on a question *despite* having clear instruction. Dr. Wallace considered if such exam questions were problematic due to learners' incoming knowledge, misconceptions, or general difficulty with a topic. Dr. Wallace questioned if the prevalence of misconceptions was related to her assessment outcomes. She knew her instructional strategy was to challenge misconceptions as much as possible and therefore questioned if student attendance was the reason for students' continuing difficulty with misconception related material.

For example, only 77% of the class answered Question 13 correctly, which asked students which model accurately depicted human evolution, a linear progression or a branching tree. Although student performance was not particularly low on this question, Dr. Wallace was disappointed. She questioned if the students difficulty was because of the prevalence of the misconception that humans were superior species or if students did not attend class the day she talked about human evolution: "I was a little surprised they didn't do better on this one, because I felt I was so explicit about it in class . . . I guess it's just one of those misconceptions that people have and it can be hard to break. Perhaps they weren't in class that day and did not watch the Tegrity" (Interview 3, p. 3).

Similarly, Dr. Wallace questioned if students' low incoming knowledge of taxonomic diversity contributed to their difficulty answering Question 33 (regarding the transition between lampreys and bony fish). She only referred to lampreys as jawless fish once and wondered if students' unfamiliarity with lampreys led to confusion about the transition between lampreys and bony fish: "A lot of them just have such poor taxonomic knowledge that that might be, you know they might not even have recognized that a lamprey is a fish" (Interview 2, p. 2).

Dr. Wallace could not always identify why students missed particular questions, but knew that low student performance was due to the inherently difficult nature of the topic. As she reflected on Question 5 about Lynn Margulis' endosymbiont hypothesis [mitochondria and chloroplasts evolved from bacteria-like cells], she related student performance (72% correct) to students' difficulty with the concept. She described being uncertain about exactly why students struggled with endosymbiosis, and thought that she should revisit how she taught this idea in the non-majors course.

> I've even noticed with my upper lever class when I cover this in community biology, which is a 3000 level course and mostly majors, endosymbiosis is one of the more difficult concepts and they specifically ask for a reading assignment about it. And it's something where I have trouble figuring out what's difficult for them about it. (Interview 3, p. 5)

Analysis of student understanding using Mermac analysis. Dr. Wallace will review statistics on her exams to determine problematic test questions. She will broadly look for questions with lower than 50% correct but will also revisit questions which were more problematic than she expected. She will then use Mermac analysis, a form of item analysis to evaluate the quality of the question. Mermac analysis sorts students into groups by grade on the exam (A-B-C-D-F) and gives the proportion of students who answered correctly on the question for each group. "I started to use Mermac distribution because I wanted to know if questions were difficult for all students or just the students that didn't study." (Interview 3, p. 4)

Dr. Wallace likes to see Mermac distribution come out so that students who did well on the exam could still answer the question even though it was difficult, but students who did poorly on the exam missed the item because it was difficult. “I liked that question, and the Mermac analysis is good, it's a nice spread, a good question at distinguishing the students that understand the material from those that don't understand” (Interview 3, p. 1). She will usually leave a question on the test if it is good at distinguishing students who understand the material from those that do not. If the question does not have a good Mermac distribution, then she will confer with a colleague about the nature of the question and then drop the question from the exam if necessary.

> And so I knew Question 8 was going to be a hard, and then I debated and conferred a little with [Dr. McCarty] and was debating whether that was a drop question. . . I don't think there's something wrong with having one difficult question and it was in the Mermac analysis that students in general who did well on the exam did better on this question and so I, and nobody has complained about the question, so I decided to leave it in. (Interview 3, pp. 1-2)

Sources of PCK Summary

Dr. Wallace had two primary sources for her PCK, experiences related to solving pedagogical issues and reflection on student outcomes. Her experiences problem solving primarily built her knowledge of learners, including learning that students are interested in evolution (end of course surveys), count nodes to interpret phylogenetic trees (problem solving an exam question with colleagues), and have a number of misconceptions about religion and evolution (confrontation with the creationist student).

Reflection on final exam outcomes informed Dr. Wallace’s PCK as well. When students did not do well on a question, she would question if she was explicit in class (knowledge of learners' requirements for learning). If she had not been explicit, she planned to revise the content (knowledge of curriculum) or method by which the content was presented (knowledge of instructional strategies). If she had been explicit, she would question the influence of students' incoming knowledge or misconceptions (knowledge of learners' areas of difficulty) or question if the format of the exam question was problematic (knowledge of assessment).

How does instruction influence student knowledge of macroevolution and acceptance of evolution by natural selection?

The influence of instruction on student outcomes was examined both quantitatively and qualitatively. This section describes the acceptance and understanding of macroevolution for the overall student population (N=270) through patterns in the quantitative data, and looks at the influence of the instruction from the perspective of the interviewed students (n=12). Pearson's correlations (Table 7) indicate a significant relationship between overall grade and pre- and post-test MATE and MUM scores ($p < .01$), but no significant relationship between attendance during the macroevolution unit and MATE/MUM scores.

Influence of Instruction: Whole Class Data

There was a significant gain ($p < .0001$) in average MATE and MUM score from pre-test to post-test as indicated by a paired samples t-test (Table 8). A factor analysis of student responses to questions on the MUM after instruction was conducted look for patterns in content understanding. The reliability of the MUM instrument was high ($\alpha = .818$) and could not be substantially increased if items were removed from the instrument. One factor with an Eigenvalue of 5.705 came out of the analysis, grouping together questions 4, 5, 7, 8, 9, 13, 15, 24 and 25 and accounting for 21.129% of the total

Table 7

Pearson's Correlations of Pre- and Post-Test MATE and MUM data, Overall Course Grade, and Attendance during the Macroevolution Unit. Abbreviations: Measure of Acceptance of the Theory of Evolution (MATE), Measure of Understanding of Macroevolution (MUM). N=270.

	Overall Grade	Unit Attendance	Pre-MATE	Post-MATE	Pre-MUM	Post-MUM
Overall Grade	—	.362**	.162**	.344**	.439**	.519**
Unit Attendance		—	-.037	.044	.036	.076
Pre-MATE			—	.725**	.448**	.245**
Post-MATE				—	.468**	.490**
Pre-MUM					—	.598**
Post-MUM						—

Note. ** = $p < .01$.

Table 8

Paired t-test Statistics for Pre- and Post-Test MATE and MUM data. Abbreviations: Measure of Acceptance of the Theory of Evolution (MATE), Measure of Understanding of Macroevolution (MUM)

Paired Differences	*M (SD)*	*df*	*t*	Normalized gain (g)
MATE Post - Pre	5.90 (10.47)	267	9.213****	.1597
MUM Post - Pre	2.47 (4.40)	267	9.193****	.1579

Note. **** = $p < .0001$.

variance. Eight other factors had Eigenvalues over 1.000, but since the Scree plot leveled out around 1.4 after the first factor, I decided that one factor best explained the data. The instructor indicated which questions the students should be able to answer correctly based on the instruction, but these questions did not factor together (Table 9).

Tree Thinking Instruction

Dr. Wallace spent one class period doing an in class activity about interpreting phylogenetic trees (Appendix J). Independent sample t-tests were conducted to compare post-instruction MATE and MUM scores between groups of students that did and did not attend the in class activity on tree thinking. Levene's test for equality of variances determined that the variances for the two populations (tree thinking/no tree thinking) were equal for the post-MATE ($F = 3.655$, $p = .057$) and post-MUM ($F = .198$, $p = .656$), therefore the t-tests which follow assume equality of variance.

There was no statistical difference ($p > .05$) between students' pre- and post-test MATE and MUM scores among those that attended versus those that did not attend the tree thinking activity (Table 10). However, the influence of tree thinking instruction on students' knowledge of macroevolution was apparent as students interpreted phylogenetic trees during interviews. Although students described how the instruction influenced their ability to interpret phylogenetic trees, none of them related this knowledge to their acceptance of evolution (see *Student Understandings about Macroevolution).*

Table 9

Factor Analysis with Post-Test MUM data using Principle Components Analysis Extraction Method, rotated with Varimax with Kaiser Normalization method. Rotations Converged in 18 Iterations. Abbreviation: Measure of Understanding of Macroevolution (MUM)

Question Number	% Correct Response (N=290)	Factor Component	Claimed Factor[1]	Instruction received related to question
1	0.92			X
4	0.86	*	Fossils	X
13	0.83	*	Classification	X
5	0.80	*	NOS	X
15	0.79	*	Deep Time	X
25	0.78	*	Fossils	
9	0.77	*	Fossils	X
8	0.76	*	Deep Time	X
10	0.73			
20	0.71			X
16	0.69			X
26	0.68			X
12	0.67			X
18	0.66			X
24	0.66	*	Speciation	X
7	0.64	*	Speciation	X
23	0.60			X
2	0.59			X
11	0.59			
17	0.57			X
21	0.44			
19	0.38			X
22	0.34			X
14	0.33			
27	0.31			
3	0.29			
6	0.21			

Note. [1] Nadelson and Southerland (2010).

Table 10

Independent sample t-test comparing average post-test MATE and MUM scores between students that attended and did not attend the tree thinking in class activity. Abbreviations: Measure of Acceptance of the Theory of Evolution (MATE), Measure of Understanding of Macroevolution (MUM)

	N	*Df*	*M (SD)*	*t*	*p*
Post-MATE					
Tree Thinking Activity	214	268	76.20 (14.55)	-.476	.634
No Tree Thinking Activity	56		75.20 (11.61)		
Post-MUM					
Tree Thinking Activity	214	268	16.85 (5.10)	-.671	.503
No Tree Thinking Activity	56		16.34 (4.98)		

Influence of Instruction: From the Perspective of Interviewed Students

The themes discussed in this sub-section of Chapter Four emerged from interviews with students who had low scores on the MATE and MUM prior to the class (see Chapter Three). These students generally became more accepting and more knowledgeable about macroevolution after the course (although they also had a number of misconceptions). Participants attributed their increased acceptance of evolution to learning about the volume of evidence for evolution (especially transitional fossils), as well as learning about the history of life. Instruction also influenced students' knowledge of phylogenetic trees and the nature of science, but students did not discuss these knowledge bases as related to their acceptance. The sub-sections that follow describe these themes in the influence of instruction and reference participants' prior acceptance and knowledge to situate the findings where appropriate.

Components of Instruction that Influenced Acceptance

After the class, nine interviewed students became more accepting of evolution. These shifts in acceptance were most pronounced when students' specific concerns about evolution were addressed by the course.

Evidence yields acceptance. Ten students cited the volume of evidence presented in class as influential to their evolution acceptance regardless of the degree of their acceptance. This fits with the nature of the instruction in class. Dr. Wallace spent more than two 50-minute class periods discussing seven different types of evidence for evolution and many examples of each type of evidence (e.g. 10 different examples of vestigial traits, Table 6).

Amelia and Brooke lacked previous knowledge on evolution and chose to accept evolution post-instruction due to the volume of evidence presented in class.

> Before this class I had no idea there was so much evidence for evolution. Our professor talked about fossils and a bunch of vestigial traits . . . and stuff like how we know one species has become two – like those Grand Canyon squirrels. I knew evolution was real after we spent two entire days talking about nothing but evidence. (Brooke, p. 16)

Brooke remarked that she had no idea there was so much evidence for evolution prior to class. She had not had evolution instruction before and listed a number of examples, including vestigial traits and speciation of squirrels at the Grand Canyon as she described reasons for accepting evolution. Brooke knew evolution was "real" after Dr. Wallace spent two *entire days* talking about nothing but evidence. Like Brooke, Amelia accepted evolution after the course due to the volume of evidence presented in class. She previously rejected evolution because she took a creationist approach to evolution from her high school biology class. Amelia recognized that she knew nothing about the science of evolution before the class and therefore related her newfound acceptance directly to the volume of evidence presented in class.

> It's kind of hard to not accept it because of so many, so much evidence they have for it with fossils and all of that stuff so, yeah I kind of believe it now, it's hard not to believe it because of so much evidence. (Amelia, p. 2)

Evidence and students with dual views of evolution. Nicholas and Adrian described accepting both views of evolution and religion after the course after previously rejecting evolution. Before the class, Nicholas distrusted the accuracy of facts taught by his “wonky” high school teacher and had concerns about carbon dating. After the class, he trusted the validity of Dr. Wallace’s evidence for evolution due to her status as a higher education faculty member. Nicholas subsequently moved from rejecting evolution to a theistic evolutionary view. “Dr. Wallace has a higher education and went into much more detail and much more, you know, showed me more evidence so that I do, I do believe stronger in the fact that the Earth has been evolving” (Nicholas, p. 2).

Adrian also had his concerns about evolution addressed by the instruction and therefore moved toward accepting evolution after the course. Adrian rejected evolution prior to the class because he thought evolution and religion could not coincide, a position he developed after learning evolution was ‘legitimate fact’ in public school but ‘just a theory’ in private school. After the class, Adrian agreed that theories were supported by a number of lines of evidence but thought that because “law was a statement of fact” (p. 13) that theories did not hold as much power as laws.

Despite misinterpreting the definitions of theory and law in class, Adrian moved away from rejecting evolution after the class. “Yes, due to that class, I learned that a lot of people really believe in that stuff and they really know a lot about it. There's a lot of evidence, and that's kind of how I ended up persuaded to believe in science, and agree with science" (Adrian, p. 14). Adrian was influenced to think in this way when Dr. Wallace presented information about the Clergy Letter Project, an online repository of signed statements by clergy in support of evolution. Learning that evolution and his religion could coincide (one of Adrian's primary concerns prior to class) allowed Adrian to move past his concerns that evolution was "just a theory" and accept both science and religious worldviews. ". . . I learned that [evolution and religion] can actually can work together and it'll be okay" (Adrian, p. 3).

Influenced by the evidence but also other factors. Five students remained conflicted about evolution after the course, unsure if both evolution and their religious beliefs could be correct. These students are individuals that did not have all of their concerns about evolution addressed by the class and therefore may not have become as accepting of evolution as other participants. Many of these students came to class without much prior evolution instruction and strong religious beliefs. The class was a new experience that influenced students to become more accepting of evolution, although students continued to be influenced by prior religious beliefs. These participants knew the evidence for evolution, and some even recognized evolution as 'legitimate', but all had difficulty reconciling their knowledge of evolution with religious views.

Ashley is an example of one such conflicted student. She had little previous evolution instruction and rejected evolution due to concerns that the science was invalid and lacked evidence. She also came to the class with religious beliefs, but did not use these beliefs to rationalize her acceptance. During instruction, Ashley's concerns about evidence for evolution were addressed and she therefore decided that evolution was 'real'. "Now that I see that people have evidence and it doesn't take as long as I thought for some things to evolve, we can see that evolution is real. When before I didn't think it was" (Ashley, p. 14). However, Ashley perceived her knowledge of evidence as in conflict with her personal views on the age of the Earth (see *Students Acceptance of Evolution* for representative quotes.)

Similar to Ashley and other conflicted students, Megan came to the class with no evolution instruction and did not think there were a lot of "scientific facts about it" (p. 4). She likewise had creationist views on evolution because of her religious upbringing. After the course, Megan's concerns about a lack of evidence for evolution were addressed - she recognized the volume of "legitimate" evidence presented in class and knew that speciation was occurring. However, Megan remained conflicted about her creationist beliefs about the origins of life. These concerns about the origins of life were not addressed by the course. Dr. Wallace noted that she left out information about abiogenesis (the generation of life out of inorganic matter) due to time constraints and lack of student interest, although she often covered the material in class.

> If we got to trace back like I was saying if we were to go back to the first insects that walked in Earth or where did the insects come from, are they just like poofed out of midair? So that's what contradicts me. I see the evolution of different species, but I don't know how it got to be in that way in the first place. (Megan, p. 30)

Evidence instruction as perceived by those that rejected evolution. Although three individuals did not increase their evolution acceptance after the course, one of these individuals still noted the volume of evidence presented in the class. The other two individuals did not realize the volume of evidence presented in class. Mary came to the course rejecting evolution due to strong religious beliefs and perceptions of counterevidence. She continued rejecting evolution after the course for the same reasons. She recognized the evidence for evolution, but thought that it was still unclear whether evolution occurred. “I mean I guess that she did put a lot of her evidence - which I consider unclear. I mean they do have a lot of evidence, but I would still say that it is unclear whether evolution occurs” (Mary, p. 13).

The other two individuals, Millie and Nathan, were undecided about evolution prior to the course. They rejected evolution after the course primarily because they did not understand the volume of evidence presented in class. Nathan somehow claimed there was a lack of evidence for evolution and Millie claimed that historical evidence was invalid because nobody was alive millions of years ago (see *Students Acceptance of Evolution* for representative quotes).

What Evidence Instruction was Influential?

Fossils as primary evidence for evolution. Although students cited a volume of evidence, many lacked knowledge about specific lines of evidence for evolution. Students primarily described their knowledge of fossil evidence when discussing evolution - six of whom mentioned only fossils as specific evidence for evolution. Some students also claimed that fossil evidence was better than other forms of evidence and others focused on the fossil examples when explaining evolution. Less frequently, students described their knowledge of other lines of evidence for evolution, including homologous traits (n=4), vestigial traits (n=4), or genetic components of evolution (n=3).

Fossils are the best form of evidence. Adrian agreed that evolution was supported by data and saw historical fossil evidence as especially compelling. “I agree evolution is supported by data, but especially the historical, and that to me is fossils.” (Adrian, p. 19). Similarly, Nicholas saw anything but fossils as insufficient evidence for evolution. “Anything but fossils, absolute proof, lay me out some fossils.” (Nicholas, p. 17). Nicholas did not qualify why he thought fossils were particularly good evidence, but stated this preference for fossil evidence in comparison to vestigial trait evidence.

Like Nicholas and Nathan, Nancy focused on fossil evidence as the predominant form of evidence for evolution. She hypothesized that only fossils could provide evidence for evolutionary relationships and therefore such relationships were not testable. “[Evolutionary relationships] are not really testable, you can only go about it if you found fossils or really just fossils because you can’t really test it and say okay we’re going to test and see if these two animals were related. You can only look at their characteristics and have your opinion on it” (Nancy, p. 15). Nancy did not mention the role of mitochondrial DNA in determining relatedness as mentioned in class.

Using fossil examples to demonstrate understanding. Brooke and Amelia did not describe a preference for fossil data, but instead focused on fossil examples to describe what they learned in class. Both Brooke and Amelia described how Dr. Wallace presented a photograph of the *Tiktaalik* fossil, and described how it represented a transition between water and land creatures.

> Mainly she would show us like . . . fossils in class and how a lot of the times in evolution they would have a fossil that, for instance, had legs and then a fossil that didn't have legs but they could find something in the middle to prove that it was evolution that caused it. (Amelia, p. 2)

Brooke and Nicholas also focused on fossil evidence to describe how they learned about the tentative nature of science in class. Brooke described how *Tiktaalik* changed scientists' ideas about the transition from water to land and Nicholas described how *Archaeopteryx* was a similar breakthrough in evolution. (see quotes in *Students' Knowledge of Macroevolution).*

Difficulties with historical/fossil evidence. Concerns about the geological evidence presented in class were common for many students. Seven of 12 participants had apprehension related to geological evidence. They perceived the data as old and therefore unreliable or thought historical data were speculative since nobody has observed the Earth over billions of years. These difficulties conveyed misconceptions in the students' knowledge of macroevolution, but the students did not describe these perceptions about historical evidence in context to their evolution acceptance. Millie was one example of a student with concerns about historical data. She claimed that since nobody was alive billions of years ago, there was uncertainty about fossils. "Studying like fossils and stuff, it's like we don't really know what exactly happened. Because it's through billions of years, we don't really know who our ancestors were back then or what species were really like back then" (Millie, p. 5).

Millie's rationale that "nobody was alive back then" was surprisingly common among the students; six other students had similar claims. These students continually commented on scientists' inability to observe historical phenomena with accuracy. Adrian, Bridget, and Nathan were three such students (see *Students' Knowledge of Macroevolution* for additional examples). Adrian had concerns about uncertainty of historical data when attempting to estimating the timeline for the break up of Gondwana.

“It's the same thing that I said before. We have no idea. None of us were alive back then” (Adrian, p. 14). Bridget had thought fossils could not provide accurate results because they were so old. “But if it happened a very, very long – quite long ago, how much of an accurate result can you possibly get?” (Bridget, p. 22). Nathan was concerned that historical data was incomplete because he learned that there were layers of rock did not contain fossils, and therefore thought there must be gaps in the fossil record. “The main thing is that they can’t fully understand fossils. . . so there are gaps because different types of rocks or something didn’t have fossils I think” (Nathan, p. 8).

Influence of History of Life Instruction

Dr. Wallace spent two class periods walking students through the tree of life from prokaryotes to modern humans, using examples of transitional fossils as she explained major transitions in phyla. Eleven of 12 students discussed how understanding the history of life was influential in their understanding of macroevolution, seven of whom cited this content as influential in their acceptance of evolution.

Students described the history of life instruction as having two influential components: deep time and transitional life forms. Similar to how students thought about evidence, learning about the history of life was something students had not considered before, and Brooke and Beverly expressed an appreciation of the detail Dr. Wallace put into describing a complete chronology of organisms. Brooke had never learned about evolution before and accepted it after the class. “ I mean I knew it worked in that fashion, I knew that we came from like where we came from, but. . . I never learned in detail. (Brooke, p. 8). Beverly had a conflicted view about evolution after the class and likewise found the chronology of organisms presented in class helpful for her understanding.

I never thought about it. The way she explained it from like bacteria to multi-cellular organisms, and other things that, developed into fish. I never knew that . . . fish which developed into mammals, land organisms, into certain types of humans, and to what we consider humans today. (Beverly, p. 2)

The history of life and acceptance. The history of life instruction particularly influenced students acceptance related to how organisms came into existence. Amelia and Nathan both described this was influential in their acceptance that life on Earth changed over time and did not appear in a single event.

Amelia and Nathan both rejected evolution prior to the course and compared their knowledge of the history of life to a previous conception that life came into existence in one single event. Amelia walked through the chronology of organisms given in class as she rationalized why she knew organisms did not all appear at the same time.

In class we talked about how . . . single-celled organisms evolved and then multicellular organisms evolved and amphibians and then all these other things so, that's why I strongly disagree that all organisms came into existence at about the same time. Because they didn't all happen at the same time. (Amelia, p. 11)

Nathan agreed that life did not appear in a single event after seeing the chronology of organisms a big chart in class; it was obvious to him that the organisms on the top appeared later than the creatures on the bottom, refuting the idea that all life appeared in a single event.

I disagree that everything on Earth came into existence at the same time just based on class and that big chart and like there were obviously those ones that went to the top came later than the one at the bottom. (Nathan, p. 31)

History of life and knowledge of deep time. Students did not express knowledge of specific time scales (i.e. whales evolved 50 million years ago). However, students gained a broader understanding of deep time through learning about the history of life. Students understood that scientists knew the Earth was billions of years old and that evolutionary processes can take millions of years to occur. More than half of the interviewees used these broad ideas about evolutionary time to consistently select a MUM answer that was the most, least, or more moderate amount of geologic time.

Mary, primarily used a convention of moderate time to answer questions on the MUM post-test (despite her personal views). She used guideposts of time from the class to determine which answers were most reasonable. Mary described that she shifted her answer from 30,000 to 3 million years ago because she had learned the first life on Earth was billions of years ago. She answered other questions similarly (see *Students' Knowledge of Macroevolution* for another example).

> I changed my answer from 30,000 years to 3 million years ago because she had like a diagram that was when everything came about on Earth, and it said like the first thing that came about was something billion years ago but since this is more recent I guess, since we're still living and so are chimpanzees, it wouldn't be billion, I would just put million since it's in the middle. (Mary, p. 7)

Nancy did not use a convention of relative time to answer questions on the MUM post-test, but described how she learned in class that at one point in time, humans came out of Africa. She inferred that the Great Ape Tree could have taken billions of years to evolve as she recalled the same tree in class took billions of years, likely referring to the tree of life. She explained:

> In class when we talked about all people were at one point in time, their common ancestors came from Africa. I saw a number and it must have been in the billion and so that's why I probably why I changed my answer to billion. (Nancy, p. 13)

Amelia also learned about relative time from the history of life lectures. She recalled that evolution takes more time than she previously thought based on the PBS *Great Transformations* video shown in class. She recalled a clock analogy in the video that demonstrated that eukaryotic life on Earth has only occurred for a relatively short period, and humans an even shorter period.

> In class [Dr. Wallace] gave us an example of evolution being like a minute of all the organisms or an hour and in the hour the first 45 minutes it's prokaryotes and then the last second or half second is everything else . . so it I know evolution takes more time than I thought. (Amelia, p. 5)

History of life and knowledge of transitional organisms. Learning about the transitions between major organismal phyla was influential for students' understanding of macroevolution. Dr. Wallace presented a replica *Archaeopteryx* fossil and several sequences of transitional organisms with supporting fossil evidence, including photos of *Tiktaalik* and a video which documented the change from a wolf-like ancestor to modern whales. Five of 12 students discussed how seeing a sequence of organisms and evidence for that sequence helped them see how species changed over time. Adrian recalled the influence of learning about transitional organisms. In the PBS *Great Transformations* video, Adrian recalled the land to sea transition of ancient wolf-life creatures to modern whales and how this demonstrated to him how species change over time: "The video was really focused on whales and them crossing paths with land animals and seeing where we came from that. Like how did you start in the land and then become species in water?" (Adrian, p. 3). Seeing evidence of species transitions also helped Brooke to visualize how life changed over time. Bridget recalled how Dr. Wallace brought in an *Archaeopteryx* fossil as evidence for transitional life forms.

> [She showed us] a dinosaur with wings. They had wings, and how they had wings showed kind of a transition. I don't know what species that she was showing us, but others became this and became this . . . I saw more evidence of how that moves from form to form in sequence. (Bridget, p. 25)

Brooke likewise recalled how Dr. Wallace's use of transitional fossils helped her to understand how life changed over time. She described the picture of *Tiktaalik* used in class and the accompanying video clip about when life came from the water. Brooke related this idea to her knowledge that science was tentative as she learned the fossil brought new understanding to the water-land transition.

> Animals were all in the water and then they migrated onto land and about how that transition took place, and then they found an animal that was millions and millions of years old that it was a fish but it had legs and it had fingers and so that said that completely changed everyone's idea. (Brooke, p. 6)

Instruction Influential to Knowledge of Macroevolution but not Acceptance

Influence of tree thinking instruction. Although not statistically significant, nine of 12 interviewed students related their knowledge of phylogenetic trees to the tree thinking activity from class (Appendix J). Students described learning from this activity including: (a) nodes and roots on phylogenetic trees are symbolic points of common ancestry and (b) relatedness of organisms can be determined by interpreting the tree.

Although students knew these general principles, they varied greatly in their ability to determine relatedness of the organisms on a phylogenetic tree correctly (see *Student Knowledge of Macroevolution* for patterns and quotes). Furthermore, students did not associate tree thinking instruction with their acceptance of evolution, unlike other areas of influential instruction (i.e. evidence for evolution and the history of life storyline).

Nature of science instruction. Dr. Wallace discussed the nature of science at the beginning of the course and repeated the same ideas during the evolution unit. She focused on defining and describing the difference between theory and law in science and how science can change over time (tentativeness). After the course, students gained an understanding that theories were backed by a substantial amount of evidence and several understood that theories were different than laws. (See *Students Knowledge of Macroevolution* for complete set of examples of students' ideas about nature of science). After class, many students had concerns about tentativeness and theories in science. Students did not cite these concerns as related to their evolution acceptance; the misconceptions were found across students of varying evolution acceptance post-instruction. In this subsection, I focus on the most influential misconception about nature of science that students gleaned from instruction - misconceptions about tentativeness.

Misconceptions about tentativeness. The most common problem students had with understanding the nature of science was related to the concept of tentativeness. Students were taught that "science was always changing" and that scientists were continuing to find new evidence for phenomena, including evolution. Some students took this to mean that because scientists continued to seek evidence that they must be unsure about evolution (n=3). Others were concerned that since science could change, evolutionary explanations remained speculative or incomplete (*n*=3). Some students commented that the existence of evidence did not guarantee validity (*n*=2).

Nancy, who was conflicted about evolution after the course, described her knowledge of tentativeness in science as an invaluable process. She held the misconception that scientists would jump on an idea bandwagon, wait for the next big idea, and then jump on another bandwagon: “When a new piece of evidence arises everybody wants to jump on the bandwagon and say that’s right. Whereas further on down the road when something else comes up then they’ll jump on that and say that is right” (Nancy, p. 14). Although Nancy had this negative perception of tentativeness, she recognized that tentativeness did not imply speculation.

Like Nancy, Millie, Nicholas and Bridget also had negative views of tentativeness in science, but they thought tentativeness implied speculation. They expected that once scientists were certain about a topic, they would stop seeking for evidence. Nicholas described scientists search for evidence as indicating missing links: “We're still finding evidence so that still means that we haven't found all the links that we're looking for, but they pretty much try to just fill it all in for us” (Nicholas, p. 8). Similarly, Millie thought new discoveries in human evolution indicated that scientists were still trying to prove if humans and apes shared a common ancestor. “Since evolution scientists are still finding more discoveries about it, I just guessed that they are still trying to prove it if [humans and apes] are related or not” (Millie, p. 13). Unlike the others, Bridget had concerns about tentativeness but did not relate these to new scientific discoveries. She saw the discerning and critical nature of scientists as akin to doubt. Bridget therefore thought that science was uncertain and speculative: “I don’t think evolution is scientifically valid because of a scientist always has to like doubt about the result and then try to confirm retest it again, they kind of always have doubt" (Bridget, p. 24).

Influence of Instruction Summary

Students were influenced by several components of instruction in both their knowledge of macroevolution and acceptance. Students' acceptance was most influenced when components of the instruction directly addressed their incoming ideas. Students had concerns that evolution was not backed by relevant data, was "just a theory" and was not compatible with their religion. Students overwhelming noted that the volume of evidence presented in class was the primary reason they made shifts toward accepting evolution after the class. Students also cited understanding the history of life (i.e. age of the Earth and the large amount of time species have been evolving) and knowledge of the Clergy Letter Project in helping them move past their incoming concerns to become more accepting of evolution after the course. Not all of the students reported their acceptance as influenced by the instruction. Mary knew the volume of evidence for evolution but thought that it was unclear in the class. Nathan and Millie did not understand the materials taught in class and therefore rejected evolution on false premises.

After the class, students' gained knowledge of macroevolution in several areas. Instruction was particularly influential for students who had little or no evolution instruction prior to the class. Students discussed their understanding of the volume of evidence for macroevolution (with a particular preference for fossil evidence) from the lists and examples of evidence given in class. They learned about the nature of theories, laws, and tentativeness in science both at the beginning of the class and during the evidence for evolution lectures, and gained relative perspective on the sequence of transitional organisms over time. The tree thinking in class activity also influenced students' understanding of macroevolution. Students gained knowledge about the meaning behind tree structure (nodes and roots) and knew the trees could be used to infer the relatedness of organisms on the chart.

Students had also had a number of misconceptions about evolution after the course. More than half of the students thought historical evidence was speculative or unreliable because nobody was around for billions of years to observe evolution. Three students thought that fossil evidence was the best or only form of evidence for evolution. Others thought that because science could change with new information that much of science was speculative. Students also had difficulty answering questions that required interpreting phylogenetic trees, despite having knowledge of roots and nodes.

Influence of PCK on Student Outcomes

To answer the overarching research question, I conclude the influence of the instruction section by discussing the influence of Dr. Wallace's PCK for teaching macroevolution as related to student outcomes. In this subsection, I provide four examples of how PCK influenced student learning outcomes, one related to students' evolution acceptance and three related to students' knowledge of macroevolution. These are primarily based in the qualitative interview data.

Influence of PCK on Acceptance

Students cited that the volume of evidence for evolution presented in multiple formats (replica *Archaeopteryx,* story of *Tiktaalik*, PBS *Great Transformations* video) in the class influenced their knowledge of macroevolution and acceptance of evolution. This influential instruction linked to Dr. Wallace's knowledge of learners' needs to see an idea multiple times and in multiple formats to understand (Knowledge of Learners). This knowledge of learners links back also to the goal to guide students to critically think about the material (Orientations toward Science Teaching).

Influence of PCK on Knowledge of Macroevolution

After the class, students developed understanding of phylogenetic tree structure, the evidence-based nature of theories, and learned about human and ape common ancestry. Each of these understandings was influenced by Dr. Wallace's PCK.

Although they continued to have difficulty answering questions about relatedness of organisms, student understood what the parts of a phylogenetic tree represented (i.e. roots and notes). Additionally, only one of the interviewed students was counting nodes to determine relatedness of organisms. Dr. Wallace emphasized phylogenetic tree structure during the tree thinking in class activity, and interviewed students primarily discussed the role of this activity in helping their understanding of trees . Dr. Wallace developed the tree thinking activity after learning that students count nodes to interpret phylogenetic trees (Knowledge of Learners), and also chose to use this activity because she saw it as important to overall scientific literacy. She believed trees were found in everyday literature (i.e. newspapers) and therefore saw relevance in developing students' ability to properly interpret them (Orientations).

After the class, students learned about the nature of scientific theories. Although some continued to think that theories held a lesser status than laws, almost all of the interviewed students knew that theories were based on a great deal of evidence and were not just guesses. Students related to Dr. Wallace discussing the nature of science twice in the class, both at the beginning of the semester and during the evolution unit. Dr.

Wallace chose to discuss the nature of theories because she saw it as having everyday relevance (Orientations) and because students come in with misconceptions about the idea (Knowledge of Learners).

Lastly, students developed knowledge about human and ape common ancestry. Interviewed students noted the overwhelming emphasis on this idea in class. Dr. Wallace used the grandmother-cousin-self analogy to target this misconception, in addition to diagrams in the human evolution subunit, the first phylogenetic tree in the tree thinking activity. She knew that students came in with the misconception that humans came from apes (Knowledge of Learners) and therefore focused on multiple examples of how humans did not come from apes throughout her instruction (Knowledge of Instructional Strategies).

What do non-science majors understand about macroevolution before and after instruction?

Students' knowledge of macroevolution was examined both quantitatively and qualitatively. This section describes students' knowledge of macroevolution for the overall student population (N=270) through patterns in the quantitative data and looks in depth at students' pre- and post-course knowledge of macroevolution from the perspective of the interviewed students (*n*=12).

Influence of Instruction: Whole Class Data

Prior to instruction, students scored arxound 50% on the MUM with mean scores of 14.32 ± 4.75 (maximum score = 27); see Table 11. This mean score significantly increased after instruction ($p < .0001$). Data on the educational background of students were analyzed to determine the possible impact of past educational experiences on students' incoming knowledge of macroevolution. This included one-way ANOVA tests comparing groups by the date of most recent instruction (Table 12) and duration (Table 13) of past evolution instruction and independent t-tests comparing groups that had completed college coursework in geology, anthropology, and another biology course (Table 14).

Table 11

Descriptive Statistics for Pre- and Post-Test MUM Data. Abbreviation: Measure of Understanding of Macroevolution (MUM). (N=270)

Measure	Min (0.0)	Max (27.0)	*M (SD)*
MUM Pre-test	2.0	24.0	14.32 (4.75)
MUM Post-test	3.0	27.0	16.75 (5.07)

Date of most recent evolution instruction. A one-way ANOVA was used to test for pre- and post-test MATE differences among four groups of students by self-reported date of most recent evolution instruction (no previous instruction, elementary/middle school, high school, another college class). Scores did not differ significantly ($p < .05$) among the four groups for the pre- and post-tests (Table 12).

Table 12

One-Way ANOVA comparing Pre- and Post-test MUM scores by Date of Past Evolution Instruction. Group Means Tested: No Past Instruction, Elementary/Middle School, High School, and College. Abbreviation: Measure of Understanding of Macroevolution (MUM).

		SS	*df*	*MS*	*F*	*p*
MUM Pre-Test	Between Groups	34.84	3	11.61	.510	.676
	Within Groups	6016.61	264	22.79		
	Total	6051.45	267			
MUM Post-Test	Between Groups	101.63	3	33.88	1.340	.262
	Within Groups	6672.89	264	25.28		
	Total	6774.52	267			

Duration of most recent evolution course. A one-way ANOVA was used to test for pre- and post-test MUM differences among four groups of students by self-reported duration of most recent evolution instruction (no previous instruction, about 1 day, about 1 week, greater than 1 week). The sample size for this ANOVA is smaller than other tests conducted as data from students that could not remember the duration of past evolution instruction were excluded. MUM pre- and post-test scores did not differ significantly among the four groups ($p > .05$; Table 13).

Previous college coursework. Independent sample t-tests were conducted to compare mean MUM scores among groups that did or did not complete particular college coursework known to contain macroevolutionary content. These statistical tests explored the impact of a college course in geology, anthropology, and/or another biology course (Table 14). There was no significant difference ($\alpha = .05$) in mean MUM scores between groups that had a past geology course or anthropology course and those that had not.

Conversely, the mean pre-test MUM scores were significantly higher for the group that had completed a prior college-level biology course (p = .028). This significance between groups did not carry over to the post-test MUM scores (p = .101).

Table 13

One-Way ANOVA comparing Pre- and Post-test MUM Scores by Duration of Past Evolution Instruction. Group Means Tested: No Past Instruction, About 1 Day, About 1 Week, and More Than 1 Week. Abbreviation: Measure of Understanding of Macroevolution (MUM).

		SS	*df*	*MS*	*F*	*p*
MUM Pre-Test	Between Groups	23.54	3	7.85	.332	.802
	Within Groups	4937.62	209	23.63		
	Total	4961.16	212			
MUM Post-Test	Between Groups	90.06	3	30.02	1.159	.327
	Within Groups	5414.77	209	25.91		
	Total	5504.83	212			

Table 14

Independent Sample t-tests Comparing Mean Pre- and Post-test MUM Scores Between Students that Completed Past College Coursework in Geology, Anthropology, or Another Biology Course and Those that had not Completed such a Course. Abbreviation: Measure of Understanding of Macroevolution (MUM)

	Past Instruction	N	*df*	*M*	*t*	*p*
Pre-MUM	No Geology	235	266	14.29 (4.76)	-.391	.696
	Geology	33		14.64 (4.84)		
Post-MUM	No Geology	235	266	16.73 (4.99)	-.572	.568
	Geology	33		17.27 (5.40)		
Pre-MUM	No Anthropology	241	266	14.41 (4.73)	.808	.420
	Anthropology	27		13.63 (5.11)		
Post-MUM	No Anthropology	241	266	16.81 (4.95)	.067	.947
	Anthropology	27		16.74 (5.83)		
Pre-MUM	No Biology	212	266	14.00 (4.84)	.052	.028*
	Biology	56		15.57 (4.28)		
Post-MUM	No Biology	212	266	16.54 (5.00)	.065	.101
	Biology	57		17.79 (5.10)		

Note. * = $p < .05$.

Concurrent biology lab. Independent sample t-tests were conducted to compare MUM scores between groups of students that did and did not enroll in the laboratory portion of the introductory biology course. It was not required for students to be concurrently enrolled in the lecture and lab sections of the course and therefore only 34 students were concurrently enrolled in a lab section. Mean post-test MUM scores did not significantly differ between students that had enrolled in the biology lab and those had not (Table 15).

Table 15

Independent Sample t-test Comparing Mean Post-Test MUM Scores Between Students Enrolled in the Optional Laboratory Section of the Biology Course Concurrently with Lecture and Those that did not. Abbreviation: Measure of Understanding of Macroevolution (MUM)

	Concurrent Instruction	N	*df*	*M (SD)*	*t*	*p*
Post-MUM	No Lab	234	266	16.82 (5.07)	.192	.509
	Lab	34		16.65 (4.87)		

Knowledge of Macroevolution Among Interviewed Students

There was a variety of evolution views for interviewed students irrespective of their MUM scores. An analysis table of participants' pre- and post-instruction MUM scores with representative quotes of their knowledge of macroevolution can be found in Appendix H. Interviewed students' unit attendance, overall grade, and pre-/post-test MATE and MUM scores can be found in Appendix I. The average pre-test MUM score for interviewed students was 9.50 ± 4.62, more than one standard deviation below the course average.

Among the students interviewed, half made gains on the MUM in regard to their knowledge of macroevolution and half did not. The students made substantive MUM gains ($\Delta > 5$ points) were Millie, Megan, and Mary (macroevolution gains only) and Bridget, Brooke, and Beverly (both acceptance and knowledge of macroevolution). The students that did not make substantive MUM gains ($\Delta \leq 4$ points) were Adrian, Ashley and Amelia (acceptance gains only) and Nathan, Nancy, and Nicholas (gains on neither instrument). However, the incoming scores of Adrian (16) and Amelia (17) were above class average and they might not have made gains on the instrument due to ceiling effects. They were selected for interview despite high MATE due to problems recruiting students with acceptance gains only that had attended class for at least 75% of lectures.

The nature of the interviews focused on how students changed their answers on the instruments after instruction and therefore did not lend itself to a comprehensive description of students' knowledge of macroevolution. This section combines student responses both pre- and post-instruction into content knowledge bases to best illustrate change pre- to post-instruction. These content areas include students' knowledge of phylogenetic trees, fossils, deep time, nature of science, and human evolution.

Knowledge of Phylogenetic Trees

Pre-Instruction. Prior to instruction, half of the interviewed students reported guessing on questions about phylogenetic trees and four students mentioned never seeing phylogenetic trees prior to the course.

Unfamiliarity with trees. Six students described being unfamiliar with phylogenetic trees prior to instruction. All of these students commented that they had guessed on questions which required interpreting a phylogenetic tree. Four students, Mary, Millie, Adrian and Brooke, had never seen phylogenetic trees before.

Mary had less than a week of previous evolution instruction and had “no idea because I had never seen this thing before” (Mary, p. 6). Millie had only one day of previous evolution instruction and similarly described that “before the class I didn’t know what this chart meant” (Millie, p. 3). Adrian had less than a week of previous instruction and described that he did not expect phylogenetic trees to look like the ones in class. “At first I looked at and didn't understand it as much. I didn't think that these, they were going to look like this. When I imagined an evolution chart, I didn't imagine that diagram” (Adrian, p. 4). Reflecting on his understanding of trees during the post-instruction interview, Adrian realized that he had no idea that the structure of the tree had any meaning prior to Dr. Wallace’s class. “Before the class started I did look at these differently and I didn't know exactly what these, what all these figures meant” (Adrian, p. 7). Brooke had a similar realization that she did not know how to interpret tree structure before the class during the interview and knew that she now viewed trees differently and understood that tree structure illustrated something about the relatedness of organisms.

> The first time I think that like once again I just didn’t know what I was looking at I didn’t know whether or not it was how I could tell like what was related to what like, cause I think the reason was because these have a lot to do with being related to something else. (Brooke, p. 5)

Post-instruction. After instruction, students gained an understanding of the symbolic parts of tree structure. They learned that nodes illustrated points of common ancestry (*n*=9) and that the base or “root” of the tree symbolized a common ancestor for all of the species on the chart (*n*=8). Despite an understanding of tree structure, most students had difficulty answering questions that required interpretation of phylogenetic trees (n=8). Five students of these student subsequently developed a consistent but incorrect method to answer tree interpretation questions on the MUM. Students had particular difficulty interpreting MUM Figure 4, which lacked specific species and was oriented vertically.

Understanding nodes and roots post-instruction. After instruction, ten students mentioned that phylogenetic tree nodes (points at which lines on the tree intersect or branch) were symbolic points of common ancestry and five mentioned that the root of the tree (base) symbolized the common ancestor for all of the organisms on the chart. Although students could explain the meaning behind these tree structures, many still had difficulty answering questions which required interpreting tree structure (i.e. questions about relatedness of organisms, see *Incorrect tree interpretation strategies)*.

Ashley and Nicholas are representative students that demonstrated a clear understanding of nodes and roots. Ashley indicated points on the Whale-Hippo phylogenetic tree as she described their symbolic meaning as common ancestors. “These are common ancestors [indicates nodes] so like we all come from this. Like all these things came from this [indicates root]. We all have a common ancestor so [Dr. Wallace] said all these things came from there” (Ashley, p. 4). Nicholas likewise understood the concept of nodes and roots, despite the fact that he did not attend the tree thinking in-class activity and had a low post-test MUM score of only 5 of 27. However, Nicholas indicated that he was in a rush completing the post-test surveys and so his score might not be illustrative of his actual understanding. Nicholas described the nodes as points where the tree “split” but was considered the common ancestor.

There's lots of splits, like obviously the toothed whale and the baleen whale, they have a common ancestor here and then they both have a common ancestor with a hippo here, and then it just keeps going like all of these guys have one common ancestor with the hippos and the whales here. (Nicholas, p. 6)

Problems with nodes and roots. Not all of the students readily understood the concept of nodes and roots. Beverly and Nathan struggled with understanding tree structure. Beverly attended the tree thinking in-class activity and had a relatively high post-test MUM score (16 of 27), but did not know if it was the intersections or the bends on the tree that represented points of ancestry. "I get confused . . . how like where I determine, where that species went into two different or where it went into two different species like do I do it like from right here [bend]? Or should I start from right here [node]?" (Beverly, p. 4)

Unlike Beverly, Nathan struggled with tree interpretation and did not attend the tree thinking in-class activity. He understood less about phylogenetic tree structure in comparison to other interviewed students, including Beverly. This lack of understanding was evident by Nathan's low post-test MUM score of only 5 of 27. "So you start with an animal here something and they mutate a split . . . then this goes, that's obviously camel and it keeps splitting until you get all these animals down. So that's I interpret it" (Nathan, p. 6).

Although Nathan and Beverly did not indicate nodes as points of common ancestry, both described nodes as points of speciation (when one species became two). The other individual to recognized nodes as points of speciation was Nancy, who was the only participant to indicate that nodes indicated both a points of speciation and a common ancestor. Nancy struggled with answering tree interpretation questions despite her knowledge of tree structure, and this contributed to a low post-test MUM score (8 of 27).

Incorrect tree interpretation strategies post-instruction. Although students understood the basic structure of trees, eight had difficulty answering questions that required interpreting phylogenetic trees. This difficulty was evident class wide. A low proportion of students (N=290) answered correctly on post-test MUM questions which required looking at a tree and correctly interpreting its structure: Q2 (59% correct), Q14 (33% correct), and Q19 (38% correct). The class did not have much difficulty with Q20 (71% correct), which also required interpretation of tree structure.

Among the eight students with difficulty interpreting trees, six developed a consistent but incorrect strategy to interpret tree structure. The other two students had no particular method for interpreting tree structure and guessed on such questions.

Reading trees at the tips. The most common incorrect strategy for students to interpret a tree was to look at the proximity of the species at the "top" of the tree (*n*=5). Nathan, who did not attend class for the tree thinking activity, typified this strategy in his interpretation of the Whale-Hippo phylogenetic tree (MUM Figure 1). He looked to see which species picture was closest to whales along the right side of the figure and disregarded the nodes on the tree to answer question 2. This disregard of nodes also fits his lack of knowledge that nodes are symbolic points of common ancestry. Nathan postulated that since deer were closer on the tree to whales in comparison to pigs. Although this was a correct answer for the question, his approach to answer it was incorrect. "I think four would be a better answer . . . because they are closer around the tree than the pig is up here, I don't know, I don't know" (Nathan, p. 5).

Node counting. Another incorrect approach used to interpret the trees was node counting. Despite attending the in-class activity which emphasized not to do so, Ashley continued to nodes between species to determine relatedness after instruction. Although she could identify where the most recent common ancestors were on the chart, Ashley looked at how many common ancestors (nodes) were between species to determine relatedness on the Great Ape Tree. She counted fewer nodes between gibbons and orangutans and more nodes between humans and gibbons, and therefore thought that humans and gibbons were less related than gibbons and orangutans.

> Chimpanzees are right here and humans are right here. And there's less things (nodes) in between then these and these and it's right here, their common ancestor is right here. So I thought that one was wrong because humans and chimpanzees aren't as closely related as those. (Ashley, p. 11)

Difficulty with MUM Figure 4. Interviewed students had difficulty interpreting Q14, which required interpreting MUM Figure 4, a vertically oriented tree with no specific species. This difficulty was also evident in the quantitative data - only 33% percent of the class answered Q14 correctly on the post-test (20% on the pre-test).

Of the seven interviewed students changed their answer on Question 14, only Mary answered correctly. She realized that the diagram showed increases and decreases in the number of species over time because she learned in class that when lines end on a phylogenetic tree, a species has gone extinct. “I feel like she said something about if they end and these keep going then they become extinct. . . so that would mean that they're not always increasing, some of them are not increasing they're like leaving” (Mary, p. 2).

Interpreting only part of the figure. The remaining six students that answered incorrectly seemed to only analyzed part of the diagram to determine their answer - the bottom portion (constant decrease) or the terminal ends (constant decrease). The four students thought the MUM Figure 4 was illustrating a constant increase in the number of species over time. Brooke typified the "constant increase in number of species" response, and described the figure as though she did not notice that the tree ended with only three extant species. Ashley and Beverly had nearly identical rationale to Brooke. " Going from this one ancestor, it diversifies into you know this animal and this one and this one, so its like, it branches off into many different types, and there's a whole bunch, right?" (Brooke, p. 13).

Bridget had slightly different rationale for why she thought MUM Figure 4 indicated constant diversification of species. She thought that the tree showed constant diversification because she learned in the concurrent biology lab that "as more time goes on there is more species" (p. 10).

> I remember conducting a program thing [in lab], so if there is a moss and then a cricket and then that it survived and then as the time goes and there are more species if there is no predator, but they're increasing and increasing. (Bridget, p. 11)

In a similar way, Nancy and Nicholas used only a portion of the figure to determine an answer. They seemed to analyze only the tips of the tree and therefore thought the tree indicated a constant decrease in the number of species. Nancy described how natural selection would have influenced some species to die out and therefore the chart indicated that the number of species over time was constantly decreasing.

> I will say [it is constantly decreasing] because some different body forms may have been created and not been successful or have not been able to survive in their environment or adapt to their environment so will have like become extinct or died off or what not. (Nancy, p. 9)

Nicholas described similar (but incorrect) natural selection based rationale behind his determination that the figure indicated a constant decrease in the number species. He noted that the diversification shown on the diagram was species trying to find "what worked", and after that point, other forms died out.

> Yeah and then all of a sudden, yeah, they find what works and then there's a decrease, but yeah it kind of, how I would, why I would say a gradual decrease just because species and it's like well you guys are all kind of just going away. (Nicholas, p. 12)

Knowledge of Fossils

Dr. Wallace discussed fossils in class in relation to transitional fossil evidence, the history of life, and similarities in layers of geological rock worldwide. Although some students had an understanding about fossils after instruction, well triangulated themes could only be established around students' misconceptions about fossils. Similar to difficulties students had understanding the relevance of historical evidence, seven students had misconceptions about fossils after instruction. These students described confusion about what was considered a fossil (*n*=4), how marine fossils could exist at inland locations (*n*=3), and how materials became fossilized (*n*=3).

Conceptualizing fossils and what can fossilize. Nathan, Amelia, Nancy and Adrian related their conception of fossils to only preserved bone material. Nathan perceived fossils as bones but was even unsure at first if even bones could be considered a fossil. He questioned himself as he discussed his knowledge of fossils. “I think of bones when you find like a dinosaur bone or something, is that a fossil? I guess would be” (Nathan, p. 19). Amelia similarly described fossils as bones and did not describe other materials as potential fossils: “I knew if it was a fossil, it had to have bones to have a fossil” (Amelia, p. 7).

Like Nathan and Amelia, Adrian and Nancy perceived fossils as bone material. They described fossils materials that were fossilized because they were hard and surmised that soft tissue did not fossilize because it was difficult to preserve. Adrian refuted the possibility of soft tissue fossilizing because he conceptualized fossils as bones. “I feel like when I think about fossils I'm thinking more about bones and eyes tissue has nothing to do with that area so I don't understand why it would be a fossil I guess” (Adrian, p. 6). Using the same logic, Nancy and Nicholas explained that since eyes were not bone, they required some sort of preservative to avoid decay. Nancy described preserving eyes in water would require a canister of water or some type of liquid. “Because the eyes aren’t bones so they would become kind of hard to preserve without water because I’ve seen eyes like in a canister with water or some type of liquid in there” (Nancy, p. 7). Like Nancy, Nicholas discussed a method to preserve soft tissue. He questioned if freezing tissue was a potential way to preserve animals as fossils. “Sometimes there are cases like if you get like a frozen animal fossil, they don't decay. . . like if you have a natural preservative where like you're frozen, you die but you're frozen” (Nicholas, p. 11).

Marine fossils at inland locations. Millie, Bridget and Ashley continued to not understand the mechanism by which marine fossils were found in locations without an ocean after instruction. They used examples from class to incorrectly justify their answers on Q4. The misconceptions displayed by these three individuals ran contrary to patterns in the whole class data, as 86% of the class answered correctly on Q4. MUM Question 4 reads (Appendix B):

> The fossils that are being examined to determine the ancestor in the evolutionary pathway of whales have been found in areas of Pakistan, Afghanistan, and India, places that are now well above sea level. The most scientifically reasonable explanation for the location of the fossils being examined is:
>
> 1. Predators of whale ancestors carried their prey to this area to eat them.
> 2. When the whales died their skeletons floated to the top of the ocean where they drifted ashore and became fossils.
> 3. This area was most likely once covered with water and the shore dwelling ancestors of whales once lived in these areas, died, and their skeletons were fossilized.
> 4. The great meteor impact caused tidal wave that forced these animals into these areas trapping them causing them to die, and their skeletons were fossilized.

Millie and Bridget were both confused by answer 1, which explained inland marine fossils by predator-prey migrations. Millie knew that during the ecology unit, Dr. Wallace talked about whale migration as related to seasonal prey distribution. She was therefore distracted by the predator-prey distracter. Millie did not explain why whales following their prey would result in marine fossils at inland locations. "We talked about migration in class . . . I guess I thought that since there is migration, I just felt that like whales would move and so their prey would move too" (Millie, p. 5). Bridget was distracted by the same predator-prey answer as Millie, but for different reasons. She incorrectly recalled that the PBS *Great Transformations* video documented whales moving onto land because a “predator was eating their species,” and therefore thought that this caused marine fossils at inland locations. In reality, the video showed land-dwelling ancestors of whales venturing into the water to pursue prey.

Ashley was distracted by the answer 2: “when the whales died their skeletons floated to the top of the ocean where they drifted ashore and became fossils.” She chose this answer because she believed a clicker question in class had something to do with skeletons floating up to the top of something.

> She had a clicker question that talked about something about skeletons floating to the top and that's... yeah. This is almost like the same question reworded as the one she had. It was about some kind of other, it wasn't whales, it was some kind of skeleton floating to the top. (Ashley, p. 6)

The only clicker question which referred to fossils asked students “Which characteristic of the fossil record provides the best evidence for evolution?”. The correct answer was that “the sequence in which organisms appear in the fossil record is consistent throughout the planet.” Dr. Wallace explained that this answer was correct because layers of fossils were consistent throughout the planet, and listed out the expected pattern of species layers (9 April 2012). Perhaps Ashley interpreted layers of fossils to imply that some fossils float to the top.

Knowledge of geologic time. In this subsection, I discuss interviewed students’ knowledge of geologic time. I do not review qualitative patterns item-by-item because data were only collected when students changed their answer from pre- to post-MUM, although students discussed broadly guessing on individual questions. Eleven students guessed on questions which required knowledge specific geologic time scales (Q3, Q21, Q27) and four continued to do so after instruction. The specific time scale questions on the MUM asked participants to select the correct geologic time scale from a set of specific time scales - i.e. 500,000 years ago, 5 million years ago, 50 million years ago. or 500 million years ago. This guessing behavior was also evident in the whole class data, as indicated by a low proportion of correct answers on the pre-test (Q3 - 29%, Q21- 47%, Q27 - 25%) and post-test (Q3 - 29%, Q21- 44%, Q27 - 31%).

Ashley typified the common response of participants regarding time specific questions. She described that she never recalled Dr. Wallace talking about specific spans of time. “I don't think [Dr. Wallace] ever talked about how long it took for things to evolve. I don't know. I don't remember ever going over that” (Ashley, p. 6).

The exception to guessing on time questions was Beverly, who based her answers the idea that all organisms require at least six million years to evolve, a fact which she somehow derived from class. “Well, we learned that it was – over everything was like a six million year process, so I guess I chose the higher one that’s close to the six million” (Beverly, p. 6).

Conventions of relative time. Although students did not usually answer time-related MUM questions using knowledge from class, seven students developed a convention to select answers on the MUM with consistency. These students consistently selected the shortest (n=1), a moderate (n=4), or longest time span (n=2) as their answer.

Shortest time scale. Nicholas thought the Earth was younger than scientists claimed because he had concerns about the validity of carbon dating. He consistently answered time questions by selecting the least amount of time. “Any of the time questions I answered the least amount of time because I think the Earth is younger than what the scientists are saying because of the gray area with carbon dating" (Nicholas, p. 8)

Moderate time scale. Megan, Mary, Millie and Nathan selected a moderate time span on time questions. Megan explained that her rationale behind this was simply to avoid extremes. "It just seemed like 50 million, they all seem too extreme to me and I thought that 500,000 seems too small" (Megan, p. 7). This view that evolution could take millions of years was consistent with Megan's acceptance that evolution took place over a long time, although she felt conflict between this idea and her belief that "the whole Earth is created in seven days" (Megan, p. 31).

Nathan and Millie likewise described selecting answers "in the middle" that were not "too high" or "too low". Since they rejected evolution for reasons other than the age of the Earth, these answers were consistent with their evolution acceptance. "I think it was just a guess I just wanted to like pick like I guess somewhere near the middle but like not too high but not too low" (Millie, p. 12). "I thought that's really a guess but I mean I think 500 million years is way too many" (Nathan, p. 6).

Mary used examples from class to justify her selection of moderate evolutionary times. She created guideposts in her mind to situate events in evolutionary history around what she learned from class. She recalled the large phylogenetic tree from the history of life lecture had origins of life "billions of years ago" (a long time ago). She also knew that humans and chimps still existed (modern day). She therefore hypothesized that African Great Ape divergence (Q21) took "millions of years", since this was a moderate time span between modern day and billions of years ago. This convention was inconsistent with Mary's opinion that the Earth was less than 20,000 years old (see *Interaction between knowledge and acceptance*).

> On the diagram [in class] it said like first thing that came about was something billion years ago. But since this is more recent I guess, since we're still living and so are chimpanzees, it wouldn't be billion, I would just put million since it's in the middle. (Mary, p. 10)

Longest time span. Brooke and Bridget selected the largest options on time questions. Brooke selected the longest time spans because she thought evolution would take a "long-long time" (p. 4) because she was taught that the Earth was billions of years old and because she recalled Dr. Wallace emphasizing that speciation took a long time. These answers were consistent with Brooke's acceptance of evolution post-instruction.

> [Dr. Wallace] emphasized that it takes a long time for a species to diversify into something else and then until they're considered to be different species of their own . . . I mean I guess I'll pick the longest amount of time because I feel I could it could be 500 million years, because the Earth is so old, its like billions and billions of years old. (Brooke, p. 4)

Similarly, Bridget consistently selected the longest spans as her answers. She remarked that if even larger time spans given as potential answers, she would have selected those answers over her current answer choices. Interestingly, Bridget consistently selected these responses in spite of her conflicted view regarding the correct age of the Earth (see *Student Acceptance of Evolution*). "I had no idea kind of guess thought the largest number. . . If the question is like 300,000 billion years, I'm going to go for that too" (Bridget, p. 16).

Knowledge of the nature of science. Students did not extensively discuss their prior knowledge of the nature of science (NOS), but had several themes emerged regarding their understandings about NOS after the course, including understandings about the nature of theory, evidence and proof, and tentativeness in science.

Nature of scientific theories. After instruction, students frequently described theories as supported by a number of lines of evidence (*n*=6) and something more than guess (*n*=4). Four students also described theories as holding a lesser status in science.

Theories are supported by evidence and are not guess. Nicholas typified the student conception that theories were supported by evidence. He had more confidence in theories after seeing the volume of evidence presented in class and recognized that scientists do not generate theories without due diligence.

> I had a lot more confidence in theories, in the science of biology so that's kind of why I was like, theories are supported of a number of different lists of evidence. There is evidence for theories, they don't just, they don't, they don't just like pop them out. (Nicholas, p. 19)

Similarly, Mary also noted that theories were generated using a broad range of ideas and therefore were not guesses. Mary also recognized that 'theory' in science meant something different than the colloquial use of the term.

> We learned that a theory was not, did not mean that it was just a hunch. I would normally say "oh I have a theory", and that's just like a guess. And in science a theory is like a description or an explanation of or like a coming together of a broad range of ideas. (Mary, p. 11)

Theories are not as legitimate as laws. Four students understood the evidence-driven nature of theories after instruction, but thought that scientific theories held a lesser status to scientific laws. "[Dr. Wallace] talked a lot about theories and laws", recalled Megan (p. 24). "She used to say that because that's like the evidence is there, a theory is like credited." Like other participants, Megan realized that theories required a lot evidence. Despite this, she described theories as inferior to laws. Megan knew theories and laws were different things and that one did not become the other, but still described laws as "more legit than theories" (p. 23). Since Megan had learned that theories had to be testable, which she saw as difficult to do, theories were less valid than laws: "it has to just be something that's testable and I think that's really hard" (p. 24).

Adrian and Millie likewise knew theories required evidence and were not hunches. Like Megan, Adrian thought theories "did not hold as much power as a law" (p. 13), because theories could change with new information (see *Tentativeness in science*). Millie likewise thought theories had a lesser status in science, although she did not compare them with laws. She defined a theory as an "explanation" but could not describe how theories to explain phenomena. Instead, she described theories as something that not all scientists agree with: "[A theory in science] is like an explanation of, I guess, something that has happened [in] evolution. . .We talked about theories in class and how other scientists can, I guess, agree with it or not" (Millie, p. 14).

The final student with confusions about theory and law was Beverly. However, she was unique in that she recognized that theories required "a lot" of evidence and was comfortable with science changing with new information. Her difficulty seemed to stem from the definitions of theory and law given in class. Like Millie, Beverly lacked meaningful understanding behind definitions given by Dr. Wallace in class. She could not recall which definition was which and did not know how the definitions given in class related to how theories and laws functioned in science.

> I learned that theories are – explanations and laws are – no, theories are thoughts and laws are explanation, so theories are just like new thoughts that – new thoughts are like evidence coming up, so it's new evidence coming up so that's why I thought it was a theory. (Beverly, p. 17)

Nature of evidence or "proof". Several students used the term 'proof' in their descriptions of evolutionary science. The students thought that when there was enough evidence for something, it became proven and/or that evidence was a form of proof (*n*=4). Similarly, three students thought that theories could be proven with enough evidence, although only Amelia thought that this evidence "threshold" had been passed and therefore evolution was proven. This was congruent with her post-instruction acceptance of evolution.

Amelia noted that the scientists in the PBS *Great Transformations* video found evidence "proved" evolution. "[Dr. Wallace] really showed us on videos that scientists have come to prove that evolution did happen" (Amelia, p. 2). Mary also talked about Dr. Wallace giving "proof" for evolution - "She gave like a list of I guess proofs of evolution" (Mary, p. 2). Contrary to Mary and Amelia, Nicholas used the term proof similarly to how it would be used in legal settings. He did not know if evolution was proven beyond "all reasonable belief" and related this to his concerns about disproving evolution through carbon dating.

> I feel like you need to prove things beyond like all disbelief to make them be factual when they are presenting like all parts as fact, when it still could be

> disproved like how I feel about carbon dating, obviously, so that's I think where I was kind of going with that answer. (Nicholas, p. 8)

Like Nicholas, Millie had concerns that evolution was unproven. Her rationale for this based in the concept that no observation in science was “official” unless it was “proven”. This illogical response was typical of Millie, who struggled with course material (60.6% overall grade) and often lacked coherency in her responses. I provide one of her responses below without the ‘likes’ removed as an examples of a typical response from Millie.

> I think like there are some valid observations but then again like there are like some that aren’t valid like we don’t really know if it's official observation or not until it's like proven I guess if we can prove it. (Millie, p. 13)

Science is tentative. Eight students described how they learned science was always changing and scientific ideas were constantly being challenged in the light of new evidence. Megan typified the common response students had about science changing. She described how Dr. Wallace talked about change in science through new information. “Our teacher told us that science is always changing, it’s always finding out new information . . . I think you can always go a little bit deeper with it and you always find out new information” (Megan, p. 8).

Brooke, Nicholas and Millie thought beyond the concept of “science changing” to apply the idea to examples of fossil discoveries discussed in class. Dr. Wallace presented several examples of newer fossil discoveries and explained how these fossils changed how scientists thought about evolutionary relationships. Brooke described how scientists discovered *Tiktaalik*, the transitional fossil between fish and tetrapods, and this changed what scientists knew about the water-land transition.

> Then they found an animal that was millions and millions of years old that it was a fish, but it had legs and it had fingers, and so that said that completely change everyone's idea. And it showed that it had, I suppose, like adapted and learned how to live on land, and it like showed that transition. (Brooke, p. 6)

Nicholas also described the role of new fossils in relation to building knowledge about evolution. He described the *Archaeopteryx* fossil (bird-reptile transitional fossil) that Dr. Wallace brought in was a breakthrough in evolution. However, Nicholas did not see new evidence as adding to the current base of knowledge. Rather, he saw new fossils as indicating that the base of evolution knowledge was incomplete. Nicholas saw this archaeopteryx as another indication that evolution remained speculative and lacked "complete proof". He did not think scientists would be looking for new fossils if they were completely certain about evolution.

> We're still finding evidence, so that still means that we haven't found all the links that we're looking for, but [scientists] pretty much try to just fill it all in for us. So [scientists are] still trying, I feel like they are speculating some things when they haven't found complete proof for it, like I think she said one time that they had just found some like huge bone set that was some major breakthrough in evolution. (Nicholas, p. 8)

Like Brooke and Nicholas, Millie described how she that science could change by describing how new fossils discoveries could change scientists' ideas. However, she did not cite a particular fossil discovery from class.

> I guess because like I felt that, whereby fossils and what they have seen and how species have developed, I guess as new fossils form . . . they find out new things, [and] they might change their ideas. (Millie, p. 5)

In similar fashion as Nicholas, Millie misinterpreted the tentative nature of science to mean that theories were hunches and much of science was speculative. She saw the emergence of new discoveries as an indication that scientists were still seeking the evidence to "prove" evolution. "Scientists are still finding more discoveries about it, so I just guessed that they are still trying to prove it if [the great apes] are related or not" (Millie, p. 13).

Defining evolution as related to humans. Seven students mentioned that before the course they thought humans evolved from monkeys or that evolution was about human origins. After instruction, four of these students mentioned that evolution was comprehensive to all life and all of these students recognized that humans did not "come from monkeys" but rather shared a common ancestor. Amelia had first learned about evolution in middle school and recalled that she learned evolution had something to do with humans evolving from chimps or monkeys. "I think maybe in maybe in middle school they hinted at it but it was the old thing of we evolved from chimps and monkeys" (Amelia, p. 1). Bridget had learned about evolution at church, where they emphasized the logical impossibility of humans becoming from monkeys. She expressed this view as her incoming definition of evolution. "I understood it is like monkeys and the humans they are kind of the same and then the monkeys became human or evolved" (Bridget, p. 1). Brooke attended a public high school that did not teach evolution and came into the class only with "her own imaginations" about what evolution was because she had not think much about evolution. Like Amelia and Bridget, she thought that evolution was about humans coming from monkeys. “I kind of had the image of my imagination as being like the monkey which like turns into the man in a way, but I obviously knew like that wasn’t true, but I didn’t really think about it much” (Brooke, p. 1).

Post-instruction ideas about human evolution. Eight students emphasized that Dr. Wallace told the class that humans did not evolve from apes, but rather shared a common ancestor. Brooke, who had previously envisioned humans coming from monkeys, discussed that the human-chimp relationship became clear to her during the tree thinking in-class activity, which focused on a phylogenetic tree of apes.

> She was trying to get it like out of us that we’re also used to saying ‘oh we originated from monkeys’ and its like we’re all are like chimpanzees or something, it’s like we’ll know really we they and us we all originated from, this common ancestor over here. (Brooke, p. 12)

Similarly, Ashley described Dr. Wallace’s emphasis on the human-chimp relationship. “She specifically told us that we didn't come from chimpanzees or anything, so that stuck” (Ashley, pp. 2-3). Beverly also mentioned the emphasis on human-ape common ancestry, but thought that common ancestry implied a lack of relatedness. She did not understand that because humans and chimps share a common ancestor, they are therefore related. Beverly did not provide much of an explanation as to why she thought in this manner, but did have the belief that humans and apes should not be classified together. “I know for sure that chimps and humans are not related. They just have a common or recent common ancestor. I know that for sure” (Beverly, p. 14).

Quantitative MUM patterns evident in the qualitative data. It was difficult to make qualitative comparisons between students on the basis of significant differences in pre-test MUM scores. Pre-test MUM scores significantly differed (p=.007) between students that had a previous college biology course and those that had not. Ashley and Nicholas were the only interviewed students that had completed such a course, although neither reported that this course involved evolution-related content. This may be the reason neither Ashley nor Nicholas described their understanding of topics assessed on the MUM in ways different than the other participants.

Students' Knowledge of Macroevolution Summary

Overall, students came to the course with little background information about macroevolution, despite the fact that ten of the participants had some form of evolution instruction in the past. Students came to class unfamiliar with phylogenetic trees, thought that humans come from monkeys, perceived evolution as a theory on human origins, had little understanding of absolute geologic time, and thought of fossils were bone material of ancient organisms (broadly excluding remains or impressions of organisms without an internal skeleton).

After the course, students had their ideas about human-monkey ancestry addressed by learning that humans and apes share a common ancestor. Students had to determine the common ancestor of humans and chimps during the tree thinking in class activity (Appendix J). This tree thinking activity also taught them about the structure of phylogenetic trees. After the activity, students developed an understanding of the symbolic meaning of nodes (intersections) and roots (base of the tree). Despite knowledge of tree structure, most students continued to have difficulty answering questions which required interpreting a tree. In particular, students had difficulty interpreting a tree that was vertically oriented and had no specific species names (MUM Figure 4).

Students did not learn much about deep time in class, but did gain a general conception that evolution occurred over a long period of time, i.e. millions of years. They guessed on questions which required knowledge of specific time scales (i.e. 5 mya or 50 mya), but often employed a convention of selecting the least, a moderate, or the longest amount of geologic time on such questions.

Lastly, students learned about the nature of theory, evidence, and tentativeness in science (the nature of science) after the course. Lectures on NOS occurred primarily during the first weeks of the semester, but the topic was touched upon on in the macroevolution unit. Dr. Wallace defined theory and discussed how science could change with new information during these early semester lessons. After the class, some students struggled with applying the definition of theory as an “explanation” to how evolutionary theory provided explanations for observed phenomena.

During the macroevolution unit, Dr. Wallace returned to the idea of science changing as she demonstrated how scientists’ ideas about ancient life could change when new fossils were found. Students related these fossil examples to their understanding of tentativeness during interviews, but some had concerns that tentativeness in science meant that scientists remained speculative about evolution. Similarly, others had concerns that theories held a lesser status in science because science could change with new information.

To what extent do non-science majors accept evolution before and after instruction?

Student acceptance of evolution was examined both quantitatively and qualitatively. This section describes the acceptance of evolution for the overall student population (N=270) through patterns in the quantitative data and looks in depth at the pre- and post-course evolution acceptance from the perspective of the interviewed students (n=12).

Influence of Instruction: Whole Class Data

Prior to instruction, students were generally accepting of evolution with an average MATE score of 70.21 ± 14.26 (20 = reject, 100 = accept); see Table 16. This mean score significantly increased after instruction ($p < .0001$). Data on the educational background of students were analyzed to determine the possible impact of past educational experiences on students' incoming evolution acceptance. This included one-way ANOVA tests comparing groups with different dates (Table 17) and durations (Table 18) of past evolution instruction and independent t-tests comparing groups that completed college coursework in geology, anthropology, and another biology course (Table 19).

Table 16

Descriptive Statistics for Pre- and Post-test MATE data. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE). (N=270)

Measure	Min (20.0)	Max (100.0)	*M (SD)*
MUM Pre-test	26.0	100.0	70.21 (14.26)
MUM Post-test	26.0	100.0	75.99 (13.96)

Date of most recent evolution instruction. A one-way ANOVA was used to test for pre- and post-test MUM differences among four groups of students by self-reported date of most recent evolution instruction (no previous instruction, elementary/middle school, high school, another college class). Scores did not differ significantly ($p < .05$) among the four groups for the pre- and post-tests (Table 17).

Table 17

One-Way ANOVA comparing Pre- and Post-test MATE scores by Date of Past Evolution Instruction. Group Means Tested: No Past Instruction, Elementary/Middle School, High School, and College. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE).

		SS	*df*	*MS*	*F*	*P*
MATE Pre-Test	Between Groups	1547.70	3	515.90	2.570	.055
	Within Groups	53001.18	264	200.76		
	Total	54548.88	267			
MATE Post-Test	Between Groups	930.74	3	310.25	1.605	.189
	Within Groups	51035.12	264	193.32		
	Total	51965.86	267			

Duration of most recent evolution course. A one-way ANOVA was used to test for pre- and post-test MUM differences among four groups of students by self-reported duration of most recent evolution instruction (no previous instruction, about 1 day, about 1 week, greater than 1 week). The sample size for this ANOVA was smaller than other tests as data from students that could not remember the duration of past evolution instruction were excluded. Scores differed significantly among the four groups for the pre- and post-tests (Table 18).

Since differences among the four groups were found in mean pre-test MATE scores, Tukey Honestly Significant Difference (HSD) post-hoc analyses were conducted to determine how the groups differed. These tests revealed that the scores of the “no previous instruction” group were significantly lower than “greater than 1 week” group

(Mean difference = -10.52, p = .017). No significant differences were found among any of the other groups at $\alpha < .05$.

Table 18

One-Way ANOVA comparing Pre- and Post-test MUM Scores by Duration of Past Evolution Instruction. Group Means Tested: No Past Instruction, About 1 Day, About 1 Week, and More Than 1 Week. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE).

		SS	*df*	*MS*	*F*	*P*
MUM Pre-Test	Between Groups	2603.35	3	867.78	4.106	.007**
	Within Groups	44175.28	209	211.37		
	Total	46778.63	212			
MUM Post-Test	Between Groups	1663.07	3	554.36	2.716	.046*
	Within Groups	42659.84	264	204.11		
	Total	44322.91	267			

Note. * = $p < .05$; ** = $p < .01$.

Similar post-hoc analyses of mean post-test MATE scores (Tukey HSD) revealed that the post-test MATE scores of the "about 1 week" group were significantly lower than the "more than 1 week" group (Mean difference = -6.15, p = .033). However, no significant differences were found among any of the other groups at $\alpha < .05$, including no significant difference between the "greater than 1 week" group and groups that received no instruction (p = .425) and about 1 day of instruction (p = .556).

It was odd that the group with more than 1 week of previous instruction significantly differed only from the "about 1 week" group and not also the "no instruction" nor "about 1 day" group. Since the post-hoc tests did not support the significant difference among groups found in the ANOVA, Scheffé post-hoc tests were conducted (an alternative single-step multiple comparison procedure) to confirm the results. These tests revealed no significant difference between any of the post-test MATE group means at $\alpha < .05$, including between the “about 1 week” and “greater than 1 week” groups ($p = .060$).

Prior college coursework. Independent sample t-tests were conducted to compare MATE scores between groups of students that did and did not have particular coursework. These tests explored the impact of a college course in geology, anthropology, and another biology course on students’ acceptance of evolution. As a side note, two students reported having evolution in another college class that had evolutionary content outside of biology, geology, and anthropology: each with about 1 day of evolution instruction. The statistics for this small group of (n=2) were not compared to the rest of the class.

Since sample size differed between each comparison group (e.g. Geology vs. No Geology), Levene’s tests for equality of variances were conducted. None of these tests were significant at alpha < .05, and therefore equal variances were assumed for each of the t-tests that follow. The t-tests revealed mean pre- and post-test MATE scores did not differ between students that had completed geology, anthropology or another biology course in college and those that had not completed such a course (Table 19).

Concurrent biology lab. Independent sample t-tests were conducted to compare MATE scores between groups of students that did and did not enroll in the laboratory portion of the introductory biology course. It was not required for students to be concurrently enrolled in the lecture and lab sections of the course and therefore only 34 students were concurrently enrolled in a lab section. Mean post-test MUM scores did not significantly differ between students that had enrolled in the biology lab and those had not (Table 20).

Table 19

Independent Sample t-tests Comparing Mean Pre- and Post-test MATE Scores Between Students that Completed Past College Coursework in Geology, Anthropology, or Another Biology Course and Those that had not Completed such a Course. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE)

	Past Instruction	N	*df*	*M*	*t*	*p*
Pre-MUM	No Geology	235	266	70.13 (14.49)	-.246	.806
	Geology	33		70.79 (13.00)		
Post-MUM	No Geology	235	266	75.63 (13.84)	-1.488	.138
	Geology	33		79.48 (14.50)		
Pre-MUM	No Anthropology	241	266	69.72 (14.52)	-1.685	.093
	Anthropology	27		74.59 (11.43)		
Post-MUM	No Anthropology	241	266	75.61 (14.06)	-1.739	.083
	Anthropology	27		80.52 (12.28)		
Pre-MUM	No Biology	212	266	70.24 (13.95)	.052	.959
	Biology	56		70.13 (15.67)		
Post-MUM	No Biology	212	266	76.14 (13.40)	.065	.948
	Biology	56		76.00 (15.99)		

Table 20

Independent Sample t-test Comparing Mean Post-Test MATE Scores Between Students Enrolled in the Optional Laboratory Section of the Biology Course Concurrently with Lecture and Those that did not. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE)

	Concurrent Instruction	N	*df*	*M (SD)*	*t*	*p*
Post-MUM	No Lab	234	266	75.89 (13.98)	-.661	.848
	Lab	34		77.59 (13.87)		

Evolution Acceptance Among Interviewed Students

Evolution acceptance among the twelve interviewed students varied in qualitatively different ways irrespective of students' pre- and post-test MATE scores. An analysis table of participants' pre- and post-instruction MATE scores with qualitative summaries for their evolution acceptance can be found in Appendix H and in summarized forms as Tables 21 and 22. Interviewed students' unit attendance, overall grade, and pre-/post-test MATE and MUM scores can be found in Appendix I.

Table 21

Participant Pseudonyms, Qualitative Determination of Incoming Evolution Acceptance, and Duration of Past Evolution Instruction and Pre-Instruction MATE scores of Interviewed Students. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE)

Pseudonym	Incoming acceptance per interview data (20=reject, 100=accept)	Pre-test MATE score	Duration of past evolution instruction
Mary	Reject	26	Less than 1 week
Nicholas	Reject	26	Less than 1 week
Ashley	Reject	34	About 1 day
Adrian	Reject	44	Less than 1 week
Bridget	Reject	45	Unknown
Beverly	Reject	58	More than 1 week
Amelia	Reject	61	None
Megan	Reject	62	Less than 1 week
Millie	Undecided	63	About 1 day
Nancy	Neutral	64	Unknown
Brooke	Neutral	65	None
Nathan	Undecided	69	About 1 day

Pre-Instruction Acceptance of Evolution

The interviewed students were selected for lower than average MATE scores and had average MATE scores of 51.42 ± 15.74 (Appendix I). The students' pre-instruction acceptance was relatively representative of their pre-test MATE scores (Table 21). Eight students, ranging in score from 26 to 62, rejected evolution prior to the class. Four students, ranging in score from 63 to 69, were undecided or neutral in their evolution acceptance prior to the class.

Religion was the predominating influence on students' acceptance on evolution prior to instruction. Ten students described themselves as religious, six of whom rejected evolution on the basis of religious conflict. Nine students had concerns about the validity of science such as perceptions of counterevidence and/or perceived controversy surrounding evolution. Two students rejected evolution exclusively on the grounds of these concerns (both of whom were religious).

Students that rejected evolution. Seven students rejected evolution prior to the course, five of whom did so on the basis of their religion and two on the basis of concerns about the validity of science. Although ten participants described themselves as religious, only six of these individuals described their initial rejection of evolution as based on these religious beliefs.

Religious influences from home and church. Megan and Amelia had religious influences from family and church, and had learned little about evolution in school. Megan had a Greek Orthodox mother, a "super Catholic" father, and had been going to church every Sunday since she was born. She basically "grew up in a church" (p. 2). Although Megan attended a public high school, her general biology course did not teach evolution. "My view was very religious. So I thought God created heaven and Earth and everything" (Megan, p. 2). Like Megan, Amelia did not learn evolution in her high school biology class (although she attended a Catholic high school). Amelia described that her rejection of evolution prior to the course was based on the principles of her high school - God created all life and humans did not evolve.

> I came from a really strict Catholic high school, they kind of just focused on . . . we didn't evolve, God created us and that's how we came here, God created everything. So we didn't really didn't believe that evolution was something that happened. (Amelia, p. 1)

Generally religious individuals. Bridget and Beverly, like Megan and Amelia, had not learned much evolution in school. Bridget learned about evolution at church, where they emphasized “everything was here from the beginning and there are no changes to animals” (p. 1). Her perception from prior to the class was that evolution claimed humans came from monkeys and that evolution was “just a theory” (p. 1). Bridget therefore initially rejected evolution. “[I was] kind of against the theory of evolution . . . So like monkeys and humans, that thing that didn’t really make sense to me, so it was just scientific theory that I didn’t accept” (Bridget, p. 1).

Beverly did not learn about evolution at church, but described herself as religious and rejected evolution prior to the class because she thought there was conflict between evolution and religion. Although she had learned about evolution in a public high school, she did not recall much about it. She said she would always prioritize her religious beliefs although she knew there was evidence for evolution. However, Beverly was unsure if the official position of her religion was against evolution.

> Like I mean I believe in my religion first. I know why, evolution does have good evidence, but I’ll always go with my religion. . . I don’t know like that’s what my religion like I believe in it, but I don’t know. It’s just – I can’t really put it together. (Beverly, p. 1)

Religious influences from home and K-8, evolution in high school. Mary and

Adrian had strong religious influences from home and both had learned creationism attending Christian schools Kindergarten through eighth grade, but learned evolution in public high schools. Mary had a very religious family and, like Bridget, attended a church with an active antievolution stance. During high school youth group, she had watched a video series with a creation scientist who refuted evolution through his own research. Her primary reason for rejecting evolution was that it was against her beliefs, although she also thought that evolution was scientifically inaccurate due to the creation science video series (see *Perceptions of counterevidence*). “I didn't believe it before. I guess I didn't believe it but I had no real reason except for my own beliefs” (Mary, p. 4).

Adrian described himself as religious and remarked that he was trying to focus more on his beliefs now that he was in college. His grandmother had told him to “keep God in your life” (p. 23), and he wanted to follow her advice. Unlike Mary and Bridget, Adrian did not attend a church that discussed evolution. Instead, like Beverly, Adrian’s primary reason for rejecting evolution was a view that religion and science were incompatible.

> Being a religious person it kind of makes me be a little more conservative as well when it comes to science, I feel like science does a lot of things and then there's religion. And they don't really coincide a lot. (Adrian, p. 3)

Rejection due to scientific concerns. Nicholas and Ashley described themselves as religious but rejected evolution prior to the course because they had concerns about its scientific validity. Nicholas took a theistic view of evolution both before and after the course. This view was based on advice from his father. Nicholas came from a religious Christian family but also had been brought up by his father to be a “smart person” (p. 3) that thought through things using logic. He knew there was substantial evidence for evolution and felt he should not ignore this evidence despite his religious beliefs.

> So I can't deny that God created the Earth because that would be just going against everything that I actually believe as a Christian, but I can't also deny the evidence that's shown to me on one hand of you know, the Earth did evolve. (Nicholas, p. 3)

I categorized Nicholas as rejecting of evolution despite his theistic view because he had concerns about the validity of evolutionary science. He attended a public high school that taught evolution for about 1 week, and described his high school biology teacher as a "wonky 70-year-old man" (p. 5). He was unsure about the validity of the biological facts taught by his teacher because he used antiquated materials. Furthermore, Nicholas had done some online research about carbon dating and believed that carbon dating was an inaccurate measurement of deep time (see *Perceptions of counterevidence)*. It was for these two reasons that he believed he could not completely accept evolution.

Ashley had a similar religious upbringing as Nicholas and also attended a public high school that taught evolution. Her high school biology teacher spent only one or two class periods on evolution and seemed to "not want to spend much time on it" (p. 2). Ashley recalled that the evolution facts she did learn were about the history of Darwin and not about evidence or mechanisms of evolution. Like Nicholas, Ashley did not reject evolution based on religion, although she believed that the Earth was less than 20,000 years old. Rather, she was distrusting of evolution prior to the class because she did not think there was much evidence for evolution and did not understand how scientists could tell if organisms evolved.

I didn't know how people could even tell if things evolved or not because you're not, nobody's around long enough to see that. So I assumed nobody would like, I mean others, older scientists could write down something then you can see it but I just thought there's no way to like, nobody's alive for a billion years and can see what evolving and what not. So I didn't think there was that much evidence. (Ashley, p. 14)

Undecided students and students with no opinion. Four participants, Brooke, Nancy, Nathan, and Millie, claimed to have either no opinion on evolution (*n*=2) or felt undecided about their views of evolution prior to instruction (*n*=2). This group gave multiple reasons behind their views including noting that they lacked background knowledge on the topic (*n*=3), had not taken the opportunity to think about evolution before (*n*=2), or did not have strong religious views (*n*=1).

Students with no opinion. Brooke and Nancy described themselves as lacking knowledge of evolution prior to the course and explained that they subsequently did not have an opinion about evolution. Brooke had no previous evolution instruction and stated that although she took biology in a public high school, she did not learn about evolution. She explained that since she was not incredibly religious and was also uninformed about evolution as a science, she had no opinion about evolution.

I'm not incredibly religious, so I didn’t have like some like really strong belief behind it . . . I wasn’t like against it or anything like that before but I just didn’t, I was so uninformed about that I wouldn’t have agreed with anything that was said. (Brooke, p. 1)

Nancy had been taught evolution in a public high school but did not recall anything about evolution information from the biology course. She attributed her lack of prior knowledge to poor study habits. Prior to the course, Nancy said that she "kind of" believed that humans came from chimps, since humans and chimps had similar characteristics. Nancy also described believing in the Bible, but did not associate her religious views with her incoming opinions about evolution.

> I really didn't have any [opinions]. So they weren't like negative or I believe this or I don't believe that . . . Just like saying how like with the chimps evolving into humans. I kind of believe it because we have like similar characteristics. (Nancy, p. 1)

Undecided students. The two remaining participants, Nathan and Millie, had undecided opinions about evolution. Their views were different than the two students with no opinion because they had contradictory statements about their evolution acceptance and overall did not articulate a clear position prior to the course.

Nathan attended a public high school that taught evolution for about a week but remembered little about the class. He described his views of evolution in nuanced ways that demonstrated multiple but unclear views of evolution. He said that he believed evolution was happening and also thought it could be true, but also said that the evidence did not seem right or could not be real. I categorized Nathan as undecided in his evolution acceptance due to the nature of his conflicting statements.

Evolution was a little sketchy to me and I didn't really believe it. When you ask other students or something they say it can't be real, it's not right. But I always thought that I don't know why couldn't be, I don't look at the evidence or I thought it was – it could be true, I was open whatever. . . I've heard people say that they just they don't want to talk about it or why would you believe that if you are Christian or something like that. (Nathan, p. 10)

Millie's data were difficult to interpret because her statements lacked logical coherency. She gave broad generalizations and provided little detail behind why she thought as she did. Furthermore, she did not provide much clear information about what she actually understood or believed, especially prior to the course.

Millie's background before the class was somewhat similar to Nathan. She attended a public high school that taught evolution but could not remember much from the course. Millie never clearly articulated her incoming acceptance of evolution during the interview. When asked about her opinion of evolution before the course, she said that she did not understand evolution beforehand (describing her knowledge about evolution but not acceptance stance) and then described the how other people had views against evolution. "I guess some people don't believe certain things like humans come from a different ancestor or something like that. . . I guess they don't want to believe it or they don't have any knowledge towards it I guess" (Millie, p. 2).

Since Millie's interview data were difficult to interpret, I investigated her MATE data to confirm the undecided nature of her pre-instruction acceptance. Her MATE data were likewise contradicted itself, and indicated that prior to instruction that she had mixed views about evolution. Millie was undecided for 11 of 20 statements on the pre-test MATE and several of her views conflicted one another. For example, she agreed that the Earth was less than 20,000 years old, but was undecided if the Earth was more than 4 billion years old. She also agreed "the theory of evolution is based on speculation and not valid scientific observation and testing" but also agreed "current evolutionary theory is the result of sound scientific research and methodology." For this reason, I categorized Millie as having an *undecided* opinion about evolution prior to the course.

Concerns about evolution as valid science. Nine of the interviewed students had incoming concerns about whether evolution was valid science. These were linchpins of rejection for Nicholas and Ashley and contributed to the incoming views of seven other participants. These concerns included ideas about counterevidence (n=3) and the perception that evolution is controversial (n=7). When these validity concerns are considered in tandem with students' religious concerns about evolution (n=10) and the difficulties students encountered during instruction with historical evidence (n=7) and nature of science (n=6) (see *Influence of Instruction*), all of the interviewed students had one or more reasons to perceive evolution as invalid science prior to instruction. These barriers are discussed in Chapter Five.

The role of counterevidence. Three students cited counterevidence as a reason for their hesitance to accept evolution. Two students, Mary and Nicholas, were versed in specific examples of "counterevidence" from the intelligent design movement. Mary learned these ideas from a creation science video series she watched at her high school youth group. She cited counterevidence that evolution broke the second law of thermodynamics, that ancient fossils could be generated over a short period of time, and that there were trees which spanned multiple geologic layers of rock. Mary also commented that she reconfirmed her knowledge of counterevidence after the evolution unit by going online. She felt compelled to do this "because actually a lot of stuff Dr. Wallace taught in class was convincing and I've been brought up in the way it was like the exact opposite" (p. 5).

Nicholas had also read about evolution evidence online and likewise believed there was counterevidence for evolution. He believed that carbon dating was an unreliable yet highly relied upon form of evidence for documenting the age of the Earth and that erosion by water could occur over a short time span but create effects which appear to be millions of years old.

> If carbon dating has to with like anything in that, that science is a gray area to me. If you like, a lot of times there's un-looked-at issues in carbon dating so I don't feel like their time of how long the Earth's been here is incredibly accurate. (Nicholas, p. 7)

Unlike Mary and Nicholas, Brooke did not cite particular examples of counterevidence, but was concerned that reliable evidence against evolution could exist. “There could be available data that says that evolution doesn’t happen. I probably just felt like I wasn’t informed enough to answer.” (Brooke, p. 24)

Evolution in school and the perception of controversy. Seven students had past educational experiences that influenced them to perceive evolution as a controversial topic.

Private school students. Mary, Adrian, and Amelia attended private religious schools and stated that evolution was not discussed in their school. Mary and Adrian went on to learn about evolution in public schools. All three participants thought since evolution was not taught in private schools, it must be taught in public schools only. Amelia rejected evolution on religious grounds prior to the course and saw evolution something not discussed by Catholic schools. She explained that her lack of evolution education was because she did not attend public school. “They just said you know, we're a Catholic high school, we don't talk about evolution.” (p. 1)

Mary and Adrian both attended private schools from Kindergarten through 8th grade but then learned about evolution at public high schools. They saw the two school systems as having conflicting views on evolution, and this influenced them to believe there were two opposing evolution factions. Both initially rejected evolution on grounds that evolution conflicted with their religion. Adrian rejected evolution because he thought that the two views could not coincide. He had developed these beliefs because evolution was taught as speculative at his religious school but was taught as legitimate science in high school.

> My private school taught it as a theory, nothing factual because obviously they taught creation and that whole deal. Then I went to public school for high school and that's when they actually taught it as like a legitimate like this is how the Earth came. (Adrian, p. 1)

Mary likewise perceived a conflicting relationship between religion and science from her two different school experiences. “I went to a Christian elementary school and then a public high school so obviously two different viewpoints there” (Mary, p. 1). Her religious school taught creationism and her high school taught evolution.

Public school students. Four of the eleven students (Ashley, Megan, Brooke, and Bridget) attended public schools but were not taught evolution or had little evolution instruction. Interestingly, all four believed that they could not be taught evolution *because* they attended public school. Ashley attended high school at a suburban school of about 2,000 students near a large metropolitan area in the Midwest. She described her high school biology teacher as hesitant to teach evolution because “not everyone was supposed to learn it". She had to bring a signed permission slip from home to attend the evolution unit of one to two class periods, which focusing primarily on the history of Darwin. She believed her teacher's hesitance to teach evolution may have been due to pressure from the school board.

> I remember my high school teacher saying that he wasn't, they weren't, like they didn't really want them to teach it. I think the school board like had a problem. He always said it was not something that everybody was supposed to learn or something. So I think he wanted to not spend much time on it. (Ashley, p. 2)

Brooke attended a public high school in different large metropolitan area in the Midwest and also was under the impression that evolution could not be taught because it might offend students. No evolution was taught in her high school biology class.

214

> I went to a public school. . . they weren't allowed to talk about it because it might offend some people because depending on the religious beliefs or backgrounds, something they could only teach in private schools because that was different it was like based on certain religious beliefs so they were allowed to talk about it, but for us they didn't want to like expose it to us I guess. (Brooke, p. 1)

Megan attended a public high school in the same metropolitan area as Brooke, although at a different high school. Her high school biology class did not teach evolution because the topic was seen as controversial and the teachers "did not want to impose on any religious people" (p. 1). Megan was also puzzled why her brother likewise did not learn about evolution at his private school.

> I think [we did not talk about evolution] because it's a public school, it can be

kind of controversial how like people feel about it. And I know my brother went to private school and they didn't teach them evolution either. I don't know why the reasoning is behind it, but they touch in more general things. (Megan, p. 1)

Quantitative MATE patterns evident in the qualitative data. It was difficult to make qualitative comparisons between students on the basis of significant differences in pre-test MATE scores. Pre-test MATE scores only significantly differed (p=.007) between students with more than one week of previous instruction (Beverly) and those with no previous instruction (Brooke and Amelia). Since Beverly rejected evolution prior to instruction, and Brooke and Amelia were split between neutral (Brooke) and rejecting (Amelia), no qualitative data were available to support why the group with more than one week of instruction was more accepting of evolution than the group with no previous instruction.

Post-Instruction Acceptance of Evolution

After the course, the class significantly increased their acceptance of evolution (*p*<.0001) to an average MATE score of 76.11 ± 13.95 (20 = reject, 100 = accept). The interviewed students saw a similar shift toward acceptance (62.64 ± 12.75). Among the students interviewed, half made gains on the MATE in regard to their acceptance of evolution and half did not. The students recruited for gains on the MATE (Δ≥9 points) were Adrian, Ashley and Amelia (acceptance only) and Bridget, Brooke, and Beverly (gains in both acceptance and knowledge of macroevolution). The students were recruited for no MATE gain (Δ ≤ 3 points) were Millie, Megan, and Mary (gains in knowledge of macroevolution only) and Nathan, Nancy, and Nicholas (gains on neither instrument).

Qualitative analysis of student interview data revealed that post-test MATE scores were relatively indicative of the nature of evolution acceptance for each student. Mary, Nathan, and Millie had post-test MATE scores of 61 or below and rejected evolution. Nicholas' post-test MATE score (26) should have indicated a similar rejection, but he reported hurrying through the MATE to submit it on time and described a theistic view on evolution during his interview. Amelia, Adriana and Brooke had post-test scores of 70 or above. They either accepted evolution or took a theistic view of evolution. Beverly likewise had a post-test score which should have indicated acceptance (73), but remained conflicted between her personal beliefs and evolution. Between the individuals in the individuals that rejected evolution (below 61) and accepted evolution (70 and above), there was a range of four students with post-test MATE scores of 60 to 65 who were conflicted about evolution (Table 22).

Table 22

Participant Pseudonyms, Qualitative Determination of Post-Instruction Evolution Acceptance, Pre- and Post-Instruction MATE Scores of Interviewed Students. Abbreviation: Measure of Acceptance of the Theory of Evolution (MATE)

Pseudonym	Incoming acceptance by qualitative determination	Pre-Test MATE (20 = reject, 100 = accept)	Post-Test MATE (20 = reject, 100 = accept)	Outgoing acceptance by qualitative determination
Nicholas	Reject	26	26*	Religion and science can co-exist
Mary	Reject	26	29	Reject
Nathan	Undecided	69	58	Reject
Megan	Reject	62	60	Conflicted between two views
Bridget	Neutral	45	61	Conflicted between two views
Millie	Undecided	63	61	Reject
Nancy	Neutral	64	64	Conflicted between two views
Ashley	Reject	34	65	Conflicted between two views
Amelia	Reject	44	70	Accept
Adrian	Reject	61	70	Religion and science can co-exist
Beverly	Neutral	58	73	Conflicted between two views
Brooke	Neutral	65	78	Accept

Note. * = student indicated rushing to complete the survey, value may not correctly represent acceptance.

Acceptance of evolution, excluding humans. Students described acceptance of evolution separately from than their acceptance of human evolution. The first section describes students' overall acceptance of evolution but excludes their beliefs about human evolution. The subsequent section describes themes in interviewed students' acceptance of human evolution. After the course, six students recognized (at least in part) the validity of evolution, but saw conflict between evolution and their religious beliefs. These students would compare their personal beliefs with scientific facts from class and try to make a choice between evolution and religion. In this process, students would try to qualify which explanation of the natural world was correct. They did not consider that the two views could potentially be compatible.

From religious rejection to conflicted. Megan, Beverly, and Bridget rejected evolution prior to the course due to their religious beliefs about the age of the Earth. Megan had a religious upbringing from her Greek Orthodox mother and had not learned about evolution in school. After instruction, Megan recognized that "you cannot ignore the evidence, the fossils, all of that" (p. 2) and said that she could see that geological processes take millions of years to occur. However, she remarked that this was difficult to accept because as a child she believed the Earth was created in seven days. Megan remarked that her opinions about evolution were changing, but that she had not yet "sorted out" her feelings.

> Oh, it's so hard because as I'm getting older, I'm – my opinions are changing. When I was a kid, I thought the whole Earth is created in seven days. I thought that God did everything instantly, but now that I see it's a longer process, so I don't really know how to sort out of my feelings at that one. (Megan, p. 31)

Bridget rejected evolution before the course due to antievolution teachings from her church which depicted evolution as just a theory. "Even though the Bible said it's not that long that the age of Earth isn't that long and that old, fossils are still recorded" (Bridget, p. 22). Like Megan, Bridget found conflict between the evidence that fossils were millions of years old and the Bible that said the Earth was not that old. This created two separate worldviews that Bridget was torn between - scientists could be correct and the Earth could be millions of years old, or the Bible could be correct that Earth was young. "So [evolution and religion] are still two topics in my mind. So that's why I am undecided." (Bridget, p. 22)

Beverly initially rejected evolution because she was religious and said she would "always go with my religion" (p. 1). "I think it's scientifically valid, but then I put undecided because like I said before between religion and stuff' (Beverly, p. 21). Beverly continued to maintain a religious view after the course, but recognized the quantity of evidence supporting evolution and thought that evolution was scientifically valid. Although Beverly continued to "support religion" (p. 23), she also recognized the validity of evolution. Since Beverly was trying to determine which explanation was "right" (evolution or religion), she was categorized as having a conflicted view about evolution. "So I mean there is so much evidence supporting evolution, but based of like Biblical stuff I can't really like determine what is right in that, so I'm really undecided if it is scientifically valid" (Beverly, p. 21).

From scientific rejection to conflicted. Prior to the course, both Ashley and Nicholas rejected evolution due to concerns about the validity of evolution science. Ashley rejected evolution due to perceptions of a lack of evidence and that she did not know how to tell if organisms were evolving. She also had strong perceptions about evolution controversy since her evolution unit required a permission slip. After the course, Ashley recognized that there actually was substantial evidence for evolution and therefore knew that evolution was real. "I'm saying is now that I see that people have evidence and it doesn't take as long as I thought for some things to evolve, we can see that evolution is real" (Ashley, p. 14).

Like Megan and Bridget, Ashley saw conflict between her view that the Earth was 20,000 years and her newfound knowledge about evidence for evolution. After the course, she had a conversation with her mother to confirm whether her religion specifically said the Earth was young, because she had learned in class that dinosaurs and humans did not exist at the same time. “I've heard my teacher say that dinosaurs were on the Earth before the humans were. And then I didn't understand how that made any sense” (Ashley, p. 17). Since Ashley became conflicted between the facts she had learned from class and their seeming incongruence with her beliefs about the age of the Earth, she was categorized as having conflicted views. “So I assumed that dinosaurs and Adam and Eve must have been on the Earth at the same time. Which wouldn't have been. I don’t know.” (Ashley, p. 18)

From neutral to conflicted. The fifth student with a conflicted view about evolution after the course was Nancy, who had a neutral opinion of evolution prior to the course. Nancy had religious beliefs but chose a previously neutral view because she did not have scientific knowledge of the topic. Like other conflicted students, Nancy found conflict between facts about evolution she learned from class and her knowledge of Biblical scripture. Since she described trying to make a decision between evolution and the Bible by whichever was correct, Nancy was categorized as having a conflicted view of evolution after instruction.

> It’s kind of hard because I do believe in the Bible and I do believe everything in the Bible and then after learning all this information, it kind of makes me think twice . . . it’s kind of hard to really say this is right and that is wrong. (Nancy, pp. 16-17)

Continuing to reject evolution. Three students, Mary, Millie, and Nathan, rejected evolution after instruction. Mary understood macroevolution after the course. This was evident in nature of her explanations about her MUM answers, post-test MUM score (17 of 27) and high overall course grade (94.2%). Although she recognized that there was extensive evidence for evolution, Mary rejection of evolution did not change after the course. She continued to be influenced by her religious upbringing from both home and private school, the counterevidence she learned from her church youth group, and her own online research about counterevidence. “So now I actually know about it and my beliefs haven't changed, I guess that's good. Just because of how I've grown up and my background, it's not what I've grown up believing” (Mary, p. 4). Mary found comfort in the fact that her views about evolution did not change although she knew more about it.

Nathan and Millie rejected evolution post-instruction but were undecided about evolution prior due to inconclusive and conflicting evolutionary views. After instruction, Nathan decreased his MATE score from 69 (pre) to 58 (post). He was the only interviewed participant to demonstrate a quantitative decrease in acceptance. Nathan claimed his rejection of evolution was because there was little evidence for evolution, a statement which ran counter to the extensive volume of evidence described by ten other participants. Nathan instead thought the evidence Dr. Wallace presented in class was about “something else” (see *Interaction* section for representative quote). Based on Nathan’s difficulty rationale behind his responses on the MUM, he seemed to not understand macroevolution (as indicated in interviews and by MUM post-test score 5 of 27) and did not seem to notice the volume of evidence for evolution presented in class. Nathan attended class during the two days that evolution evidence was presented and had an overall course grade of 82.5%.

Similar to Nathan, Millie’s rejection of evolution after the course was also based on a perception that there was little evidence to support evolution. Her interview responses indicated a below average understanding about macroevolution (10 of 27), and were qualitatively different from Nathan, i.e. they had other scientific misconceptions and logical fallacies. “I feel there should be more evidence on evolution because we don’t really know what happened back then . . . I feel it's not really a “for sure” answer to prove if it's evolution or not” (Millie, p. 18).

Millie thought that evidence did not imply “proof” and also had difficulty conceptualizing how scientists knew evolution occurred since “nobody was alive then.” Millie’s overall course grade (60.6%) reflected her low understanding of the biological content. Although Millie was a freshman in spring 2012, she was no longer enrolled in the university by spring 2013.

Accepting evolution. Brooke and Amelia were the only interviewed students that accepted evolution after the course. Brooke previously described no religious views and had not been taught evolution before. However, she did have incoming concerns that counterevidence for evolution might exist. After instruction, Brooke recognized that the scientific perspective on evolution was valid and did not describe another view as equally valid. She did not use religious explanations during her interviews. “I was pretty much convinced I suppose you could say by the evidence and things that we’ve learned that it obviously happens” (Brooke, p. 24).

Unlike Brooke, Amelia initially rejected evolution due to religious concerns. She had attended a religious high school which focused on creation. Although Amelia remained uncertain whether evolution contradicted the Biblical account of creation, she repeated her acceptance throughout the interview by citing examples of evidence from class and how this evidence informed her view that evolution was scientifically valid.

In class we talked about how, like I said before, single-celled organisms evolved and then multi-cellular organisms evolved and amphibians and then all these other things so, that's why I strongly disagree that [organisms all appeared at the same time]. Because they didn't all happen at the same time. (Amelia, p. 11)

Students with both religious and evolutionary explanations. After the course, both Adrian and Nicholas students saw religious and science as equally valid explanations of the natural world. Both men came into the course discussing separate scientific and religious worldviews. Adrian thought religion and science conflicted with one another and therefore rejected evolution. Nicholas thought evolution and religion agreed with one another but rejected evolution due to concerns about counterevidence a distrust of science as taught by his “wonky” high school biology teacher.

After instruction, Adrian discussed the merits of science and agreed that species change over time. He also had learned in class that religion and science could work together and therefore overcame his conception that the two worldviews were incompatible. Dr. Wallace’s discussion of the Clergy Letter Project influenced Adrian to realize that a number of people believed both religion and evolution. This directly addressed his concerns about compatibility from prior to the class.

I don't believe any more that [evolution] completely contradicts what the Bible says. In this class I learned that religion and science actually can work together and it'll be okay. I can understand and I agree with the fact that we can descend, we change as species. (Adrian, p. 3)

Nicholas continued to hold both scientific and religious explanations after instruction. “I still do believe the same thing, I still do believe that the Earth was created by God to evolve as certain things happen" (Nicholas, p. 1). In the course, he gained trust of the evidence for evolution through respect for the expertise of his instructor. "[Dr. Wallace] has a higher education and went into much more detail and much more, you know, showed me more evidence so that I do, I do believe stronger in the fact that the Earth has been evolving" (Nicholas, p. 2). Nicholas continued to have some reservations about carbon dating after the class. However, since he described believing more so in the validity of the science as a result of the class and believed both evolution and science were equally true, he was categorized as having both worldviews.

Acceptance of Human Evolution

Several of the students who shifted toward accepting evolution did so for animal evolution only, i.e. not human evolution. Five students did not accept human evolution, four thought humans might evolve and only three agreed that humans evolve. The three students that accepted human evolution were not the same students that accepted evolution for animals, with the exception of Brooke.

I agree that humans have evolved. Like the students who described reasons for their overall acceptance of evolution, Megan and Brooke accepted human evolution due to specific examples of fossil evidence from class. Megan, who was generally conflicted about evolution and religion due to a religious upbringing, agreed that human evolution was valid. She supported this claim by discussing the sequence of intermediate humanoid skulls and jaws presented in class.

> I just see on the skeletons how human faces has been flattened, because like I said the jaws of the people that lived like a lot before us stuck out a lot more. And then eventually our faces flattened. . . She showed us a bunch of different fossils from

early primates to what we are today. So it’s apparent in fossils. (Megan, p. 4)

Brooke also described her acceptance of human evolution in relation to fossil evidence. “[Dr. Wallace] is like we’re all from Africa. Like I think of it, we are all like from the same ancestor which derived from Africa. There’s fossils for this.” (Brooke, p. 12). Brooke acknowledged the validity of human evolution because of fossil remains of the human migration out of Africa.

Rejection of human evolution. The five students that completely rejected human evolution rationalized their thoughts in three primary ways. Some discounted human evolution by misrepresenting ideas learned in class (*n*=3), others saw humans as special or unique in comparison to animals (*n*=4), and two conceptualized humans only from their moment of creation and therefore did not see evidence of macroevolutionary change in humans.

Misusing facts from class to refute human evolution. Beverly, Ashley, and Mary used information presented in class about human evolution to rationalize their rejection of human evolution after the course. Ashley used the biological definition of species learned in class to delineate humans by definition as a species that could not successfully mate with other species. Ashley then incorrectly rationalized since humans were their own species could not mate with other animals (species), humans must not have evolved from animals.

> I don't think that humans can, maybe it's an animal thing. I don't, we, there's the nothing for us evolve with. Because all humans are the same. If that makes sense. Like we can't like, humans don't like mate with animals so I don't know we could change into something else. Because there's no other species of humans, right?

(Ashley, p. 15)

Beverly likewise misunderstood a concept from class and used the idea to refute human evolution. Common ancestry between human and apes was emphasized in class to refute the misconception that humans “came from monkeys”. Beverly interpreted common ancestry to therefore be a different concept than relatedness. Beverly agreed that humans and chimps shared a common ancestor but then mistakenly thought that because they shared a common ancestor, the species were actually not related. “We learned specifically that chimps and humans are not related. They just have a common or recent common ancestor.” (Beverly, p. 13)

Mary also misinterpreted information from class to incorrectly answer Question 22 on the MUM regarding Figure 5, the great ape tree. Mary knew that Dr. Wallace had explained how several human species had gone extinct. “Humans remain at the top of the tree because she taught us that everything has gone extinct but humans are still going” (Mary, p. 10). She interpreted this sentence to imply that some human species had gone extinct while others had not. She had learned that *Homo sapiens* were the only living humanoid species, and therefore inferred that they must be at the “top of the tree”.

Human superiority.

In addition to their misuse of facts from class, Mary and Beverly (as well as Nicholas and Adrian) viewed humans are superior to other forms of life. All four students had religious backgrounds and rejected evolution prior to the course on account of their religious beliefs (Mary, Beverly, Adrian) or perceptions of science as invalid (Nicholas). Mary discredited human evolution by describing animals and humans as physically and cognitively different. “How my brain works and everything, all of our functions in our body and how we can speak and have such a incredible language and stuff, and monkeys don't have the ability to talk and think like we do" (Mary, p. 4). It was therefore illogical to Mary to think that humans and monkeys should could share a common ancestor (although she was also very religious).

Adrian, Nicholas, and Beverly each described humans as 'above' other animals. Adrian used his religious beliefs to argue that humans were created to be dominant over other creatures and were therefore at the top of the food chain. "I feel like we were made and we were made to be dominant over, not just monkeys, but all animals. And therefore we are at the top of the food chain" (Adrian, p. 5). Similarly, Nicholas stating that he saw humans as "severely above animals", and also commented that he thought the science about human evolution was incorrect. Beverly likewise saw humans as "more complex" than animals. She did not explain her stance on religion or concerns about evidence, but rather said she simply "wouldn't classify humans as apes" (p. 5).

Humans have evolved since their creation. Adrian and Nicholas rejected human ancestry on grounds of human superiority, but also rejected their evolution because they did not think there was evidence that humans had undergone speciation. They only conceptualized humans after their moment of speciation (creation). This is congruent with their blended views of religion and evolution for non-human evolution. Both Adrian and Nicholas believed that God directed evolution, and this worldview included the possibility that humans had been created and then evolved. Nicholas explained his views of human evolution by describing that humans have undergone changes since today's detrimental environmental conditions did not exist in "Bible times." He therefore believed humans had selection in response to environmental changes, but continued to believe humans did not evolve from apes.

> Humans have had changes since Bible times to me, it was like rich and it was awesome. Versus our atmosphere now it's kind of sketch because of everything we've done to it. . . But I don’t think that they came from apes. (Nicholas, p. 17)

Adrian likewise described that he supported small (microevolutionary) changes in humans, but did not support human-ape common ancestry. “There may have been subtle changes in I guess our genetic makeup, and that that may have forced us to change a little bit, but I don't know want to say completely that yes, we have evolved” (Adrian, p. 14). Since Adrian had previously indicated that he thought humans were created to be superior to animals, but also thought humans had undergone small changes, a view on human creation followed by allelic changes (but not speciation) best describes Adrian’s views.

Student Acceptance Summary

Prior to the class, eight interviewed students rejected evolution and four were neutral or undecided. Students were influenced primarily by their religious backgrounds, but also were influenced by concerns about the validity of evolution and perceptions of counterevidence. They were also influenced by high school biology instruction that portrayed evolution as controversial. Their teachers communicated this controversy by excluding or minimizing evolution content, giving disclaimers prior to evolution units, and/or requiring permission slips.

After the class, nine students became more accepting of evolution. These shifts in acceptance were most pronounced when students’ specific concerns about evolution were directly addressed by the course. Amelia and Brooke lacked previous knowledge on evolution and chose to accept evolution due to the volume of evidence presented in class. Nicholas distrusted the accuracy of facts taught by his "wonky" high school teacher, but trusted the validity of Dr. Wallace's evidence for evolution due to her status as a PhD faculty member. He subsequently moved from rejecting evolution to a theistic evolutionary view. Adrian rejected evolution because he thought evolution and religion could not coincide, and was then influenced by learning about the Clergy Letter Project in class (signed statements of evolution support by clergy).

Five students remained conflicted about evolution after the course, unsure if evolution and their religious beliefs could both be correct. These students saw the evidence for evolution but had difficulty reconciling the information with their religious views.

Three students rejected evolution after the course, only one of whom rejected evolution beforehand. Mary understood the evidence for evolution but had so many influences counter to this information from her family, church, and past school experiences, that she did not shift her evolution acceptance. The other two individuals, Millie and Nathan, were undecided about evolution prior to the course. Neither student seemed to understand evolution after the course and rationalized their views toward rejecting evolution by claiming a lack of evolution evidence (Nathan) or claiming that historical evidence is impossible to obtain (Millie).

What is the relationship between students knowledge of macroevolution and acceptance?

The relationship between students' knowledge of macroevolution and acceptance was examined both quantitatively and qualitatively. This section describes students' knowledge of macroevolution for the overall student population (N=270) through quantitative analysis and looks in depth at the potential sources of correlation between these two knowledge bases from the perspective of the interviewed students (*n*=12).

My approach answering this research question was to first examine the quantitative data for evidence of the correlations both before and after instruction. However, since I interviewed students with little incoming knowledge of macroevolution, the interview data only provided reasons for a post-instruction correlation. The reasons for a post-instruction correlation were supported by themes in the interview data for the nine interviewed students fit the post-test correlation model.

The second step to answering the research question was to examine data for the three interviewed students with scores that did not match the correlation model. After instruction, two participants had mid-range MATE scores with low MUM scores and one had mid-range MUM score with low MATE scores. I therefore examined the interview data for these individuals with the goal of understanding reasons for a lack of correlation between knowledge of macroevolution and evolution acceptance.

The results of this section are convergent to those for the influence of the instruction. This is because the instruction influenced knowledge of macroevolution and this section documents quantitative and qualitative support for the correlation between these two pieces. I kept this section in the dissertation to answer the research question regarding correlation, but merge the findings for interaction (correlation) and influence of the instruction in Chapter Five.

Overall Correlation Data

Prior to instruction, acceptance of evolution and knowledge of macroevolution were correlated for the class, $r(268) = .448$; $p < .01$ (Figure 12). There was also a correlation after instruction, $r(268) = .490$; $p < .01$ (Figure 13). This indicates that after

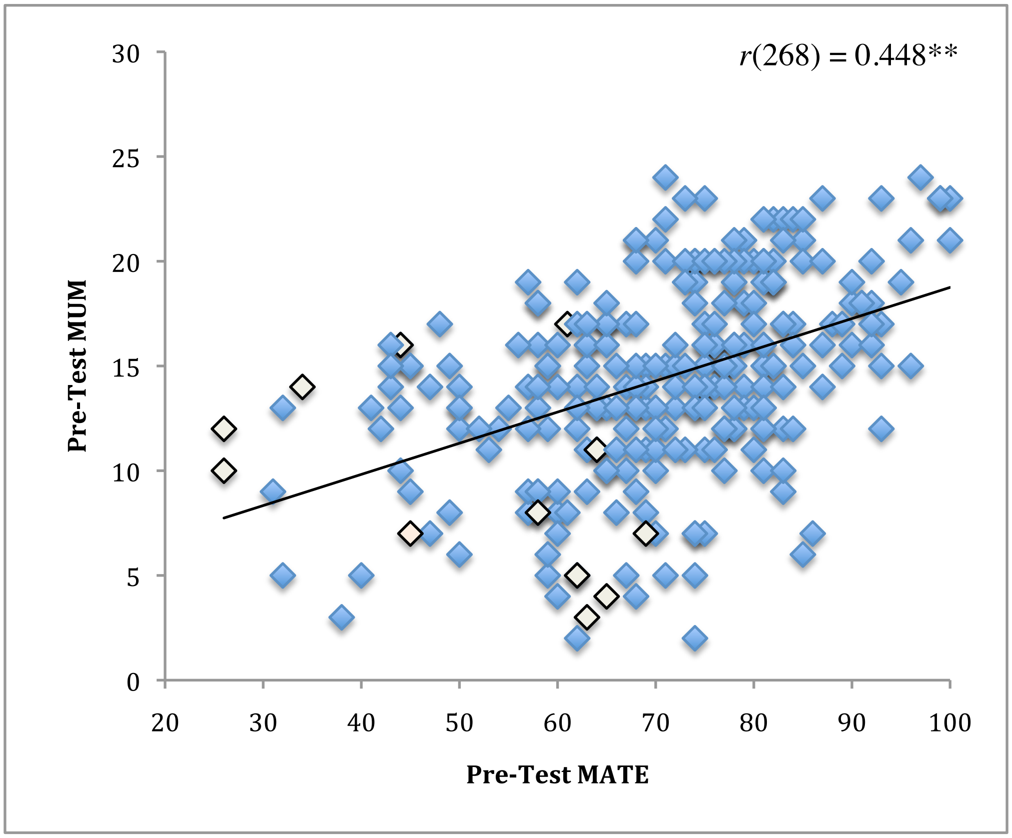


Figure 12. Pre-instruction MATE and MUM scores for non-interviewed students (◆) and interviewed students (◇). Abbreviations: Measure of Understanding of Macroevolution (MUM), Measure of Acceptance of the Theory of Evolution (MATE). N=270.

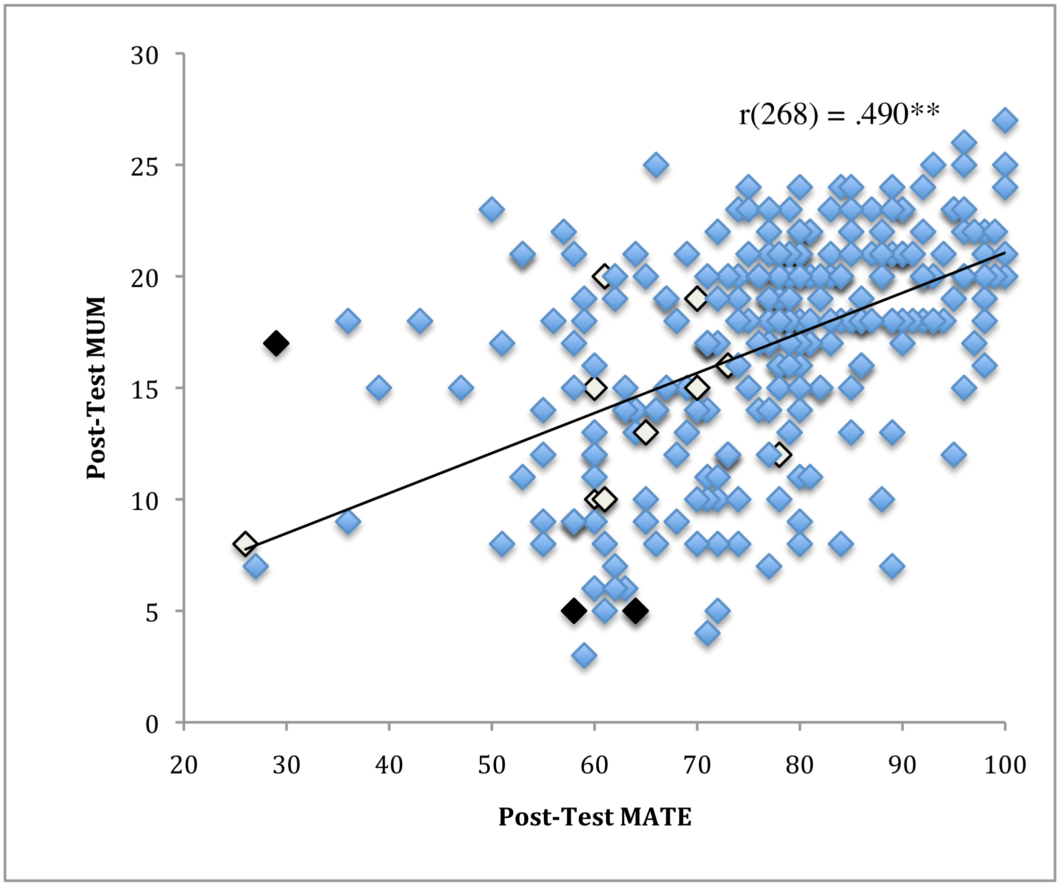


Figure 13. Post-instruction MATE and MUM scores for non-interviewed students (◆), interviewed students (◇), and interviewed students with disparate scores (◆). Abbreviations: Measure of Understanding of Macroevolution (MUM), Measure of Acceptance of the Theory of Evolution (MATE). N = 270.

instruction, 49% of the variance in the data is explained by the relationship between knowledge of macroevolution and acceptance of evolution.

Qualitative support for post-instruction correlation.

Knowledge of the evidence and acceptance. Overall knowledge of macroevolution may have a relationship with acceptance of evolution when other influences (i.e. strong religious beliefs) are not a factor. When students rationalized their acceptance or partial acceptance of evolution, they cited the overwhelming evidence from class, especially fossil evidence, as the reason they had changes in the evolution acceptance. This supports a correlation between knowledge of macroevolution, in particular knowledge of the *evidence for* macroevolution and acceptance of evolution. Amelia was a prime example of a student that shifted her evolution acceptance due to understanding of the evidence from class (see *Influence of the instruction* for additional examples).

> It's kind of hard to not accept it because of so many, so much evidence they have for it with fossils and all of that stuff so uh, yeah I kind of believe it now, it's hard not to believe it because of so much evidence. But I do believe it. (Amelia, p. 1)

Knowledge of geologic time and acceptance. Knowledge of geologic time (MUM component of macroevolution) may also have a relationship to evolution acceptance. This was most evident among the students that remained conflicted about evolution, who primarily saw the conflict between what they had learned about the history of life and their beliefs about the age of the Earth. All of these students had influence from both their religious beliefs and their knowledge from class on their conflicted view about evolution. These influences on acceptance were primarily the evidence the Earth was as least millions of years old and their literal religious beliefs.

Bridget described these conflicts between her knowledge of the Bible and her knowledge of fossils from class. Megan similarly agreed that her knowledge of fossil age influenced her acceptance. “You cannot ignore the evidence, the fossils, all of that” (Megan, p. 2). “I thought [before the class] that God did everything instantly, but now that I see it’s a longer process” (Megan, p. 31).

Ashley likewise attempted to combine her religious views on the age of the Earth with her knowledge from class. “So I just assumed that [the Earth] wasn't that old because I know Jesus died like 2,000 years ago. So I would assume the Old Testament and the New Testament were like billions of years apart” (Ashley, p. 17). Ashley tried to fit the concept that the Earth was 4 billion years old and her knowledge of the time between the Old Testament (creation) and New Testament (Jesus). Since both religious and scientific ideas influenced her acceptance and she thought one had to be incorrect, this left her in conflict.

Examining disparate cases. All but three of interviewed students fell near the correlation curve for acceptance and knowledge of macroevolution. I considered these three individuals as *disparate* cases because their two scores were not correlated. That is one student had low acceptance of evolution but average knowledge of macroevolution - Mary (26, 17), and two students had average acceptance yet low knowledge of macroevolution - Nathan (58, 5) and Nancy (64, 5). I examined the qualitative data to determine the nature of the relationship (or lack thereof) between knowledge of macroevolution and acceptance for these individuals.

Low acceptance, high understanding. Mary had understanding of macroevolution but did not use this new information to inform her acceptance. The primary reason for a lack of relationship between these factors was Mary’s religious views and perceptions of counterevidence. “It just kind of makes sense, but not necessarily true I guess. Like the tree thing, I mean, just because I don't believe it doesn't mean I can't understand it” (Mary, p. 15). Mary believed that simply because evolution was logical and something she understood did not make it true nor something she believed.

Average acceptance, low understanding. Nathan and Nancy had low MUM scores for their corresponding average MATE scores. Prior to instruction, Nancy (64, 5) had a neutral opinion about evolution and average MUM understanding (64, 11). The interview data support the fact this drop in MUM scores was because Nancy was guessing (correctly) on the MUM questions prior to the course. She did not have scientific rationale behind selecting answers on the pre-test MUM. After the course, Nancy claimed that the evidence from class made her lean toward accepting evolution, but did not know specific examples of evidence that influenced her acceptance. “I do believe everything in the Bible and then after learning all this information, it kind of makes me think twice” (p. 16). Perhaps Nancy had some knowledge of macroevolution, but not enough to influence her acceptance.

The other individual with disparate scores post-instruction was Nathan (58, 5). Nathan came into the course with an undecided opinion about evolution, citing that he thought it could happen but knew others thought someone would not be Christian if they believed in evolution. Although Nathan appeared to not support a correlation between knowledge and acceptance post-course, he does because his post-MATE score of did not represent his rejection of evolution. “I don’t think there is much evidence that evolution could be like based on. If they interpret it, I think it will have more – with more I would believe evolution" (Nathan, p. 9). Nathan had a difficult time articulating his rationale on MUM questions, did not think the course presented evidence for evolution, and subsequently went from a high neutral acceptance of evolution (69) to rejecting evolution (58). This represents a relationship between low understanding and low acceptance as expected by the correlation data.

Answering "correctly" despite beliefs. Mary and Ashley both answered questions on the MUM to be scientifically correct although these answers conflicted their personal views about the age of the Earth. Mary (26, 17) understood the evidence and mechanisms behind evolution and but continued to reject it after instruction. When I asked Mary why she answered some of the questions on the MUM in "millions of years" despite her view that the Earth was 6,000 years old. "Everything I answered after was because I tried to answer with what I felt other people like would think was right. Or like my teacher would grade right. So that I wouldn't get it wrong on the test" (Mary, p. 11). Mary answered questions on the MUM based on her knowledge of what was scientifically correct; if she would have answered using her beliefs, she would have answered differently.

Like Mary, Ashley selected answers to be scientifically correct although she believed the Earth was less than 20,000 years old. When I asked her about answering a question in million of years, she responded: "Really and I said millions? I think I was just trying to find the right answer. . . scientists think it's old, it's been here longer than 20,000 years. I guess I was searching for the right answer" (Ashley, p. 16). Ashley wanted to select the 'right' answer, even if that answer did not represent her beliefs.

Interaction Summary

Knowledge of macroevolution and evolution acceptance were significantly correlated before (r[268]=.448; $p < .01$) and after the course (r[268]=.490, $p < .01$). I was unable to explore the pre-instruction correlation in the qualitative data, but post-instruction students cited knowledge of evidence for evolution as rationale for accepting evolution, in particular, knowledge of the fossil evidence. Learning about the age of the Earth (i.e. history of life timeline) was also influential to students' acceptance of evolution, particularly for students with Biblical views about a 'young' Earth. This relationship between knowledge of macroevolution and acceptance was also supported by Nathan and Millie, who rejected evolution and had poor understanding of macroevolution (despite near average MUM scores).

A counter case to the knowledge and acceptance correlation was Mary, who understood macroevolution but rejected evolution. However, this was due to her strong religious background and perceptions of counterevidence. Mary's case is similar to those who had disparate scores pre-instruction. Religion and counterevidence were reasons for less of relationship between knowledge and acceptance despite having knowledge about macroevolution. The other reason that some of the variance was not explained by the correlation may have been due to students like Mary and Ashley. Students may have selected scientifically correct answers to get questions 'right', even if the answer went against their personal views.

CHAPTER FIVE: DISCUSSION AND IMPLICATIONS

In the first section of Chapter Five, I summarize the major findings from Chapter Four around a unifying representation of the findings. The second section contextualizes these major findings in the relevant literature and highlights the contributions of the study. This is followed by a discussion of the limitations of the study. The chapter concludes with implications for future research, practice, and policy.

Summary of the Findings

This section of Chapter Five summarizes the findings from Chapter Four around a unifying representation for the study (Figure 14). This representation encapsulates the research questions of the study around four major topics: the nature the instructor's PCK (RQ1), reflection on student outcomes that informed her PCK (RQ2), the nature of student outcomes (RQ3: knowledge of macroevolution, RQ4: acceptance of evolution, RQ5: interaction between knowledge of macroevolution and evolution acceptance), and the influence of instruction on student outcomes (RQ6). The diagram is not meant to represent all findings in the study, but rather to propose a relationship among major findings.

RQ1. What is the nature of a college instructor's pedagogical content knowledge for teaching macroevolution?

Dr. Wallace had a student-centered teaching orientation with three central goals to her practice. First, she wanted to engage the students' interest. She knew that students were interested in evolution, but also knew students were interested in specific topics over others - such as vestigial structures, human evolution, and phylogenetic trees. The second of Dr. Wallace's overarching goals was to engage students in critical thinking.

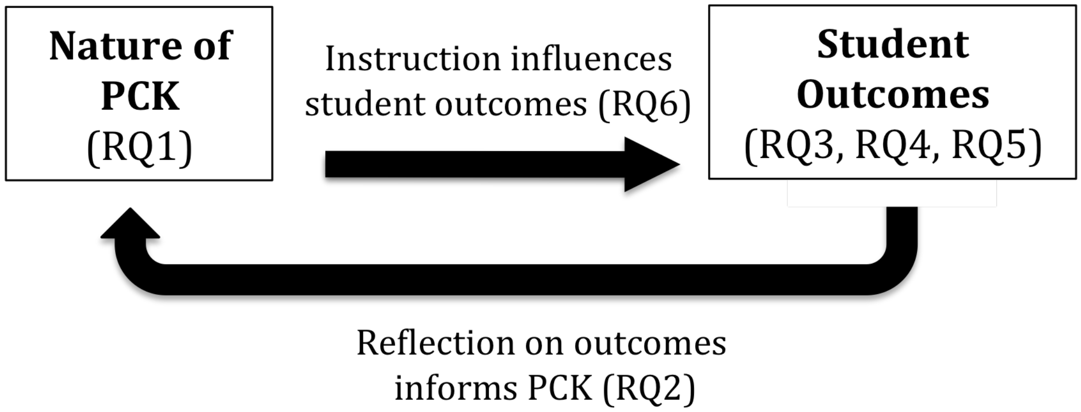


Figure 14. Unifying Representation Documenting the Relationship between PCK, the Influence of Instruction on Student Outcomes, and Instructor Reflection on Student Outcomes to inform PCK.

This was most evident in assessment items that required higher order thinking and Dr. Wallace's instructional strategy of providing students multiple opportunities to uncover/challenge their misconceptions. Dr. Wallace's final goal was for students to be scientifically literate. She wanted students to have practical applications of the content and to see the predictive power of scientific theories for explaining natural phenomena. This goal was clear in her choice of curriculum for the evidence for evolution lectures, which focused around the significance behind natural observations that are difficult to explain without evolution (i.e., vestigial traits).

Dr. Wallace's student-centered teaching orientation was reflected in her deep knowledge of learners, and this knowledge informed other components of her PCK. She knew students had little prior scientific knowledge of evolution. She integrated her knowledge of learners with her knowledge of curriculum by sequencing topics by which topic was prerequisite to the next, i.e., she defined evolution and described selection mechanisms before discussing speciation and evidence for evolution. She also integrated her knowledge of learners and her knowledge of curriculum by selecting interesting content examples (i.e. vestigial traits, human examples) and removing less interesting curriculum (i.e. forms of speciation) based on her knowledge of students' interests. Dr. Wallace's knowledge of learners was also integrated with her knowledge of instructional strategies and knowledge of assessment. She knew students needed clear, explicit instruction to understand a concept. She also knew students struggled with a number of particular concepts in the class, including phylogenetic trees, the connection between genetics and evolution, mechanisms of speciation, and the nature of science. Dr. Wallace therefore gave multiple examples of each concept in the course. These examples provided multiple opportunities to challenge students' misconceptions. Dr. Wallace's knowledge of learners was also evident in her development of assessment items. Both clicker and final exam questions were written based on the topics that she knew were most problematic for students.

RQ2. What are the sources of a college instructor's pedagogical content knowledge for teaching macroevolution?

Dr. Wallace had two primary sources for her PCK, reflection on student outcomes and experiences related to resolving pedagogical issues. As she reflected on student answers on the final exam, Dr. Wallace hypothesized reasons for students' difficulty with particular questions. In doing this, she tacitly informed each component of her PCK. When students did not do well on a question, she would first question if she was explicit enough for students to understand (knowledge of learners). If she had not been explicit, she planned to revise the nature of the content (knowledge of curriculum) or method by which the content presented to the class (knowledge of instructional strategies). If she had been explicit, she would question the influence of students' incoming knowledge or misconceptions (knowledge of learners) or question if the format of the exam question was problematic (knowledge of assessment). This reflective process is depicted in Figure 15 by an arrow connecting student outcomes to PCK (*outcomes* in this case refers to student performance on the final exam).

Dr. Wallace also developed her PCK through experience. As she experienced challenges with teaching evolution - expertise clouding her ability to determine student interests and areas of difficulty, students' resistance to learning evolution, and student difficulty with phylogenetic trees - she drew from the misconceptions literature and sought help from colleagues to learn more about students. This knowledge of learners in turn influenced other components of her PCK and supported her student-centered orientation (see RQ1).

RQ3. What do non-science majors understand about macroevolution before and after instruction? Does past coursework impact this knowledge?

Past coursework. Prior to instruction, students who had completed another college course in biology had significantly higher MUM scores than students without such a course (p=.028). This difference did not exist between the groups post-instruction. There was no significant difference in pre- or post-test MUM score between students who had and had not completed college coursework in geology and anthropology. Likewise, there was no significant difference in MUM score among groups of students with varied durations of past evolution instruction (none to greater than one week) and varied dates of most recent evolution instruction (elementary/middle school to college).

Pre-instruction knowledge of macroevolution. As a class, students scored an average of 14.32 ± 4.75 out of a maximum 27. The interviewed students (MUM average 9.50 ± 4.62) provided some insight into what students knew coming into a non-science majors' biology class, although the data were not collected in a manner that elicited this information in detail. Prior to the class, students were unfamiliar with phylogenetic trees (many had not seen them before), were likewise unfamiliar with the history of life from first prokaryotes to modern life forms, and had little understanding of geologic time. Students also thought evolution was a theory on human origins and/or thought evolution claimed humans came from chimpanzees. More than half of the students had difficulty thinking about historical evidence, claiming that evolution was speculative since no one was alive millions of years ago.

Post-instruction knowledge of macroevolution. After instruction, the class significantly increased their knowledge of macroevolution ($p < .0001$) to 16.80 ± 5.04 out of a maximum 27. Interviewed students (MUM average 12.92 ± 5.05) described that the course influenced their knowledge of phylogenetic tree structure (roots and nodes), relative geologic time, and the history of life (especially transitions in major vertebrate phyla). They also learned that evolution was a theory that applied to all forms of life (not just humans), that humans and apes share a common ancestor, and developed a better understanding of the nature of scientific theories, evidence, and tentativeness in science. Despite these new understandings, interviewed students had difficulty answering questions that required interpreting relatedness on phylogenetic trees, questions which required knowledge of absolute geologic time, and struggled to understand the value behind tentativeness in science.

RQ4. To what extent do non-science majors' accept evolution before and after instruction? Does past coursework impact acceptance?

Past coursework. Prior to instruction, students who had more than one week of previous evolution instruction had significantly higher MATE scores than students with no previous evolution instruction (*p*=.007). However, this difference did not exist between the groups post-instruction. There was no significant difference in pre- or post-test MUM score between students that had and had not completed college coursework in geology, anthropology, or another biology course. Likewise, there was no significant difference in MATE score among groups of students with varied dates of most recent evolution instruction (elementary/middle school to college).

Pre-instruction acceptance. Prior to the course, the majority of the class accepted evolution, with an average MATE score of 70.21 ± 12.29 (20 = reject, 100 = accept). The interviewed students were selected for lower than average MATE scores and had an average MATE score of 51.42 ± 15.74. Among the twelve interviewed students, four were neutral or undecided about evolution. The two students with neutral opinions had religious beliefs but withheld judgment on evolution because they knew they did not understand the science behind it. The two students with undecided opinions had conflicting statements both for and against evolution.

Eight interviewed students rejected evolution prior to the course. Six rejected evolution on grounds of religious conflict (four others described themselves as religious but did not reject evolution due to these beliefs). Two students rejected evolution due to concerns about the scientific validity of evolution, both of whom were also religious. Seven other students likewise had concerns about the validity of science, but did not reject evolution due to these concerns.

Additionally, many students had the perception that evolution was a controversial topic prior to the class. This was primarily due to the nature of their past evolution instruction in middle and high school. Students had instructors that avoided teaching evolution, required evolution permission slips, gave disclaimers about religion, or told students that they would not learn much (or anything) about evolution because of its controversial nature. Students at both public and private schools experienced this atmosphere of controversy. Although students did not reject evolution due to these experiences, it added to their concerns about the validity of evolution.

Post-instruction acceptance. After the course, the class significantly increased their acceptance of evolution ($p<.0001$) to an average score of 75.99 ± 13.97 (20 = reject, 100 = accept). The interviewed students saw a similar average shift toward acceptance (62.64 ± 12.75). Nine of the interviewed students shifted toward accepting evolution: two accepted evolution, two had theistic views on evolution, and five became conflicted between evolution and their religious beliefs. These students cited the volume of evidence for evolution and their knowledge of the history of life in rationalizing their increased acceptance of evolution.

Three students rejected evolution after the course, two of whom were previously undecided and one who continued to reject evolution. The individuals who moved from undecided to rejecting evolution did not understand the material presented in class and thought there was little evidence for evolution. The student who continued to reject evolution after the class understood the evidence for evolution, but rejected it due to strong religious beliefs and perceptions of counterevidence.

RQ5. What is the relationship between understanding of macroevolution and acceptance of evolution by natural selection for non-science majors?

Knowledge of macroevolution was significantly correlated to evolution acceptance both before (r[268]=.448, $p<.01$) and after the course (r[268]=.490, $p<.01$). Qualitative data were not collected in a fashion that allowed for understanding the nature of the pre-course correlation, but themes surrounding the post-course correlation emerged from the data.

The sources of the correlation were the same as the primary influences of the instruction. Students cited knowledge of the evidence for evolution as rationale for accepting evolution, in particular, knowledge of the fossil evidence. Developing knowledge about the age of the Earth and sequence of life forms over time (the history of life) was also influential to students' acceptance of evolution, particularly for students with Biblical views about a 'young' Earth. The correlation was less supported among the participants with strong religious worldviews, perceptions of counterevidence, and for students selecting MUM answers that were scientifically correct but conflicted their personal views.

RQ6. How does instruction influence student knowledge of macroevolution and acceptance of evolution?

The influence of Dr. Wallace's instruction was evident in both qualitative and quantitative student data. This influence is depicted in Figure 14 by an arrow between PCK and student outcomes. *Outcomes* in this case refers to students' knowledge of macroevolution and evolution acceptance as described by performance on the MATE and MUM and by themes in the interview data.

There were significant differences ($p<.0001$) in both average MATE and MUM score for the entire class (N=270) before and after instruction. These gains were also evident during student interviews, which provided insight into *why* Dr. Wallace's instruction was influential. Students most often cited the volume of evidence for evolution as the primary reason they increased their evolution acceptance after the course. The evidence for evolution lectures was a major focus for Dr. Wallace. These lectures had over 30 examples of evolution evidence over two 50-minute class periods, including seven different lines of evidence and up to 12 different examples for each line of evidence. As Dr. Wallace discussed the evidence for evolution, she repeatedly emphasized how the evidence was just as scientists would predict. Although students had difficulty recalling specific lines of evidence for evolution, they frequently cited their knowledge of the transitional fossil record as related to their evolution acceptance. In particular, students referenced the mesonychid-whale fossils in the *PBS Great Transformations* video, the replica *Archaeopteryx*, and the discovery of *Tiktaalik* as they discussed their knowledge of transitional fossils.

Dr. Wallace returned to transitional fossils as evidence for the history of life, adding the evidence piece by piece onto a diagram to show major transitions in vertebrate life forms. This history of life 'story' emerged as influential to students' acceptance. Students recalled how they did not know this sequence of organisms from prokaryotes to modern life forms before the class. Seeing the evidence supporting this sequence helped them to see a step-by-step story of *how* species had changed over time and *why* scientists knew this happened.

Some components of the unit were only influential for improving students' knowledge of macroevolution and were not cited as reasons students became more accepting of evolution. The course influenced students' knowledge of the nature of science, the structure of phylogenetic trees (i.e. the tree thinking in class activity), human evolution, and relative geologic time.

Discussion and Contributions to the Literature

This portion of Chapter Five discusses major findings of the study in context of the literature and highlights how these findings contribute to the literature. I return to Figure 14 as a conceptual guide for the reader, highlighting each component of the representation as appropriate.

Overview

This study addresses several gaps in the literature. Foremost, it is one of the few studies to connect PCK with student learning outcomes, answering the call of Abell (2008), and may be the first to do so at the post-secondary level. In particular, the study connects student learning outcomes to instructor PCK by using a mixed methods approach. Other studies use student test scores and rubrics to quantify teacher PCK with the goal of correlating PCK with student outcomes (Alonzo, Kobarg, & Seidel, 2012; Anderson & Clark, 2012; Gardner & Gess-Newsome, 2011). However, as researchers begin to relate PCK to student learning outcomes, it is important to use quantitative measures *and* student voices to qualify PCK (Nilsson, 2013). This study takes such an approach. The study is therefore unique in identifying not only *to what extent* instruction was influential in student outcomes, but *how* and *why* instruction was influential from a students' perspective.

The mixed methods design was also valuable for understanding the nature of the students' knowledge of macroevolution and acceptance of evolution. The quantitative data provided generalized statistics across the entire class: significant increases in evolution acceptance (p<.0001) and knowledge of macroevolution (p<.0001) and a significant correlation between these two components (r[268]=.510, p<.01). The qualitative data supported these trends and provided in-depth knowledge on the influence of the instruction from students' perspectives.

Nature of Dr. Wallace's PCK

Dr. Wallace's case is valuable as it highlights constraints that faculty likely face when developing their PCK. When first teaching her course, her deep personal interest and rich SMK for evolution constrained her ability to create student-centered instruction. To overcome these constraints, Dr. Wallace developed her knowledge of learners through conducting interest surveys, interactions with students in class, and discussions with colleagues. This rich knowledge of learners served as a base to inform her instructional strategies, curriculum, and assessments.

Balancing personal interest with student interest. Dr. Wallace was interested in every aspect of evolution and felt compelled to load the course with 'cool' examples of evolution. This constrained her ability to design curriculum that was interesting from the perspective of her students. Dr. Wallace moved beyond this constraint by learning about her students' interests. She conducted interest surveys and reflected on her experiences with students in class. As she revised her curriculum based on students' interests, she focused more on human evolution and vestigial traits, and removed less interesting topics like the origin of life and modes of speciation. In the literature, balancing a strong personal interest in a content area is largely unexplored as a constraint to developing PCK. Experienced faculty build curriculum based on students' interests (Padilla & van Driel, 2011; Witzig, 2012), but these studies do not explore how faculty balance their own interests with those of students. This study is one such case.

Strong subject matter knowledge (SMK). Like most faculty, Dr. Wallace had rich SMK but lacked formal pedagogical training (Lederman & Niess, 1999; Lynd-Balta et al., 2006). As Shulman (1986) would predict, this rich SMK did not yield Dr. Wallace the ability to translate expert-level content knowledge into a form easily accessible to students. In other words, SMK was necessary but not sufficient for effective teaching (Abell, 2007).

Dr. Wallace could more easily transform content for teaching that she had to relearn in preparation for the course (i.e. photosynthesis and cellular respiration) over content for which she had expertise (evolution). This finding brings to light an important consideration: does expert-level SMK constrain the ability to communicate and relate information to students? How then is PCK development different for college faculty than for K-12 teachers?

The general consensus is that coherent and thorough understanding of subject matter facilitates PCK development for K-12 teachers (van Driel, De Vos & Verloop, 1998; Abell, 2007). Pre-service teachers generally lack strong SMK (e.g. Abell, 2007) and describe learning content in preparation to teach; a process analogous to how Dr. Wallace described re-learning photosynthesis and cellular respiration. In contrast, faculty generally have rich SMK and there is no need to learn content prior to teaching it. Since faculty are not compelled to take a learners' perspective as they prepare lessons, they may have more difficulty translating content to forms accessible to students.

Dr. Wallace transformed her rich SMK into PCK in the same way she balanced her personal interest in evolution: she developed her knowledge of learners. Since evolution was conceptually intuitive, she drew from the misconceptions literature and had discussions with colleagues to learn how and why evolution was difficult for students.

Examples of faculty overcome the constraints of expertise and personal interest to relate to their learners are largely undocumented in the literature. This study documents one such case of a faculty member overcoming expertise and interest constraints by building her knowledge of learners.

Rich knowledge of learners. A rich knowledge of learners was central to Dr. Wallace's PCK: central to transforming her expert-level SMK and balancing her personal interest, and central to informing her instructional strategies, assessments, and curriculum. Dr. Wallace's instructional strategies were guided by her knowledge of learners' throughout the macroevolution unit, including students' areas of difficulty (e.g., Tree Thinking Activity), needs for multiple examples in multiple formats (*Tiktaalik*, PBS *Great Transformations,* and replica *Archaeopteryx*), and areas of interest (e.g., human evolution). This rich knowledge of learners was also evident in how she chose curriculum based on the interests of her students and how she wrote assessments to elicit higher order thinking and target students' misconceptions.

Van Driel et al. (1998) note that K-12 teachers must build knowledge of learners before developing other components of their PCK. The central role of understanding learners in Dr. Wallace's PCK may indicate a similar relationship for other student centered faculty. Other studies describe faculty with a similar rich knowledge of learners (Bond-Robinson, 2005; Lenze & Dinham, 1994; Major & Palmer, 2002), but generally do not describe how faculty draw on their knowledge of learners to inform their knowledge of assessments, curriculum, and instructional strategies. This study is one of the first to describe how a faculty member used her knowledge of learners to inform all components of her PCK.

Sources of Dr. Wallace's PCK

Dr. Wallace drew on a number of resources to develop her PCK. Like some faculty, Dr. Wallace learned about pedagogy through discussion of best practices with others (Mintzes & Leonard, 2006; Witzig, 2012) and by reading pedagogical literature (Mintzes & Leonard, 2006; Witzig, 2012). Mentorship may have also played a role in helping Dr. Wallace develop her PCK (Major & Palmer, 2002), since she sought advice from colleagues on difficult assessment items (Lenze & Dinham, 1994). Unlike other studies (Lynd-Balta et al., 2006; Kahveci et al., 2006; Sirum et al., 2009; Witzig, 2012; Zhao et al., 2012), Dr. Wallace did not cite structured programs of support as a source of her PCK (although she was known to attend these).

Witzig (2012) described sources of PCK for faculty using Dewey's (1938) reflective thought and action model. He proposed that this process of experiential learning was one way to explain how instructors developed PCK. Components of reflective problem solving led to the development of Dr. Wallace's PCK, in particular her reflection on problematic exam questions.

Reflection on student exam outcomes was an important process for Dr. Wallace to develop her PCK. This is an important piece to understanding the iterative relationship between student outcomes and PCK (Figure 14). Student outcomes informed Dr. Wallace beyond telling her that the students did not understand (Fernandez-Balboa & Stiehl, 1995; Lenze & Dinham, 1994). Problematic exam items were important opportunities for Dr. Wallace to hypothesize ways to change her instruction (strategies, curriculum, and assessment). As she reflected on problematic exam questions, she considered if her curriculum was explicit, if her instructional strategies failed in some capacity, if she needed to revise the assessment question, or if the students lacked the background knowledge to understand the question. Never did she assume that the students did not study.

Reflection of an experience in light of prior experiences leads to learning (Dewey, 1938; Witzig, 2012). These results support the role of such reflection in developing PCK (Park & Oliver, 2012; Davis, 2003). However, the process of reflecting on exam outcomes to develop PCK is largely unexamined in the literature. This study highlights this process as potentially influential to developing faculty PCK. It also highlights a potential need for faculty professional development that focuses on how to hypothesize revisions to instruction through reflection on problematic assessment items.

Student Outcome: Knowledge of Macroevolution

This study contributes and relates to research on students' knowledge of several components of macroevolution, including knowledge of fossils, the history of life, and deep time. The major theme among these components of macroevolution knowledge is that students conceptualized the evidence for evolution and the history of life though their knowledge of fossils.

Knowledge of fossils. The major underlying theme in students' knowledge of macroevolution was their knowledge of fossils. Fossils were the most cited line of evidence for evolution (despite several molecular lines of evidence presented in class) and students used transitional fossils to frame the history of life. Fossils were also an area of difficulty for students as many had difficulty understanding why historical evidence was legitimate in absence of observational data.

Knowledge of fossils includes understanding their formation, location, and discovery, as well as how to interpret fossils (Dodick & Orion, 2003). There is limited research on college students' knowledge of fossils. Libarkin and Anderson (2005) broadly describe students as having a "limited understanding" of fossils but do not provide specific examples of how students conceptualize fossils.

The qualitative portion of this study provides baseline data about college students' conceptions of fossils. Students focused on fossils as evidence for evolution yet many struggled conceptualizing fossils and fossilization processes, did not see the legitimacy of historical evidence in absence of observational data, and had difficulty understanding why marine fossils were found at inland locations. There are several potential reasons for these conceptions.

Fossils as evidence for evolution. Students focused on fossils as the best and/or most memorable evidence for evolution. This was in spite learning six other lines of evidence, including vestigial traits, homology, observable cases of evolution (i.e., antibiotic resistance), cases of artificial selection (i.e., domesticated dogs), and the universality of DNA code.

The notion that students focus on fossil evidence to legitimize evolution may be key to understanding how knowledge of macroevolution influences acceptance. Perhaps students focus on fossil evidence because it provides concrete, visible evidence of the evolutionary past (Dodick & Orion, 2003). Another possibility may be related to the nature of the other lines of evidence provided by Dr. Wallace. The other examples were evidence of evolution in modern organisms, but were not historical in nature. This may indicate that students do not readily associate non-historical data as representative of evolutionary change.

Difficulty with historical evidence. Although students focused on fossil evidence to explain why they became more accepting of evolution, seven still distrusted the legitimacy of fossils since the original organisms were not directly observed by humans. Lawson et al. (2000) also note that college students struggle with phenomena they cannot directly observe, which they relate to students' conceptual stage. A post-formal cognitive operational stage is required to understand entities that cannot be observed (Perry, 1970). Since as many as two thirds of introductory biology students lack post-formal level skills (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000), cognitive stage may have influenced these findings. This study contributes another possible example of college students struggling with evolution for these reasons.

Other ideas about fossils. It is more puzzling why students struggled with conceptualizing fossils (as bones, impressions, etc.), the process of fossilization, and the process by which marine fossils are found at inland locations. A similar study of college students found that students had difficulty thinking about how geological processes occurred over time (Libarkin, Anderson, Dahl, Beilfuss, & Boone, 2005). Dr. Wallace did not discuss how the Earth had changed over time. It is therefore possible that students' ideas about inland marine fossils stemmed from a difficulty understanding that the Earth has changed over time. This finding implies that understanding the nature of fossils may also require a discussion of geological history (i.e. plate tectonics).

Knowledge of the history of life. Students' knowledge about the history of life emerged as a major theme in their knowledge of macroevolution. Dr. Wallace spent two class periods using the evidence for evolution to explain major transitions in the history of life from prokaryotes to modern life forms.

There is limited research on students' ideas about the history of life. Previous work has focused on students' ability to sequence evolutionary events (Catley & Novick, 2009; Hidalgo, Fernando, & Otero, 2004). Students in this study described the history of life by describing both a sequence of events (Catley & Novick, 2008) and the fossil evidence for transitions between these events (*Tiktaalik, Archaeopteryx*, and mesonychids). This emphasizes the importance of fossil evidence from the student perspective, and denotes the importance of focusing on evidence for transitions and not exclusively a sequence of events when teaching the history of life.

Knowledge of deep time. Dr. Wallace did not focus on geologic time periods related to the history of life, and subsequently students did not develop knowledge of dates related to evolutionary events. However, students did learn an approximate age of the Earth (billions of years) and had a general perception that evolution occurred over millions of years. They used these ideas in tandem with their personal beliefs about the age of the Earth to inform how they answered deep time questions on the MUM. This supports the work of Libarkin et al., (2005), which reported that college students do not have knowledge of specific dates for geologic events.

Although students were guessing on these questions (even after class), they guessed by consistently choosing the earliest, moderate, or latest date relative to the other three answer choices. This finding supports the work of Trend (2001), who found that teachers sequenced geologic events in relative time (extremely ancient, moderately ancient, and less ancient). This study adds to the literature that college students likewise think in relative time. This finding is also unique in that students did not sequence multiple events in relative time, but rather chose among possible dates for a single event based on their perceptions of relative time.

Student Outcome: Evolution Acceptance

Students in the course had significantly higher evolution acceptance after the course ($p<.0001$). Interviewed students explained that their acceptance was influenced primarily by the volume of evidence for evolution and the history of life sequence (see *Influence of the Instruction*). Religion played a role in acceptance outcomes, particularly among students' views of human evolution and for students who remained conflicted about evolution after the course. These conflicted students raise interesting implications regarding mid-range MATE scores.

Evolution acceptance and knowledge of content. Most interventions to date have produced little or no gain in acceptance of evolution with increases in knowledge of evolution (Bishop & Anderson, 1990; Demastes et al., 1995; Jensen & Finley, 1996; Nehm & Reilly, 2007; Scharmann & Harris, 1992). Sinatra, Southerland, McCounaughy, and Demastes (2003) suggest that the relationship between knowledge and belief/acceptance varies with the degree of controversy of the topic. The more controversial the topic, the weaker the link between knowledge and belief/acceptance. It is important to note, however, that these studies find no relationship between knowledge of *natural selection* and evolution acceptance (Bishop & Anderson, 1990, Demastes-Southerland et al., 1995, Demastes-Southerland et al., 1992).

My findings support a relationship between knowledge of macroevolution and evolution acceptance. This correlation existed both prior to instruction (r[268]=.448, $p<.01$) and after instruction (r[268]=.490, $p<.01$). These findings are similar to Nadelson and Southerland (2010b), who found that knowledge of macroevolution (measured by the

MUM) and evolution acceptance (measured by the MATE) were correlated for freshman biology majors ($r[741]=.47$, $p<.01$). Nadelson and Southerland also found that acceptance significantly increased after a one-semester majors' biology course, but did not interview participants about the course nor their responses on the MATE and MUM. It remained unclear why knowledge of macroevolution was related to acceptance for biology majors and likewise how instruction influenced these components.

This study makes a major contribution to the literature because it documents a significant increase in acceptance after macroevolution instruction *and* how that instruction influenced evolution acceptance. Furthermore, these findings were found among non-biology majors, a population unlikely to be internally motivated to accept evolution due to mastery goals (Sinatra, Southerland, McConaughy, & Demastes, 2003).

The results are meaningful since increases in evolution acceptance were documented for students with low incoming knowledge of macroevolution and acceptance. This supports that notion that rejecting evolution does not inhibit developing knowledge of evolution (Bishop & Anderson, 1990; Demastes et al. 1995; Sinatra, Southerland, McConaughy, & Demastes, 2003), and low knowledge of macroevolution did not inhibit evolution acceptance (contrary to Lawson & Worsnop, 1992; Lawson et al., 2000). This brings into question whether knowledge of macroevolution and evolution acceptance are completely distinct constructs (Nehm et al., 2009).

Influence of religious beliefs. Students' religious beliefs also played a role in their evolution acceptance. Perceived conflicts between religious beliefs and evolution are well documented in the literature (Almquist & Cronin, 1988; Hokayem & BouJaoude, 2008; Sinclair et al., 1997). In this study, these conflicts were most evident among the nine interviewed students that did not accept human evolution after instruction but did shift toward accepting evolution for other life forms. Several studies (i.e., Lovely & Kondrick, 2008) report this disparity among college educated individuals between accepting evolution for plants and animals (49% acceptance) and accepting evolution for humans (22% acceptance).

Religious beliefs were also evident among the five individuals who remained conflicted about evolution after the course. These individuals were unable to reconcile their religious beliefs about the age of the Earth and their newfound knowledge of evolution. This may have been due to an inability to negotiate the literalness of the Book of Genesis (Winslow et al., 2011) or because the students took a dualistic worldview in regard to evolution (Chi et al., 1994; Chinn & Brewer, 1993). Epistemological dualists view the world in terms of black/white or right/wrong (Perry, 1970) and are less comfortable with ambiguity than individuals with multiplistic epistemologies (Sinatra et al., 2003).

Qualifying MATE scores. The MATE as a quantitative instrument provides a single number which broadly indicates an individual's acceptance of evolution. In his dissertation, Rutledge (1996) sorted individuals into six categories based on score: 89-100, very high acceptance; 77-88, high acceptance; 65-76, moderate acceptance; 53-64, low acceptance; and 20-52, very low acceptance (Rutledge, 1996). These distinctions were arbitrarily created by dividing the distribution of participant scores into equal categories.

Due to the mixed method nature of this study, the findings provide qualitative labels for scores on the MATE. Individuals with scores below 61 generally rejected evolution. Individuals with scores about 73 accepted evolution or were theistic evolutionists (Table 20). The remaining five individuals had post-test MATE scores in the low-60s. These individuals did not demonstrate “moderate acceptance” (Rutledge, 1996), but were conflicted between their religious views and knowledge of macroevolution. It seems illogical that an individual could simultanously agree that the Earth is less than 20,000 years old and that the Earth is over 4 billion years old, but conflicting MATE statements were common for these individuals. The perspectives of conflicted individuals remain undiagnosed by current evolution acceptance instruments and by some descriptions of the wide spectrum of evolution acceptance (e.g. Scott, 1997). This implies a need for a ‘degree of conflict’ measure to be added to an individual’s base MATE score.

Influence of the Instruction

A number of studies suggest that knowledge-oriented interventions do not change students’ beliefs or acceptance of evolution (Angiullo et al., 1996; Carmel et al., 1992; Erickson et al., 2003; Harris et al., 1991; Koumi & Tsiantis, 2001; Showers & Shrigley, 1995). Likewise, there is little evidence to suggest that classroom instruction in evolutionary biology provokes a change in students’ acceptance of evolution (Demastes-Southerland et al., 1995; Sinatra et al., 2003; Southerland & Sinatra 2003, 2005). Contrary to these studies, Nadelson and Southerland (2010a) found that after a one semester course in evolution, biology majors significantly increased (p<.01) their understanding of macroevolution (as measured by the MUM) and acceptance of evolution (as measured by the MATE). Furthermore, there was a significant correlation between knowledge of macroevolution and acceptance for this population (r[741]=.47,

$p<.01$). However, these statistics could be attributed to biology majors having mastery goals and therefore being inclined to adopt the views of scientists (Sinatra et al., 2003) (see Chapter Two regarding mastery orientation).

My study contributes to the literature as it documents the relationship between knowledge of macroevolution and evolution acceptance in a population unlikely to have a mastery orientation. After a general education biology course, non-science majors significantly increased both their understanding of macroevolution ($p<.0001$) and acceptance of evolution ($p<.0001$). These components were significantly correlated ($r[268]=0.490$, $p<.01$), as was seen in Nadelson and Southerland (2010b). This supports the need for macroevolution content to be included in general education biology courses. Additionally, this study contributes *what* specific macroevolutionary content influenced evolution acceptance. Foremost, students overwhelmingly cited the volume of the evidence for evolution behind why they shifted their evolution acceptance. Among these lines of evidence, students most often cited transitional fossils as the most compelling evidence for evolution. This aligns with the two 50-minute class periods Dr. Wallace spent talking about seven different lines of evidence and 30 different examples of evolution.

Understanding the history of life also contributed to students' acceptance of evolution. Seeing *how* the species had changed from prokaryotes to modern organisms was more meaningful to students than being told that 'all life has a common ancestor'. Dr. Wallace told the history of life story by using fossils at major transitions in vertebrate evolution, including *Tiktaalik*, *Archaeopteryx*, and mesonychids (land-dwelling ancestor to modern whales).

Novick and Catley (2009) examined students' sequences of events in the history of life. They argue that since evolution provides a predictive framework for understanding the history of life, it should be considered a critical component of scientific literacy. Although they described how students thought about the history of life and deep time (see *Student Outcomes*), Novick and Catley did not provide data to support *why* the history of life was an integral component of scientific literacy. My study addresses this gap in the literature. Learning about the history of life influenced students to become more accepting of evolution because they saw how life had changed from a single common ancestor. The history of life should therefore be included in general education biology courses and potentially be considered a critical component of scientific literacy.

Limitations

Potential areas of limitation for this study include the unique nature of the instruction, non-random sample selection, the MUM instruments, and timing of the interviews.

An exemplary case. Dr. Wallace represents an idealized case of teaching a general education biology course with nine macroevolution oriented lectures. Most general education biology courses I have observed spend about one week (3 lectures) on evolution in general, and often do not discuss macroevolutionary content. Although this limits the transferability of the study, the case was selected to address the call by Catley (2006) and others to examine the influence of learning macroevolutionary content on student learning outcomes.

Non-random sampling. The instruction that influenced interviewed students' acceptance and knowledge of macroevolution cannot be generalized to all students in the course. I interviewed targeted students with low incoming MUM and MATE scores. The influence of the instruction can best be generalized to students within this demographic. Since knowledge of macroevolution and evolution acceptance significantly increased after the course, I can hypothesize that the instruction influenced the entire class, but the components of influential instruction for the whole class may not be the same as for the interviewed students.

Limitations of the MUM. A primary limitation of the study is the MUM. I had concerns about the validity of the MUM prior to the study (note Chapter Three) but still chose to use the MUM since its outcomes were correlated with MATE scores for biology majors and because it was the only tool available assessing (at least in some capacity) students' knowledge of macroevolution. After data were collected, Novick and Catley (2012) identified extensive semantic and conceptual issues with the instrument (see also *Implications for instruments)*. This is because some answers stand out as scientifically correct (e.g. only one of the answers mentions a common ancestor) and some answers seem implausible (e.g. Q22, Answer 4: "The great meteor impact caused tidal wave that forced these animals [onto land]").

Participants' comments support these validity concerns. Themes related to participants' problems with the instrument will be written in a response paper to Novick and Catley (2012). This paper will include the exploratory factor analyses from this study. These analyses (Appendix F) indicated additional validity issues for the MUM. Questions reportedly associated with one of five tenets of macroevolution did not cluster together in any of the three exploratory factor analyses (pilot, pre-test, post-test). Since the questions did not factor together as Nadelson and Southerland (2010a) would predict, these questions do not validly assess knowledge of fossils, phylogenetics, speciation, deep time, and nature of science.

Fortunately, the limitations of the MUM are primarily limited to the quantitative data. Students' explanations about MUM answers were triangulated with data from other lines of questioning. During interviews, students described what they learned about evolution in class and interpreted the figures from the MUM prior to reviewing actual questions from the MUM. This provided triangulating support for what the students knew about macroevolution independent of specific (and perhaps problematic) questions on the MUM.

Timing of the interviews. I had great difficulty finding students to participate in this study, which may be attributable to conducting interviews near the time of semester finals. The timing of the interviews also affected my ability to triangulate themes around students' knowledge of macroevolution and evolution acceptance *prior* to the course. The students were interviewed after instruction but not before instruction. I cannot claim that their descriptions of knowledge and acceptance pre-instruction were representative of their actual views. Although the quantitative data provided some insight into their pre-instruction views, the validity issues of the MUM instrument add to the limitation of any pre-instruction student themes. Furthermore, I cannot claim the shifts in acceptance seen in this study have been retained by the students. In many studies, knowledge-oriented interventions have not changed long-term attitudes, beliefs, or acceptance (Demastes, Good, & Peebles, 1996).

Implications of the Study

Summary

The results of the study inform goals for teaching evolution in grades 13-16 (Smith, 2009) and suggest refinements to policy documents related to teaching evolution in grades 13-16 (AAAS, 2011; Siebert & McIntosh, 2001). I also suggest future research related to faculty development (Abell, 2008) and evolution education, including a call for revisions to the MUM instrument.

Implications for Practice

For the general education biology course. This study has major implications for teaching evolution at the college level. Foremost, general education biology courses should include macroevolution in addition to natural selection content, since understanding macroevolution is correlated with accepting evolution. These courses should also include examples of evolution evidence, with emphasis on how evidence supports what scientists predict regarding common ancestry. This approach should include a discussion of the major transitions in the history of life, and using transitional fossils as evidence for speciation events.

General education biology instructors should also use caution in how they teach the tentative nature of science. Students can misconstrue new scientific discoveries or the notion of “science changing” to imply speculation or distrust in scientific theories. Instructors should also provide examples that demonstrate the meaning of theory and law in science. Providing only a definition of ‘theory as an explanation’ and ‘laws as a description of nature’ is too broad for non-science majors to develop meaningful understanding, even with emphasis on evidence supporting theories.

For professional development. This study highlights the process of reflecting on student assessment outcomes as influential to developing faculty PCK. There may be a need to develop faculty professional development that focuses on how to hypothesize revisions to instruction through reflection on problematic assessment items.

Implications for Policy

Vision and Change in Undergraduate Biology (AAAS, 2011) outlines evolution as one of six major themes in biology. However, it does not outline specific topics essential to evolution literacy. A list of these concepts should be developed in the next policy document. Macroevolution should be included on this list. I also recommend that the policy document include examples of instruction known to influence evolution acceptance. Such examples may include multiple and diverse lines of evidence for evolution, illustrative examples of transitional fossils, and the history of life with emphasis on transitional forms.

Implications for Future Research

Foremost, future work on evolution acceptance and knowledge of macroevolution requires a revised instrument to measure student knowledge of macroevolution. Future research studies should include interviews with randomly selected participants to paint a wider picture of how macroevolution instruction influences acceptance for all students. This study is a single case of an instructor and her students in a general education biology course. The next step is to design a quasi-experimental study to compare learning outcomes for multiple general education biology courses, some of which use macroevolution content.

Lastly, this study implies a need to investigate how faculty develop their knowledge of learners when they have deep interest and knowledge of a topic. How they translate this knowledge may be quite different than how they translate knowledge for topics they have less knowledge about and/or find less interesting. Future work should also investigate how faculty reflect upon and revise their practice using assessment outcomes and how this may assist in developing PCK. Both of these approaches could provide insight into the nature of PCK development at the post-secondary level and how it may differ from that of K-12 instructors.

References

Abd-El-Khalick, F. (2006). Over and over again: College students' views of nature of science. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and the nature of science: Implications for teaching, learning and teacher education* (pp. 389-426). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Abell, S. K. (2007). Research on science teacher knowledge. In S. K. Abell & N. G. Lederman (Eds.), *Handbook on research in science education* (pp. 1105-1149). Mahwah, NJ: Lawrence Erlbaum.

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education, 10*, 1405-1416. doi: 10.1080/09500690802187041

Almquist, A. J., & Cronin, J. E. (1988). Fact, fancy and myth on human evolution. *Current Anthropology, 29*, 520-529. doi: 10.1086/203672

Alonzo, A. C., Kobarg, M., & Seidel, T. (2012). Pedagogical content knowledge as reflected in teacher-student interactions: Analysis of two video cases. *Journal of Research in Science Teaching, 49*, 1211-1239.

Alters, B. T. (2005). *Teaching biological evolution in higher education: Methodological, religious, and nonreligious issues*. Sudbury, MA: Jones and Bartlett Publishers.

American Association for the Advancement of Science [AAAS]. (1989). *Science for all Americans. A project 2061 report on literacy goals in science, mathematics, and technology*. Washington, DC: AAAS.

American Association for the Advancement of Science [AAAS]. (1993). *Benchmarks for science literacy: A Project 2061 report*. New York, NY: Oxford University Press.

American Association for the Advancement of Science [AAAS]. (2011). *Vision and change in undergraduate biology education: A call to action*. Washington, DC: AAAS.

Anderson, D., & Clark, M. (2012). Development of syntactic subject matter knowledge and pedagogical content knowledge for science by a generalist elementary teacher. *Teachers and Teaching: Theory and Practice, 18*, 315-330. doi: 10.1080/13540602.2012.629838

Anderson, D. L., Fisher, K. M., & Norman, G. L. (2002). Development and evaluation of the conceptual inventory of natural selection. *Journal of Research in Science Teaching, 39*, 952-978. doi: 10.1002/tea.10053

Anguillo, L., Whitbourne, S., & Powers, C. (1996). The effects of instruction and experience on college students' attitudes toward the elderly. *Educational Gerontology, 22*, 483-495.

Baker, E. A. (1995). *The nature of literacy activities in a high technology environment from a meaning making perspective.* Doctoral dissertation, Peabody College of Vanderbilt Universtiy, Nashville, TN.

Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree-thinking challenge. *Science, 310*, 979-980. doi: 10.1126/science.1117727

Baxter, J. A., & Lederman, N. G. (1999). Assessment and measurement of PCK. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 147-161). Dordrect, The Netherlands: Kluwer Academic Publishers.

Bell, R. L., Lederman, N. G., & Abd-El-Khalick, F. (2000). Developing and acting upon one's conception of the nature of science: A follow-up study. *Journal of Research in Science Teaching, 37*, 563-581.

Berkman, M. B., & Plutzer, E. (2011). Defending evolution in the courtroom, but not in the classroom. *Science, 331*, 404-405.

Bezzi, A. (1999). What is this thing called geoscience? Epistemological dimensions elicited with the repertory grid and their implications for scientific literacy. *Science Education, 83*, 675-700.

Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching, 27*, 415-427. doi: 10.1002/tea.3660270503

Bok, D. (2006). *Our underachieving colleges: A candid look at how much students learn and why they should be learning more*. Princeton, NJ: Princeton University Press.

Bond-Robinson, J. (2005). Identifying pedagogical content knowledge (PCK) in the chemistry laboratory. *Chemistry Education Research and Practice, 6*, 83-103.

Bond-Robinson, J., & Rodriques, R. A. B. (2005). Instruments to drive effective constructivist laboratory teaching *The Chemical Educator, 10*, 154-162. doi: 10.1333/s00897050899a

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience and school*. Washington, D. C.: National Academy Press.

Brem, S. K., Ramsey, M., & Schindel, J. (2003). Perceived consequences of evolution: College students perceive negative personal and social impact in evolutionary theory. *Science Education, 87*, 181-206. doi: 10.1002/sce.10105

Brophy, J., & Good, T. L. (1986). Teacher behavior and student acheivement. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed., pp. 328-375). New York, NY: Macmillan.

Brumby, M. N. (1984). Misconceptions about the concept of natural selection by medical biology students. *Science Education, 68*, 493-503.

Biological Sciences Curriculum Study [BSCS]. (1993). *Developing biological literacy*. Colorado Springs, CO: Kendall Hunt Publishing Company.

Butler, W. (2009). *Does the nature of science influence college students' learning of biological evolution?* PhD dissertation, Florida State University, Tallahassee, FL.

Butler, W., & Southerland, S. A. (2010, March). *Influence of the nature of science instruction on the learning of evolution: A qualitative study.* Paper presented at the Annual international conference of the National Association for Research in Science Teaching, Philadelphia, PA.

Bybee, R. W. (1997). *Achieving scientific literacy: From purpose to practices*. Portsmouth, NH: Heinemann.

Campbell, N. A., & Reece, J. B. (2005). *Biology* (7th ed.). San Francisco, CA: Pearson Benjamin Cummings.

Carmel, S., Cwikel, J., & Galinsky, D. (1992). Changes in knowledge, attitudes, and work preferences following courses in gerontology among medical, nursing, and social work students. *Educational Gerontology, 18*, 329-342.

Catley, K. M. (2006). Darwin's missing link - A novel paradigm for evolution education. *Science Education, 90*, 767-783. doi: 10.1002/sce.20152

Catley, K. M., Lehrer, R., & Reiser, B. (2004). Tracing a prospective learning progression for developoing understanding of evolution. In N. A. o. Sciences (Ed.), *National Academies Committee for Test Design for K-12 Science Achievement*. Washington, DC.

Catley, K. M., & Novick, L. R. (2008). Digging deep: Exploring college students' knowledge of macroevolutionary time. *Journal of Research in Science Teaching, 46*, 311-332. doi: 10.1002/tea.20273

Cavallo, A. M. L., & McCall, D. (2008). Seeing may not mean believing: Examining students' understandings and beliefs in evolution. *The American Biology Teacher, 70*, 522-530.

Catley, K. M., Novick, L. R., & Shade, C. K. (2010). Interpreting evolutionary diagrams: When topology and process conflict. *Journal of Research in Science Teaching, 47*, 861-882. doi: 10.1002/tea.20384

Chan, Y. H. (2003). Biostatistics 101: Data presentation. *Singapore Journal of Medicine, 44*, 280-285.

Chi, C. A., Leeuw, N. E., Chiu, M.-H., & Lavanchar, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439-477. doi: 10.1016/0364-0213(94)90016-7

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*, 1-49.

Coburn, W. W. (1994). Belief, understanding, and the teaching of evolution. *Journal of Research in Science Teaching, 31*, 583-590.

Colt, H. G., Davoudi, M., Murgu, S., & Zamanian Rohani, N. (2011). Measuring learning gain during a one-day introductory bronchoscopy course. *Surgical Endoscopy, 25*, 207-216.

Counts, M. C. (1999). *A case study of college physics professor's pedagogical content knowledge.* Unpublished doctoral dissertation, Georgia State University, Atlanta, GA.

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five traditions*. Thousand Oaks, CA: Sage Publications, Inc.

Creswell, J. W. (2002). *Educational research: Planning, conducting, and evaluating quantitative and qualitative research.* Upper Saddle River, NJ: Merrill Prentice Hall.

Creswell, J. W. (2003). *Research design: Qualitative, quantitative, and mixed methods approaches* (2nd ed.). Thousand Oaks, CA: Sage Publications.

Creswell, J. W., & Maitta, R. (2002). Qualitative research. In N. Salkind (Ed.), *Handbook of research design and social measurement* (pp. 143-184). Thousand Oaks, CA: Sage Publications.

Creswell, J. W., & Plano Clark, V. L. (Eds.). (2006). *Designing and conducting mixed methods research*. Thousand Oaks, CA: Sage Publications, Inc.

Creswell, J. W., Goodchild, L. F., & Turner, P. P. (1996). *Integrated qualitative and quantitative research: Epistemology, history, and designs.* In J. C. Smart (Ed.), *Higher Education Handbook of Theory and Research, Vol. XI* (pp. 90-136). New York, NY: Agathon Press.

Creswell, J. W., Plano Clark, V. L., Gutmann, M. L., & Hanson, W. E. (2003). Advanced mixed methods research designs. In A. Tashakkori & C. Teddlie (Eds.), *Handbook of mixed methods in social and behavioral research*. Thousand Oaks, CA: Sage Publications, Inc.

Dagher, Z. R., & BouJaoude, S. (1997). Scientific views and religious beliefs of college students: The case of biological evolution. *Journal of Research in Science Teaching, 34*, 429-445.

Dagher, Z. R., & BouJaoude, S. (2005). Students' perceptions of the nature of evolutionary theory. *Science Education, 89*, 378-391.

Dagher, Z. R., Brickhouse, N. W., & Shipman, H. L. (2004). How some college students represent their understanding of the nature of scientific theories. *International Journal of Science Education, 26*, 735-755. doi: 10.1080/0950069032000138806

Davis, E. A. (2003). Prompting middle school science students for productive reflection: Generic and directed prompts. *The Journal of the Learning Sciences, 12*, 91-142. doi: 10.1207/S15327809JLS1201_4

DeHaan, R. (2005). The impending revolution in undergraduate science education. *Journal of Science Education and Technology, 14*, 253-269.

Demastes, S., & Wandersee J. H. (1992). Biological literacy in a college biology classroom. *BioScience*, *42*, 63-65.

Demastes, S. S., Good, R. G., & Peebles, P. (1996). Students' conceptual ecologies and the process of conceptual change in evolution. *Science Education, 79*, 637-666. doi: 10.1002/sce.3730790605

Demastes, S. S., Settlage, J., & Good, R. G. (1995). Students' conceptions of natural selection and its role in evolution: Cases of replication and comparison. *Journal of Research in Science Teaching, 32*, 535-550.

Dewey, J. (1938). *Experience & education*. New York, NY: Macmillan Publishing Company.

Dobson, C. (2001). Career advice for life scientists: Teaching and learning - the scholarship of teaching. In American Society of Cell Biology (Ed.), *Women in cell biology* (pp. 15-23).

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *The American Biology Teacher, 35*, 125-129.

Dodick, J. (2007). Understanding evolutionary change within the framework of geological time. *McGill Journal of Education, 42*, 245-264.

Dodick, J., & Orion, N. (2003). Introducing evolution to non-biology majors via the fossil record: A case study from the Israeli high school system. *The American Biology Teacher, 65*, 185-190.

Draper, S. W., & Brown, M. I. (2004). Increasing interactivity in lectures using an electronic voting system. *Joural of Computer Assisted Learning, 20*(4), 81-94.

Duncan, D. (2005). *Clickers in the classroom: How to enhance science teaching using classroom response systems*. San Francisco, CA: Pearson/Addison-Wesley.

Eisner, E. W. (1991). *The enlightened eye: Qualitative inquiry and the enhancement of educational practice*. New York, NY: Macmillan.

Erickson, C. K., Wilcox, R. E., Miller, G. W., Littlefield, J. H., & Lawson, A. E. (2003). Effectiveness of addiction science presentations to treatment professionals: Using a modified Solomon study design. *Journal of Drug Education, 33*, 197-216.

Evans, E. M. (2000). The emergence of beliefs about origins of species in school-age children. *Merrill-Palmer Quarterly: A Journal of Developmental Psychology, 46*, 221-254.

Evans, E. M. (2008). Conceptual change and evolutionary biology: A developmental analysis. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 263-295). New York, NY: Routledge.

Fernandez-Balboa, J.-M., & Stiehl, J. (1995). The generic nature of pedagogical content knowledge for college professors. *Teaching and Teacher Education, 11*, 293-306. doi: 10.1016/0742-051X(94)00030-A

Fleming, R. (1988). Undergraduate science students' views on the relationship between science, technology and society. *International Journal of Science Education, 10*, 449-463.

Friedrichsen, P. (2002). A substantive-level theory of highly-regarded seconday biology teachers' science teaching orientations. *Dissertation Abstracts International, 63*(07), 2496A (UMI No. 2060018).

Friedrichsen, P., Abell, S. K., Pareja, E., Brown, P., Lankford, D. E., & Volkmann, M. J. (2009). Does teaching experience matter? Examining biology teachers' prior knowledge for teaching in an alternative certification program. *Journal of Research in Science Teaching, 46*, 357-383. doi: 10.1002/tea.20283

Friedrichsen, P., van Driel, J. H., & Abell, S. K. (2011). Taking a closer look at science teaching orientations. *Science Education, 95*, 358-383. doi: 10.1002/sce.20428

Futuyma, D. J. (2005). *Evolution.* Sunderland, MA: Sinauer Associates.

Gardner, A., & Gess-Newsome, J. (2011, April). *A PCK rubric to measure teachers' knowledge of inquiry based instruction using three data sources.* Paper presented at the Annual conference of the National Association for Research in Science Teaching, Orlando, FL.

Gelman, S. A. (2003). *The essential child: Origins of essentialism in everyday thought.* Oxford: Oxford University Press.

Gess-Newsome, J. (1999). Pedagogical content knowledge: An introduction and orientation. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 3-17). Dordrect, The Netherlands: Kluwer Academic Publishers.

Gilbert, S. W. (1991). Model building and a definition of science. *Journal of Research in Science Teaching, 28*, 73-80.

Gould, S. J. (2002). *The structure of evolutionary theory*. Cambridge, MA: Belknap Press of Harvard University Press.

Greene, E. D. (1990). The logic of university students' misunderstanding of natural selection. *Journal of Research in Science Teaching, 27*, 875-885.

Green, J. C., Caracelli, V. J., & Graham, W. F. (1989). Toward a conceptual framework for mixed-method evaluation designs. *Educational Evaluation and Policy Analysis, 11*, 255-274.

Gregory, R. T. (2008). Understanding evolutionary trees. *Evolution: Education and Outreach, 1,* 121-137. doi: 10.1007/s12052-008-0035-x

Griffith, J. A., & Brem, S. K. (2004). Teaching evolutionary biology: Pressures, stress and coping. *Journal of Research in Science Teaching, 41*, 791-809.

Grose, E. C., & Simpson, R. D. (1982). Attitudes of introductory college biology students toward evolution. *Journal of Research in Science Teaching, 19*, 15-24. doi: 10.1002/tea.3660190103

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. New York, NY: Teachers College Press.

Guba, E. G., & Lincoln, Y. S. (1989). *Fourth generation evaluation*. Thousand Oaks, CA: Sage.

Hake, R. R. (1998). Interactive engagement vs. traditional method: A six thousand student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66*, 64-74.

Hake, R. R. (2008). Design based research in physics education research: A review. In A. E. Kelly, R. A. Lesh & J. Y. Baek (Eds.), *A handbook of design research methods in education: Innovations in science, technology, engineering, and mathematics learning and teaching*. New York, NY: Rutledge.

Halverson, K. L. (2009). *Investigating the development and use of phylogenetic representations by college undergraduates in a plant systematics course.* Unpublished doctoral dissertation, University of Missouri, Columbia, MO.

Harris, M. B., Walters, L. C., & Waschull, S. (1991). Altering attitudes and knowledge about obesity. *Journal of Social Psychology, 131*, 881-884.

Hashweh, M. (1985). *An exploratory study of teacher knowledge and teaching: The effects of science teachers' knowledge of their subject matter and their conceptions of learning on their teaching.* Unpublished doctoral disseration, Standford Graduate School of Education, Stanford, CA.

Hatch, J. A. (2002). *Doing qualitative research in education settlings*. Albany, NY: State University of New York Press.

Hawley, P. H., Short, S. D., McCune, L. A., Osman, M. R., & Little, T. D. (2010). What's the matter with Kansas?: The development and confirmation of the evolutionary attitudes and literacy survey (EALS). *Evolution, Education and Outreach*, *4*, 117-132. doi: 10.1007/s12052-010-0294-1

Henze, I., van Driel, J., & Verloop, N. (2008). Development of experienced science teachers' Pedagogical Content Knowledge models of the solar system and the universe. *International Journal of Science Education, 30*, 1321-1342. doi: 10.1080/09500690802187017

Hesse-Biber, S. N. (2010). *Mixed methods research: Merging theory with practice*. New York, NY: The Guilford Press.

Hidalgo, A., Fernando, S., & Otero, J. (2004). An analysis of the understanding of geological time by students at the secondary and post-secondary level. *International Journal of Science Education, 26*, 845-857.

Hodson, D. (1998). *Teaching and learning science: Towards a personalized approach*. Buckingham, United Kingdom: Open University Press.

Hokayem, H., & BouJaoude, S. (2008). College students' perceptions of the theory of evolution. *Journal of Research in Science Teaching, 45*, 395-419. doi: 10.1002/tea.20233

Ivankova, N. V., Creswell, J. W., & Stick, S. L. (2006). Using mixed methods sequential explanatory design: From theory to practice. *Field Methods, 18*, 3-20. doi: 10.1177/1525822X05282260

Jang, S. (2010, March). *Assessing university students' perceptions of the physics teacher's pedagogical content knowledge using a developed instrument.* Paper presented at the Annual International Conference of the National Association for Research in Science Teaching, Philadelphia, PA.

Jensen, M. S., & Finley, F. N. (1996). Changes in students' understandings of evolution resulting from different curricular and instructional strategies. *Journal of Research in Science Teaching, 33*, 879-900.

Johnson, R. L., & Peeples, E. E. (1987). The role of scientific understanding in college: Student acceptance of evolution. *American Biology Teacher, 49*, 93-98.

Kagan, D. M. (1992). Implications of research on teacher belief. *Educational Psychologist, 27*, 65-90.

Kahveci, A., Southerland, S. A., & Gilmer, P. J. (2006). Retaining undergraduate women in science, mathematics and engineering. *Journal of College Science Teaching, 36*, 34 – 38.

Kelemen, D., & Rosset, E. (2009). The human function compunction: Teleological explanation in adults. *Cognition, 111*, 138-143. doi: 10.1016/j.cognition.2009.01.001

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551-578. doi: 10.1002/tea.10036

King, P. M., & Kitchener, K. S. (1994). *The development of Reflective Judgment in adolescence and adulthood*. San Francisco, CA: Jossey Bass.

Koumi, I., & Tsiantis, J. (2001). Smoking trends in adolescence: Report on a Greek school-based, peer-led intervention aimed at prevention. *Health Promotion International, 16*(65-72).

Lankford, D. E. (2010). *Examining the pedagogical content knowledge and practice of experience secondary biology teachers for teaching diffusion and osmosis.* PhD dissertation, University of Missouri, Columbia, MO.

Latessa, R., & Mouw, D. (2005). Use of an audience response system to augment interactive learning. *Family Medicine, 37*, 12-14.

Lawson, A. E., Alkhoury, S., Benford, R., Clark, B. R., & Falconer, K. A. (2000). What kinds of scientific concepts exist? Concept construction and intellectual development in college biology. *Journal of Research in Science Teaching, 37*, 996-1018.

Lawson, A. E., & Weser, J. (1990). The rejection of nonscientific beliefs about life: Effects of instruction and reasoning skills. *Journal of Research in Science Teaching, 27*, 589-606.

Lawson, A. E., & Worsnop, W. A. (1992). Learning about evolution and rejecting a belief in special creation: Effects of reflective reasoning skill, prior knowledge, prior belief and religious commitment. *Journal of Research in Science Teaching, 29*, 143-166.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Lederman, N. G., & Niess, M. L. (1999). Training college teachers. *School Science and Mathematics, 99*, 413-417.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of Nature of Science Questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497-521. doi: 10.1002/tea.10034

Lenze, L. F., & Dinham, S. M. (1994, April). *Examining pedagogical content knowledge of faculty new to teaching.* Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, LA.

Libarkin, J. C., Anderson, C. W., Dahl, J., Beilfuss, M., & Boone, W. (2005). Qualitative analysis of college students' ideas about the Earth: Interview and Open-Ended Questionnaries. *Journal of Geoscience Education, 53*, 17-26.

Libarkin, J. C., Anderson, S., Dahl, J., Beilfuss, M., Boone, W., & Kurdziel, J. (2005). College students' ideas about geologic time, Earth's interior, and Earth's crust. *Journal of Geoscience Education, 53*, 17-26.

Libarkin, J. C., & Anderson, S. W. (2005). Assessment of learning in entry-level geoscience courses: Results from the Geoscience Concept Inventory. *Journal of Geoscience Education, 53*, 394-401.

Libarkin, J. C., Kurdziel, J. P., & Anderson, S. W. (2007). College student conceptions of geological time and the disconnect between ordering and scale. *Journal of Geoscience Education, 55*, 413-422.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. Thousand Oaks: CA: Sage Publications, Inc.

Lord, T. R., & Marino, S. (1993). How university students view the theory of evolution. *Journal of College Science Teaching, 22*, 353-357.

Lortie, D. C. (1975). *Schoolteacher*. Chicago, IL: University of Chicago Press.

Loughran, J., Gunstone, R., Berry, A., Milroy, P., & Mulhall, P. (2000, April). Science cases in action: Developing an understanding of science teachers' pedagogical content knowledge. Paper presented at the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*, 370-391. doi: 10.1002/tea.20007

Loughran, J., Berry, A., & Mulhall, P. (2006). *Understanding and developing science teachers' pedagogical content knowledge*. Rotterdam, The Netherlands: Sense Publishers.

Lovely, E. C., & Kondrick, L. C. (2008). Teaching evolution: Challenging religious preconceptions. *Integrative and Comparative Biology, 48*, 164-174. doi: 10.1093/icb/icn026

Lynd-Balta, E., Erklenz-Watts, M., & Freeman, C. (2006). Professional development using an interdisciplinary learning circle: Linking pedagogical theory to practice. *Journal of College Science Teaching, 35*(4), 18-24.

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 95-132). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Major, C., & Palmer, B. (2002). Faculty knowledge of influences on student learning. *Peabody Journal of Education, 77*, 138-162. doi: 10.1207/S15327930PJE7703_8

Martin, J. W. (2010). Compatibility of major U.S. Christian denominations with evolution. *Evolution: Education and Outreach, 3*, 420-431. doi: 10.1007/s12052-010-0221-5

Mayr, E. (1982). *The growth of biological thought*. Cambridge, MA: Harvard University Press.

McKeachie, W. J., Lin, Y.-G., & Strayer, J. (2002). Creationist versus evolutionary beliefs: Effects on learning biology. *American Biology Teacher, 64*, 189-192.

Medin, D., & Atran, S. (2004). The native mind: Biological categorization and reasoning in development and across cultures. *Psychological Review, 111*, 960-983.

Meir, E., Perry, J., Herron, J. C., & Kingsolver, J. (2007) College students' misconceptions about evolutionary trees. *American Biology Teacher*, *69*, 71–76.

Merriam, S. B. (1988). *Case study in education: A qualitative approach*. San Francisco, CA: Jossey-Bass.

Merriam, S. B. (1998). *Qualitative research and case study applications in education: Revised and expanded from case study research in education*. San Francisco, CA: Jossey-Bass Publishers.

Metcalfe, J., & Shimamura, A. P. (1994). *Metacognition: Knowing about knowing*. Cambridge, MA: MIT Press.

Mintzes, J. J., & Leonard, W. H. (2006). *Handbook of college science teaching*. Arlington, VA: NSTA Press.

Moore, R., Mitchell, G., Bally, R., Inglis, M., Day, J., & Jacobs, D. (2002). Undergraduates' understanding of evolution: Ascriptions of agency as a problem for student learning. *Journal of Biological Education, 36*, 65-71.

Morse, J. M. (1991). Approaches to qualitative-quantitative methodological triangulation. *Nursing Research, 40*, 120-123.

Mortimer, E. F. (1995). Conceptual change or conceptual profile change? *Science and Education, 4*, 267-285.

Nadelson, L. S., & Southerland, S. A. (2010a). Development and evaluation for a measuring understanding of macroevolutionary concepts: Introducing the MUM. *Journal of Experimental Education, 78*, 151-190. doi: 10.1080/00220970903292983

Nadelson, L. S., & Southerland, S. A. (2010b). Examining the interaction of acceptance and understanding: How does the relationship change with a focus on macroevolution. *Evolution: Education and Outreach, 4*, 82-88. doi: 10.1007/s12052-009-0194-4

National Academy of Sciences. (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academy Press.

National Association of Biology Teachers. (2010). Mission statement, from http://www.nabt.org/websites/institution/index.php?p=1

National Geographic. (2005). Evolution less accepted in U.S. than other western countries, study finds, from http://news.nationalgeographic.com/news /2006/08/060810-evolution_2.html

National Research Council [NRC]. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council [NRC]. (2011). *A framework for K-12 science education: Practices, cross-cutting concepts, and core ideas.* Washington, DC: National Academies Press.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

National Science Teachers Association [NSTA]. (1998). NSTA position statement on informal science education. *Journal of College Science Teaching, 28,* 17–18.

Nehm, R. H., Poole, T. M., Lyford, M. E., Hoskins, S. G., Carruth, L., Ewers, B. E.. . . (2009). Does the segregation of evolution in biology textbooks and introductory courses reinforce students' faulty mental models of biology and evolution? *Evolution: Education and Outreach, 2*, 527-532. doi: 10.1007/s12052-008-0100-5

Nehm, R. H., & Reilly, L. (2007). Biology majors' knowledge and misconceptions of natural selection. *BioScience, 57*, 263-272.

Nehm, R. H., & Schonfeld, I. (2008). Measuring knowledge of natural selection: A comparison of the CINS, an open-response instrument, and an oral interview. *Journal of Research in Science Teaching, 45*, 1131-1160. doi: 10.1002/tea.20251

Nehm, R. H., & Schonfeld, I. S. (2010). The future of natural selection knowledge measurement: A reply to Anderson et al. (2010). *Journal of Research in Science Teaching, 47*, 358-362. doi: 10.1002/tea.20330

Newport, F. (2009). On Darwin's birthday, only 4 in 10 believe in evolution. Retrieved from http://www.gallup.com/poll/114544/Darwin-Birthday-Believe-Evolution.aspx

Nilsson, P. (2013, April). *When teaching makes difference - Developing science teachers' Pedagogical Content Knowledge (PCK) through the approach of learning study*. Paper presented at the National Association for Research in Science Teaching, San Juan, Puerto Rico.

Nilsson, P., & Loughran, J. (2010, March). *Understanding and assessing primary science student teachers' pedagogical content knowledge.* Paper presented at the Annual Conference for the National Association for Research in Science Teaching, Philadelphia, PA.

Novick, L. R., & Catley, K. M. (2012). Assessing students' understanding of macroevolution: Concerns regarding the validity of the MUM. *International Journal of Science Education, 34*, 2679-2703. doi: 10.1080/09500693.2012.727496

Nunnally, J. C. (1978). *Psychometric theory* (2nd ed.). New York, NY: McGraw-Hill.

Padian, K. (2010). How to win the evolution war: Teach macroevolution! *Evolution Education and Outreach, 3*, 206-214. doi: 10.1007/s12052-010-0213-5

Padilla, K., & van Driel, J. (2011). The relationships between PCK components: the case of quantum chemistry professors. *Chemistry Education Research and Practice, 12*, 367-378. doi: 10.1039/C1RP90043A

Padilla, K., Ponce-de-Leon, A., Rembado, F. M., & Garritz, A. (2008). Undergraduate professors' pedagogical content knowledge: The case of 'amount of substance'. *International Journal of Science Education, 30*, 1389-1404. doi: 10.1080/09500690802187033

Pareja, J. I. (2007). *Prospective faculty developing understanding of teaching and learning processes in science.* Unpublished doctoral dissertation, University of Missouri, St. Louis, MO.

Park, S., & Oliver, J. S. (2008). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education, 38*, 261-284.

Park, C., & Ramos, M. (2002). The donkey in the department? Insights into the graduate teaching assistant experience in the UK. *Journal of Graduate Education, 3*, 47-53.

Passmore, C., & Stewart, J. (2000). A course in evolutionary biology: Engaging students in the "practice" of evolution. Madison, WI: National Center for Improving Student Learning and Achievement in Mathematics and Science.

Patton, M. Q. (2002). *Qualitative research & evaluation methods*. Thousand Oaks, CA: Sage Publications.

Perry, W. G. (1970). *Forms of ethical and intellectual development during the college years: A scheme*. New York, NY: Holt, Rinehart, & Winston, Inc.

Piaget, J. (1952). *The origins of intelligence in children*. New York, NY: International Universities Press.

Pintrich, J., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 6*, 167-199.

Robbins, J. R., & Roy, P. (2007). Identifying and correcting non-science student preconceptions through an inquiry-based critical approach to evolution. *The American Biology Teacher, 69*, 460-466.

Rodriques, R. A. B., & Bond-Robinson, J. (2006). Comparing faculty and student perspectives of graduate teaching assistants' teaching. *Journal of Chemical Education, 83*, 305-. doi: 10.1021/ed083p305

Rutledge, M. L. (1996). *Indiana high school biology teachers and evolutionary theory: Acceptance and understanding*. Unpublished doctoral dissertation, Ball State University.

Rutledge, M. L., & Mitchell, M. A. (2002). Knowledge structure, acceptance, & teaching of evolution. *The American Biology Teacher, 64*, 21-28.

Rutledge, M. L., & Sadler, K. C. (2007). Reliability of the Measure of Acceptance of the Theory of Evolution (MATE) with university students. *The American Biology Teacher, 69*, 332-335.

Rutledge, M. L., & Warden, M. A. (1999). The development and validation of the Measure of Acceptance of the Theory of Evolution instrument. *School Science and Mathematics, 99*, 13-18.

Rutledge, M. L., & Warden, M. A. (2000). Evolutionary theory, the nature of science & high school biology teachers: Critical relationships. *The American Biology Teacher, 62*, 23-31.

Ryder, J., Leach, J., & Driver, R. (1999). Undergraduate science students' images of science. *Journal of Research in Science Teaching, 36*, 201-219.

Scharmann, J. C. (1990). Enhancing an understanding of the premises of evolutionary theory: The influence of a diversified instructional strategy. *School Science and Mathematics, 90*, 91-100.

Scharmann, J. C., & Harris, W. M. (1992). Teaching evolution: Designing successful instruction. *The American Biology Teacher, 55*, 481-486.

Schneps, M. H., & Sadler, P. (Writers). (1988). A private universe [Videotape]: Pyramid Film and Video.

Schwab, J. J. (1978). *Science, curriculum and liberal education*. Chicago, IL: University of Chicago Press.

Scott, E. C. (1997). Antievolution and creationism in the United States. *Annual Reviews of Anthropology, 26*, 263-289.

Settlage, J., & Odom, A. L. (1995, April). *Natural selection conceptions assessment: Development of the two-tier test "Understanding Biological Change."* Paper presentation at the National Association of Research in Science Teaching annual meeting, San Francisco, CA.

Seymour, E., & Hewitt, N. M. (1997). *Talking about leaving: Why undergraduates leave the sciences*. Boulder, CO: Westview Press.

Showers, D. E., & Shrigley, R. L. (1995). Effects of knowledge and persuasion on high-school students' attitudes toward nuclear power plants. *Journal of Research in Science Teaching, 32*, 29-43.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*, 1-21.

Siebert, E. D., & McIntosh, W. J. (Eds.). (2001). *College pathways to the Science Education Standards*. Arlington, VA: NSTA Press.

Sinatra, G. M., Brem, S. K., & Evans, M. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach, 1*, 189-195. doi: 10.1007/s12052-008-0037-8

Sinatra, G. M., Southerland, S. A., McConaughy, F., & Demastes, J. W. (2003). Intentions and beliefs in students' understanding and acceptance of biological evolution. *Journal of Research in Science Teaching, 40*, 510-528. doi: 10.1002/tea.10087

Sinclair, A., Pendarvis, M. P., & Baldwin, B. (1997). The relationship between college zoology students' beliefs about evolutionary theory and religion. *Journal of Research and Development in Education, 30*, 118-125.

Sirum, K. L., Madigan, D., & Klionsky, D. J. (2009). Enabling a culture of change: A life science faculty learning community promotes science teaching. *Journal of College Science Teaching, 38(*3), 38-44.

Smith, M. U. (2009). Current status of research in teaching and learning evolution I: Philosophical/epistemological issues. *Science & Education*. doi: 10.1007/s11191-009-9215-5

Smith, M. U., & Scharmann, J. C. (1999). Defining versus describing the nature of science: A pragmatic analysis for classroom teachers and science educators. *Science Education, 83*, 493-509.

Smith, M. U., & Siegel, H. (2004). Knowing, believing, and understanding: What goals for science education? *Science & Education, 13*, 553-582.

Southerland, S. A. (2000). Epistemic universalism and the shortcomings of curricular multicultural science education. *Science and Education, 9*, 289-307.

Southerland, S. A., & Sinatra, G. M. (2003). Learning about biological evolution. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change*. Mahwah, NJ: Lawrence Erlbaum Associates.

Southerland, S. A., & Sinatra, G. M. (2005). *Beyond Cartesian dualism: Encountering affect in the teaching and learning of science*. Dordrecht, The Netherlands: Springer.

Stake, R. E. (2000). Case studies. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 134-164). Thousand Oaks, CA: Sage Publications, Inc.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 147-176). Albany, NY: SUNY.

Swami, R. K. (2002). *Perceptions of physical science faculty at the college level about teaching introductory level science courses.* Unpublished doctoral dissertation, University of Cincinnati, Cincinnati, OH.

Tashakkori, A., & Teddlie, C. (Eds.). (2003). *Handbook of mixed methods in social and behavioral research*. Thousand Oaks, CA: Sage Publications, Inc.

Thorndike, R. (1997). *Measurement and evaluation in psychology and education* (6th ed.). Upper Saddle River, NJ: Prentice-Hall, Inc.

Tobin, K. G., Tippins, D. J., & Gallard, A. J. (1994). Research on instructional strategies for teaching science. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 45-93). New York, NY: Macmillan.

Trend, R. D. (2001). Deep time framework: A preliminary study of U.K. primary teachers' conceptions of geological time and perceptions of geoscience. *Journal of Research in Science Teaching, 38*, 191-221.

Trigwell, K., Prosser, M., & Taylor, P. (1994). Qualitative differences in approaches to teaching first year university science. *Higher Education, 27*, 75-84.

University of Missouri. (2011). Fall 2011 enrollment summary Retrieved March 21, 2013, from http://registrar.missouri.edu/statistics/fall-2011/Fall-2011-Enrollment-Summary-combined.htm

van Driel, J., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching, 35*, 673-695.

Veal, W. R., & MaKinster, J. G. (1999). Pedagogical content knowledge taxonomies. *Electronic Journal of Science Education, 3*(4), 1-17.

Verloop, N., van Driel, J., & Meijer, P. (2001). Teacher knowledge and the knowledge base for teaching. *International Journal of Educational Research, 35*, 441-461.

Verhey, S. D. (2005). The effect of engaging prior learning on student attitudes toward creationism and evolution. *BioScience, 55*, 996-1003.

von Glasersfeld, E. (1984). An introduction to radical constructivism. In P. Watzlawick (Ed.), *The invented reality: How do we know what we believe we know?: Contributions to constructivism*. New York, NY: Norton.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the Earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Wallace, J., & Louden, W. (1992). Science teaching and teachers' knowledge: Prospects for reform of elementary classrooms. *Science Education, 76*, 507-521.

Winslow, M. W., Staver, J. R., & Scharmann, J. C. (2011). Evolution and personal religious belief: Christian university biology-related majors' search for reconciliation. *Journal of Research in Science Teaching, 48*, 1026-1049. doi: 10.1002/tea.20417

Wellman, H. M., & Gelman, S. A. (1998). Knowledge acquisition in foundational domains. In W. Damon, D. Kuhn & R. Siegler (Eds.), *Handbook of child psychology* (5th ed., Vol. 2. Cognition, perception and language, pp. 523-574). New York, NY: Wiley.

Wilson, R. (2010, 10 September 2010). Why teaching is not priority no. 1. *Chronicle of Higher Education, 57,* A1-A8.

Witzig, S. B. (2012). *Investigating experiences that inform university instructors' specialized knoeldge for teaching protein synthesis.* Unpublished doctoral dissertation, University of Missouri, Columbia, MO.

Wulff, D. H., Austin, A. E., & Associates. (2004). *Paths to the professoriate: Strategies for enriching the preparation of future faculty*. San Francisco, CA: Jossey-Bass.

Yin, R. (1994). *Case study research: Design and methods (2nd ed.)*. Thousand Oaks, CA: Sage Publishing.

Zhao, N., Witzig, S. B., Weaver, J. C., Adams, J. E., & Schmidt, F. J. (2012). Transformative professional development: Inquiry-based college science teaching institutes. *Journal of College Science Teaching, 41*(3), 18-25.

Appendix A

Descriptions of the key concepts of natural selection (Nehm & Schonfeld, 2008, p. 1138). [1] = addressed on the original Conceptual Inventory of Natural Selection (Anderson, Fisher & Norman, 2002) but not on the open response instrument and interviews done by Nehm and Schonfeld (2008).

Key Concept	**Definition**
Origin and existence of variation	Random mutations and sexual reproduction produce variations; while many are harmful or of no consequence, a few are beneficial in some environments; individuals of a population vary extensively in their characteristics
Variation heritability	Much of variation is heritable.
Limited survival	Production of more individuals than the environment can support leads to a struggle for existence among individuals of a population, with only a fraction surviving each generation.
Biotic potential	All species have such great potential fertility that their population size would increase exponentially if all individuals that are born would again reproduce successfully.
Natural resources	Natural resources are limited; nutrients, water, oxygen, etc. necessary for living organisms are limited in supply at any given time
Differential survival	Survival in the struggle for existence is not random, but depends in part on the heredity of the surviving individuals. Those individuals whose surviving characteristics fit them best to their environment are likely to leave more offspring than less fit individuals
Change in a population	The unequal ability of individuals to survive and reproduce will lead to gradual change in a population, with the proportion of individuals with favorable characteristics accumulating over the generations.
Population stability[1]	Most populations are normally stable in size except for seasonal fluctuations.
Origin of species[1]	An isolated population may change so much over time that it becomes a new species.

Appendix B

Measure of Understanding of Macroevolution (MUM); Nadelson & Southerland, 2010a

Directions: This survey asks questions about your knowledge of evolutionary principles. Completion of the questions is required to receive homework points. However, it is your choice if you wish for your answers to be included in the research study.

Consent Questions

Question A

1. Yes, I understand the information presented about the research project and have had an opportunity to ask questions and receive answers pertaining to this project.

Question B

1. I am at least 18 years of age.
2. I am less than 18 years of age.

Question C

1. I have been informed of this study and agree for my answers to the questions and final grade in the Bio 1010 course to be included in data analysis and publications of the research study. I am aware that my information will be kept confidential. I am aware that participation is voluntary and I am free to withdraw participation at any time without penalty.
2. I have been informed of this study and do not agree for my answers to the questions to be included in data analysis and publications of the study.

Question D

1. I am not majoring in biology.
2. I am majoring in biology.

Directions: Read each of the passages. Select the best option for each of the associated items that follow.

Questions 1-5: Consider Figure 1 and passage below and answer the questions that follow.

Consider the proposed evolutionary tree below. Mammals originated on land, yet whales are adapted to life in the sea and can never come onto the land. The exact process of how land animals evolved into whales has been difficult to understand. However, new discoveries in India, Afghanistan and Pakistan are providing evidence for the transition of the whale family from ancient shore dwelling ancestors.

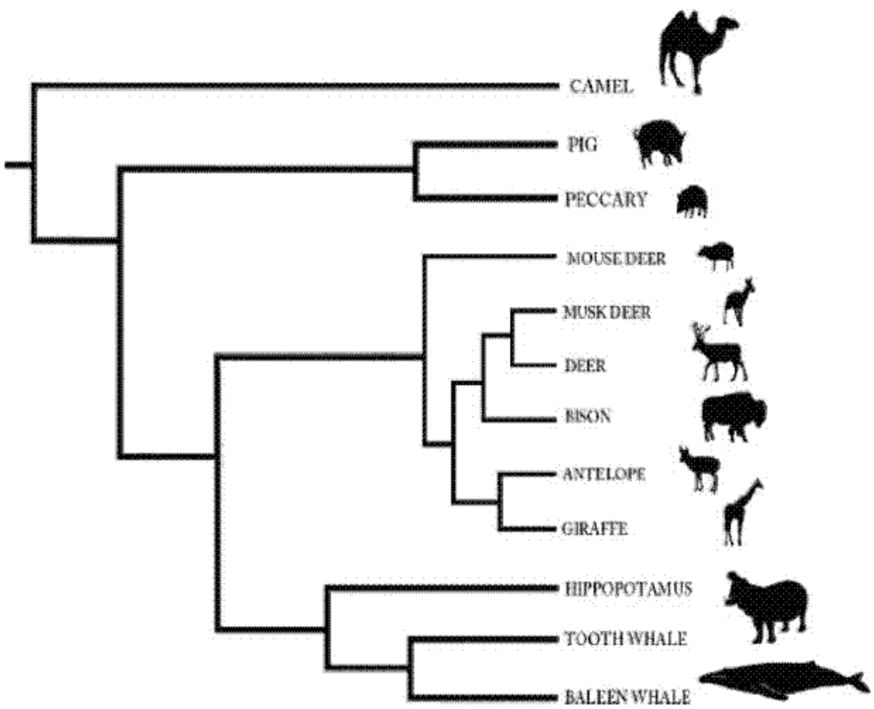


FIGURE 1 The evolutionary tree of some mammals.

1. The whales are classified with a group of mammals which are called even toed ungulates. Whales have been classified as part of this group along with their closest relative the hippopotamus because:
    1. Whales and hippos are big, heavy, and have round bodies with large mouths.
    2. Whales and hippos share a more recent common ancestor.
    3. Whales and hippos have similar diets and need to live in water.
    4. Whales and hippos display similar social and parenting behaviors.

2. The chart (Figure 1) above suggests that:
    1. The animals in this classification tree have four legs.
    2. Baleen whales are not related to camels.
    3. Whales are more closely related to giraffes than to bison.
    4. Whales are more closely related to deer than to pigs.

3. According to evolutionary theory, whales have evolved from land animal ancestors over time. How much time do you think the evolution process might have taken?

1. Fifty million years (50,000,000). 3. Five hundred thousand years (500,000).
2. Five million years. (5,000,000). 4. Five hundred million years (500,000,000).

4. The fossils that are being examined to determine the ancestor in the evolutionary pathway of whales have been found in areas of Pakistan, Afghanistan, and India, places that are now well above sea level. The most scientifically reasonable explanation for the location of the fossils being examined is:

1. Predators of whale ancestors carried their prey to this area to eat them.
2. When the whales died their skeletons floated to the top of the ocean where they drifted ashore and became fossils.
3. This area was most likely once covered with water and the shore dwelling ancestors of whales once lived in these areas, died, and their skeletons were fossilized.
4. The great meteor impact caused tidal wave that forced these animals into these areas trapping them causing them to die, and their skeletons were fossilized.

5. The evolutionary history and development of whales has been hotly debated. Recently there has been a major shift in our understanding of the processes used to detail whale evolution. This indicates that:

1. Gaps in the fossil records will never allow us to fully understand evolution.
2. Scientists studying evolution typically present ideas with very little evidence, leaving it to others to find proof of their ideas.
3. Aspects of evolution are constantly being challenged and explored in light of new evidence.
4. Much of the science of evolution is based on speculation that can easily be changed when scientists think of new ideas.

6. The origins of the transformation from land animal to sea creature may be observed among some wild sheep who have lived on the coast for hundreds of years. These sheep like to eat seaweed and kelp so much that they are often observed swimming into the water to eat it. If we returned millions of years later to observe these animals, what might you see?

1. Sheep who wanted to be better swimmers and so developed the ability to swim great distanced to eat kelp.
2. Two distinct but related sheep like organisms, one that lives in the water and eats kelp, the other lives on land and eats plants.
3. These sheep will become extinct because they will not be able to find other food and only their fossil will remain.
4. There are so many possible outcomes that there is really no way to predict what will be seen.

Questions 7-12: Consider the two figures and passage below and answer the questions that follow.

The evolution of the eye has been studied extensively. It is a good example of an organ that at present has a wide range of forms in a wide variety of species (see Figure 2). Most experts think that all modern eyes have their origins dating back some 540 million years. An examination of the density of photoreceptors of the pigment cup and the complex eye reveal a variation within species as well as between species. The plots of the relative density of photoreceptors of the present day Nautilus and Octopus are presented in Figure 3.

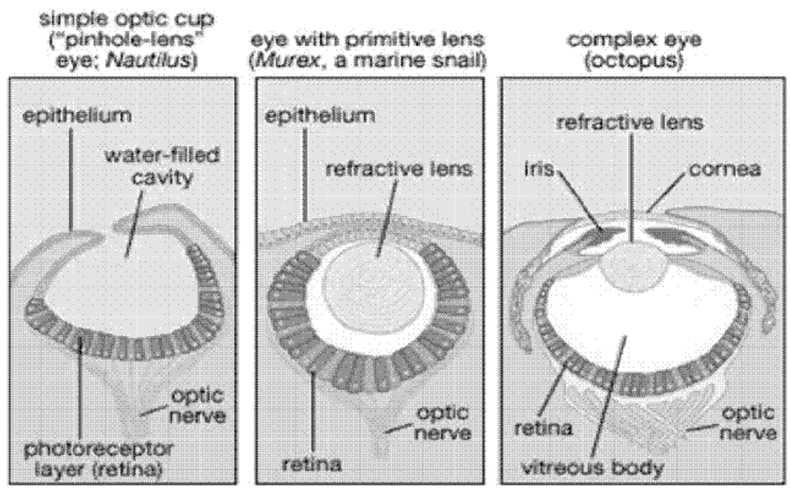


FIGURE 2 The different levels of eye complexity in mollusks.

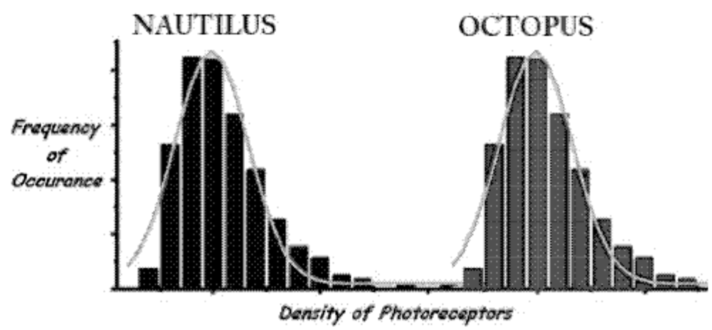


FIGURE 3 Variation in the relative density of photoreceptors in nautilus and octopus eyes.

7. In the evolution of the molluscan eye, it is apparent that some fundamental characteristics are retained. This supports the idea that:

1. The organisms displaying these fundamental characteristics all have descended from an ancestor who most likely also had eyes.
2. These are the only features that are effective for sight and therefore animals want to keep them so that they can see.
3. Eyes are essential for survival of species so organisms and struggle and work to retain these features.

4. Mollusk eyes have such similar features to all other seeing marine organisms that none of these eyes could have developed independently.

8. Some speculate that the eye is too complex to have resulted from evolution. Yet, evidence suggests organisms may have had eyes for nearly 500 million years. What might scientists infer about the eyes of ancient organisms?

1. Only animals living in the bright sunlight develop eyes because they need them and use them.
2. Eyes would bear no resemblance to how eyes are structured today, and would not be recognized as eyes.
3. The eyes of ancient organisms would have some characteristics that are similar to eye found in organisms alive today.
4. Only animals with bones would really be trying to develop useful eyes.

9. Most vertebrate fossils are the bones of these ancient organisms, and it is unlikely that we will find fossils of their eyes. This is because:

1. Animals close their eyes when they die and the eyes are buried under layers of fossils.
2. Primitive eyes were so small that they are easily overlooked as fossils.
3. Primitive eyes were so different that scientists are not looking for the right structures.
4. Eye tissue typically decays before it can form fossils.

10. There is a variation in the number and density of photoreceptors in the eyes (see Figure 3, page 4) within a population. This is an important consideration when trying to understand evolution because:

1. Some individuals in a population are trying harder to see better than others.
2. The variation in eye structure within a population can lead to the development of new eye structures.
3. There are variations happening within all populations and they have no evolutionary significance.
4. Variations indicate a species is no longer evolving but now stabilized.

11. Evidence for the evolution of the eye is based primarily on the observations of organisms alive today. This means:

1. Since present day animals have all developed very complex eyes, useful inferences about changes in primitive eyes are very difficult to make.
2. Scientists must assume that the eyes of organisms today are the same as their extinct ancestors.
3. Eyes are a recent development, evolutionarily speaking, and scientist cannot understand the structure of the eyes in the past based on evidence of eyes today.
4. The structure of the eyes in some organisms today support scientists' views of how eyes developed over time.

12. Different organisms are classified based on similar functions and forms. All of the eyes in Figure 2 (page 4) are from a group of animals referred to as mollusks. Yet, the eyes of these three species of organisms do not seem to be very similar in structure, which suggests that classification of these organisms has been based on evidence that indicates:

1. They can be traced back to a common ancestor that had a primitive eye.
2. That they all live in a similar location and need eyes that allow them to see in the water.
3. They want to be able to see in the water to catch prey and avoid predators.
4. Mollusks' eyes are not considered when grouping these organisms together.

Questions 13-17: Consider Figure 4 and the passage below and answer the questions that follow.

Extinction is extremely important in the history of life. It can be a frequent or rare event within a lineage. Every lineage has some chance of becoming extinct. Over 99% of the species that have ever lived on Earth have gone extinct. This diagram illustrates the evolution lineages of several animal species.

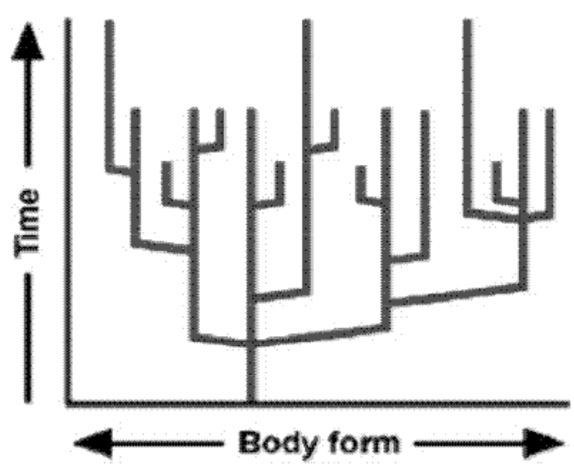


FIGURE 4 The historical development of the lineages of several animal species.

13. The diagram above (Figure 4) indicates that all of the organisms originated from the same:

1. Kingdom.	3. Location on the planet.
2. Relatives.	4. Ancestor.

14. If each of the vertical lines in the diagram above represents a lineage, what is being shown about the number of living species present over time?

1. Increases and decreases in the number of species present over time.

2. Constantly diversified into an increased number of species with different body forms.
3. Mostly remained unchanged and stable and have experienced little change over time.
4. Constant, yet gradual, decrease in number of species and body forms.

15. The branching of the animal species as displayed in Figure 4 (previous page) would happen:

1. Everyday.
2. Over relatively long periods of time-millions of years.
3. Occur within a few generations.
4. Within the life span of an organism.

16. The formation of branching diagrams like the one presented in Figure 4 (previous page) is based on:

1. Common names of the organisms.
2. Genes and body structures.
3. Habitat in which modern organisms are now naturally found.
4. Elevation and location in which the ancient fossils were discovered.

17. A number of lineages in Figure 4 (previous page) terminate prior to the top of the tree. This indicates that these species are now extinct. Our awareness of their existence is based on fossils and this suggests that they:

1. Were organisms with bones, exoskeletons, or left impressions.
2. All had similar life cycles because they are all present in the fossil record.
3. Were thought to be primarily prey killed off by the surviving predators.
4. Died in locations in which there was no more food.

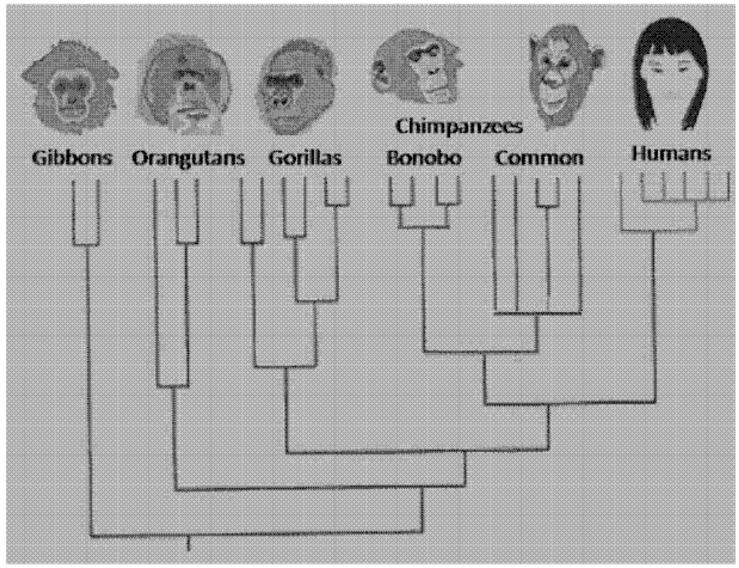


FIGURE 5 A hypothesized evolutionary lineages of the African Great Apes.

18. The branching in Figure 5 above indicates the development of several new species. When new species arise:

1. New species immediately appear different and that is why the branch is created.
2. The original species will no long have the need or desire to evolve.
3. The original species will soon become extinct because the new species is better adapted to the environment.
4. New species have characteristics that are similar to the original species.

Questions 19-23: Consider the Figure 5 on the previous page and passage below and answer the questions that follow.

Figure 5 is a suggested evolutionary pathway of the African Great Apes. The arrangement of this pathway is based on genetic information taken from the mitochondria of the various apes.

19. The diagram on the previous page (Figure 5) suggests that:

1. Gibbons and Orangutans are more closely related than Gibbons and Humans.
2. Humans are much more complex than the other apes.
3. Humans and Chimpanzees are the most closely related of all the Great Apes.
4. Gibbons are unrelated to Humans.

20. The diagram on the previous page (Figure 5) suggests that:

1. Orangutans include the most recently evolved species and Gibbons are the most ancient species of apes.
2. There has always been at least 5 species of Great Apes.
3. Gorillas represent the most diverse of the different groups of Great Apes.
4. Humans and Chimpanzees share a more recent common ancestor than Gibbons and Orangutans.

21. The African Great Apes are theorized to have evolved from a common ancestor. Given that this process took place over time, how much time do you think the process of evolution in this group of organisms might take?

1. Thirty million years. (30,000,000)
3. Thirty thousand years. (30,000)
2. Three billion years. (3,000,000,000)
4. Three million years. (3,000,000)

22. The fossil record for early humans is very sparse compared to many other organisms. In the context of the Great Ape tree this means:

1. Much of the evolutionary relationships of humans and the other Great Apes is opinion and based on guess.
2. Analysis of genetic codes and anatomy are used to derive such relationships.
3. The evolutionary relationships of humans are relative easy to determine based on the wide variety of humans alive today.
4. Humans have not undergone many evolutionary changes and remain at the top of the tree.

23. In advanced discussions of the evolution of the Great Apes, one will see a number of different evolutionary pathways, each suggesting a different relationship between the different groups of Apes. These discrepancies suggest:

1. Scientists remain uncertain if any of the Great Apes are really related and are continuing to try to prove this.
2. Scientists remain uncertain why humans would want to evolve and are continued to be seen as the superior species.
3. Anything aside from fossils is a weak form of evidence for the support of evolutionary theory.
4. Processes and small differences in methods can produce very different evidence that can be interpreted in different ways.

Question 24-27: Consider Figure 6 and passage below and answer the questions that follow.

The graphic below is a map depicting where the fossils of various organisms have been found on different continents. This map also depicts our best understanding of the relative position of some of the continents in the Earth's early history.

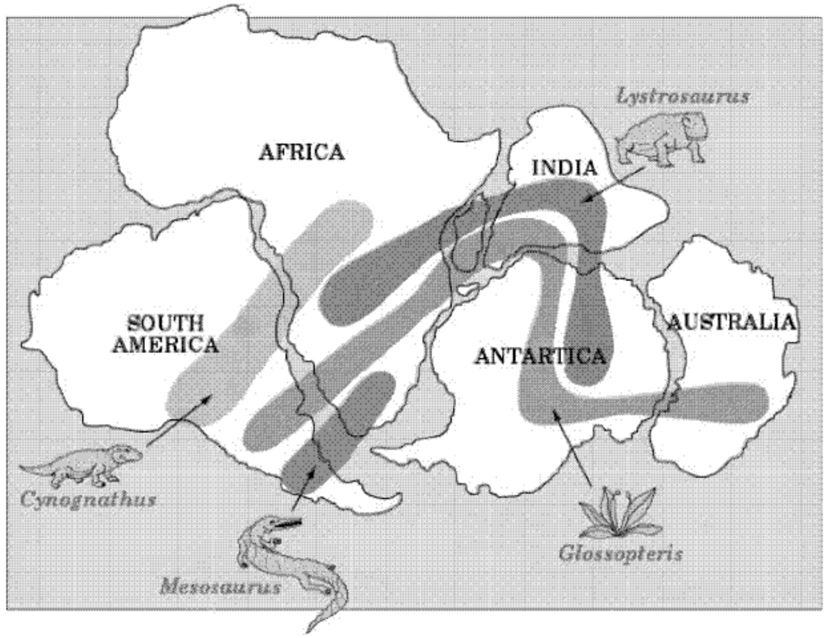


FIGURE 6 The distribution of fossils for 4 species across today's continents. The map shows how the continents may have once been located.

24. The separation of the continents and the separation of the organisms on these continents allowed for:

1. Extinction, as the organisms were separated they could not survive as smaller groups.
2. The production of new species, as groups of organisms were permanently separated.
3. Organisms to remain unchanged, given the very slow movement of the continents and the slow rate of evolution.
4. Organisms to interbreed, as their home ranges changed they joined together with other groups of organisms.

25. If a similar fossil was found on different continents, scientists might infer that:

1. The continents involved were once connected.
2. Eventually, the organisms will want to spread out and will be found on every continent.
3. They must have come from different species but all look the same.
4. The organisms were aware enough to know it was vital to move between continents.

26. The theory of plate tectonics was largely discredited when it was first proposed. Fossil evidence (as shown in Figure 6) gave additional support to this theory. The theory then began to be much more widely accepted by scientists. This demonstrates that:

1. Theories are often supported by a number of different lines of evidence.
2. Scientific theories change very easily and are frequently just seen as hunches.
3. Knowledge about historical events is particularly weak.
4. Nobody can ever really know how plate movement as described by plate tectonics takes place.

27. The supercontinent depicted in Figure 6 is known as Gondwana. This supercontinent existed roughly:

1. Five million years. (5,000,000)
2. One and a half billion years. (1,500,000,000)
3. One hundred fifty million years. (150,000,000)
4. Three hundred and fifty thousand years. (350,000)

Appendix C

Measure of Acceptance of the Theory of Evolution (MATE); Rutledge & Warden, 1999

Overview: This survey asks questions about your views of evolution. Completion of the questions is required to receive homework points. However, it is your choice if you wish for your answers to be included in the research study.

Consent Questions

Question A

1. Yes, I understand the information presented about the research project and have had an opportunity to ask questions and receive answers pertaining to this project.

Question B

1. I am at least 18 years of age.
2. I am less than 18 years of age.

Question C

1. I have been informed of this study and agree for my answers to the questions and final grade in the Bio 1010 course to be included in data analysis and publications of the research study. I am aware that my information will be kept confidential. I am aware that participation is voluntary and I am free to withdraw participation at any time without penalty.
2. I have been informed of this study and do not agree for my answers to the questions to be included in data analysis and publications of the study.

Question D

1. I am not majoring in biology.
2. I am majoring in biology.

Directions:

For the following items, please indicate your agreement/disagreement with the given statements using the following scale.

A	B	C	D	E
Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree

1. Organisms existing today are the result of evolutionary processes that have occurred over millions of years.
2. The theory of evolution is incapable of being scientifically tested.
3. Modem humans are the product of evolutionary processes which have occurred over millions of years.
4. The theory of evolution is based on speculation and not valid scientific observation and testing.

5. Most scientists accept evolutionary theory to be a scientifically valid theory.
6. The available data are ambiguous as to whether evolution actually occurs.
7. The age of the Earth is less than 20,000 years.
8. There is a significant body of data which supports evolutionary theory.
9. Organisms exist today in essentially the same form in which they always have.
10. Evolution is not a scientifically valid theory.
11. The age of the Earth is at least 4 billion years.
12. Current evolutionary theory is the result of sound scientific research and methodology.
13. Evolutionary theory generates testable predictions with respect to the characteristics of life.
14. The theory of evolution cannot be correct since it disagrees with the Biblical account of creation.
15. Humans exist today in essentially the same form in which they always have.
16. Evolutionary theory is supported by factual, historical, and laboratory data.
17. Much of the scientific community doubts if evolution occurs.
18. The theory of evolution brings meaning to the diverse characteristics and behaviors observed in living forms.
19. With few exceptions, organisms on Earth came into existence at about the same time.
20. Evolution is a scientifically valid theory.

Appendix D

Instructor Observation and Interview Protocols

Prior to first observation:
Researcher role: My role is to assume a stance of empathic neutrality. That is, I empathize with the participant and care about her. However, my role is to UNDERSTAND, not to Evaluate or Teach. I will keep these ideas in mind during my visit.

Pre-Observation Interview
Purpose: to clarify the plans and uncover participant's PCK

Opening Questions

1. Update me about what is going to occur over the few weeks that I am observing.
   a. What will we see across the macroevolution lectures?
   b. What are your purposes and goals for these lectures?
   c. How did you decide on these purposes and goals?
   d. Why are these purposes and goals important to you?

Knowledge of Learners
Say to the participant: Another part of what a teacher knows has to do with how students think about science. The next questions are designed to probe what you know about how students might think about macroevolution.

1. Tell me about the students in this class, in terms of macroevolution.
   a. What ideas about macroevolution do you want the students to learn?
   b. What understandings or alternative conceptions about macroevolution do your students have? How do you know this?
   c. What do you know about your students' attitudes and potential conflicts about macroevolution?
   d. Tell me about your students' abilities to understand macroevolution. In what ways do students naturally vary in their abilities?
   e. How do you think this particular group of students learn macroevolution best? Why do you think that?
   f. How have your experiences with this group and past classes influenced the way you teach macroevolution?
   g. Do what degree do your students accept evolution?

2. Tell me about the students in this class, in terms of context for learning macroevolution.
   a. Tell me about your students' family and religious influences? Influence of friends?
   b. How have you come to know about how these factors influence the students?
   c. What do you know about your students' high school evolution learning experiences?

3. In order for students to learn macroevolution, what should they already know?
   a. How well do you think your students already know that information?
   b. What misunderstandings do you think students may have that would influence their learning of macroevolution?
   c. How did you come to know this?

4. After instruction, how do you expect students to perform on the Measure of Understanding Macroevolution? MATE?

- What strategies might students use?
- What responses might students provide?
- What, if anything, about this topic do you expect students to have difficulty with?
    a. Why do you think they will have difficulty with that?

[Probe for SOURCES of Knowledge of Learners]

Knowledge of Instructional Strategies

Say to the participant: I want to know more about how you organized the instruction during the unit. The next questions will help me better understand your decisions about what and how to teach macroevolution.

1. Talk to me about how you plan to help students learn the important macroevolution ideas you talked about earlier.

2. I noticed that you used a picture (video clip…) in your lecture. Tell me why you used that ____________ at that point in your lecture.
    a. How do you think this (picture, graph, equation, analogy) helps students learn about (this topic)?
    b. Did you consider representing that idea another way?

Knowledge of Curriculum

Say to the participant: These next questions are designed for us to know something about where your ideas for the unit came from.

1. Where did you get your ideas for teaching (this topic)? *Probe for sources.*
    a. Tell me about the materials (PowerPoints, handouts, transparencies) you prepared. Where did the materials (PowerPoints, activities, worksheets, etc.) come from? *Probe for sources of activities as necessary.*
    b. What modifications did you make to existing materials? Why did you make modifications to the materials?
    c. How do you think these materials will help or hinder achieving the purpose of your plans?

2. From your lesson plans, you chose to structure the lecture series in this particular order and using these examples. Talk to me about making these decision.
    a. Why did you choose to order the lectures this way?
    b. Where did you learn about this way to start (continue; end) the lecture series?
    c. Did you consider starting (continuing; ending) the lecture series in a different way? Why/why not?
    d. What other factors influenced your planning decisions?
    e. What other topics and examples have you considered for the class? What has influenced you to choose the current examples over these other ideas?

3. I have some questions for you related to how these plans relate to other topics that you might teach.
    a. How do you see macroevolution as related to other topics you teach?
    b. How does macroevolution fit into the greater evolution unit?
    c. How does macroevolution fit into the bigger picture of what students learn in this class?
    d. How does (this topic) fit into the “big picture” of what students learn about science in college?
4. How has your teaching of evolution and macroevolution changed over the years? Why?

Knowledge of Assessment

Say to the participant: The last area I want to ask you about is how you will know what students learn from this unit.

1. While you are teaching the evolution unit, what ideas about macroevolution do you plan to assess? Why do you think it is important to assess these ideas?

2. What macroevolution ideas do you plan to assess after instruction? Why do you think it is important to assess these ideas?

3. How do you plan to assess the students about macroevolution during and after the evolution unit? (i.e. clickers, unit exam)
    a. Describe how you will find out if students learned what you intended?
    b. Where did you learn about those strategies for finding out about what students learned?
4. What will you do with the information you gain from the assessment? (Ex: clicker responses)
5. How do you select clicker questions?

6. What challenges do you foresee as you assess students?

Is there anything else about your plans that you want me to know? ***Thank you again for participating in this interview.***

During the Observation
The observer will have selected 3-5 interesting instances to discuss. What constitutes an interesting instance?

Knowledge of Learners
Student making a profound comment and the teacher does or doesn't recognize it or misinterprets what the student says or does.
Student makes a comment that demonstrates confusion, and the teacher does or doesn't recognize or misinterprets why the student is confused?
Teacher explicitly recognizes potential student difficulties.

Knowledge of Instructional Strategies
The teacher makes an instructional decision that alters the flow of the classroom by asking a question or directing students to perform a particular task.
The teacher uses an example or analogy or representation to clarify an idea.

Knowledge of Curriculum
A particular task is chosen that may or may not elicit the student thinking that was intended.
The teacher modifies the plan "on the fly" based on what occurs in the classroom.
Teacher refers to math/science content in other parts of the course/curriculum (vertical or horizontal curriculum alignment).

Knowledge of Assessment
Teacher implements assessment to ascertain student prior knowledge.
The teacher recognizes that the students are having difficulty with a particular idea.
The teacher uses a low-level assessment strategy such as providing an "exit slip" that requires students to define rather than explain or synthesize.
The teacher acts on data collected during student assessment.

Interviews During and After Evolution Unit:

Purpose: to have the participant immediately reflect on the instruction as a window into PCK and connect to pre-observation interview.

1. How do you think the week went? In what ways were the lectures I observed different than other times you taught it? Different from your plans?
2. We have selected some parts of the instruction we found particularly interesting. We want to listen to them together and ask you some questions about them.

Let's listen to this part of the lecture using the Tegrity recording (interviewer asks questions starting in one of the following categories based on the reason for selecting the specific interesting instance).

   a. What were you thinking when this was occurring? Tell me more about what was happening when you __________.
   b. **[K of Learners]** What do you think the student was thinking? Why do you think the student was having difficulty at that point? What knowledge about students did you use to make instructional decisions? In what ways, did students influence your teaching decisions today?
   c. **[K of Instructional Strategies]** Tell me about that (example/analogy/activity)? Why did you decide to use that? How did this teaching strategy help you achieve your overall goals? How could you teach this topic in a different way? Where did you learn to teach it that way? [NOTE: questions about instructional strategies should probe all of the different ways that the participant might know to teach a particular topic. For this PCK component, we are interested in "mining" the participants' knowledge about all kinds of different instructional strategies. You should ask this series of questions many times during the interview.]
   d. **[K of Curriculum]** Did the activities achieve the purpose you intended? Why do you think that? How did your curriculum materials support or hinder you in implementing your plan?
   e. **[K of Assessment]** What do you think students got out of the lesson? How do you know? Tell me about how you found out about student learning. Why did you decide to do that? Where did that idea come from? How do you think it worked?
3. Was there a time during the instruction when you changed your plan? Tell me about that.
4. Based on what happened this week, what do you plan to do next week? Will you change anything from your original plans?
5. How do you think this week's instruction may have influenced students' understandings about macroevolution?
6. How do you think this week's instruction may have influenced students' personal acceptance of evolution?

Additional Questions for Final Interview after the evolution unit

Purpose: To understand the teaching orientation(s) of the participant and to understand what she learned from assessing the students on the unit exam.

Prior to interview:

- The participant should send a copy of the unit exam.
- The participant should have time to review and reflect upon student performance on the exam.

1. **[Assessment].** Describe the unit exam for me.
    a. How did you determine the macroevolution questions you asked on the exam?
    b. How did students generally perform on macroevolution questions on the exam? What was difficult for students? Why do you think this was difficult for students?
    c. How will students' performance on the exam influence your instruction or assessments next time you teach the course?
    d. What was your favorite exam question and why?

2. [**Orientations**]. Now consider a typical day of teaching for you.
    a. What is the professor's role in a typical lesson?
    b. What is the students' role in a typical lesson?
    c. How do you prefer to teach?
    d. How does this compare to what you perceive as an ideal professor?
    e. In what ways have your ideas about teaching changed since you first began teaching? Probe for sources of these changes.
    f. Now think of yourself as a learner of science, how do you best learn science concepts?

Appendix E

Student Interview Protocols

Say to the participant: The purpose of the interview is two fold. The first is to understand your ideas about evolution acceptance and your scientific knowledge about macroevolution. The second purpose is to understand your thoughts on how the biology class may or may not have influenced your thinking in these areas. Please keep in mind that <u>there are no right or wrong answers</u>, I just want to understand your thinking.

Student Pre-Conceptions

Macroevolution

1. What was your scientific knowledge about macroevolution <u>before this class</u>? (*Probe for details when necessary, students may have little previous knowledge)*
2. Where do you think your ideas came from? (i.e. school, religion, home)
3. Think about what your professor did and talked about during class.
    a. Can you recall specific things about what you did or discussed that made you think about your previous knowledge of macroevolution?
    b. What did you think about? Why do you think you thought of this?
4. Think about what you were assigned outside of class.
    a. Can you recall specific things that made you think about your previous knowledge of macroevolution?
    b. What did you think about? Why do you think you thought of this?
5. Can you explain this figure to me? (*Go through different MUM figures)*. What does it mean?

Acceptance

6. Can you describe your acceptance evolution <u>before this class</u>? (*Probe for details when necessary)*
7. Where do you think your ideas came from? (i.e. school, religion, home)
8. Think about what your professor did and talked about during class.
    a. Can you recall specific things that made you think about your acceptance of evolution?
    b. What did you think about? Why do you think you thought of this?
9. Think about what you were assigned outside of class.
    a. Can you recall specific things made you think about your acceptance of evolution?
    b. What did you think about? Why do you think you thought of this?

Students Development of Factual Knowledge and a Conceptual Framework

Macroevolution

1. What new scientific knowledge have you developed about macroevolution since this class began?
    a. How does this compare or add to your previous knowledge of macroevolution?
2. Think about what your professor did and talked about during class.

    a. Can you recall specific things about what you did or discussed that influenced your knowledge of macroevolution? *If so, explain why/how.*

3. Think about what you were assigned outside of class.
    a. Can you recall specific things about what you did that influenced your knowledge of macroevolution? *If so, explain why/how.*

4. Probe regarding changes in answers on the Measure of Understanding of Macroevolution (MUM):
    a. On the pre-test, you selected this answer. However, on the post-test, you selected this answer. Can you explain your reasoning for me?
    b. How do you think the Bio 1010 class influenced or did not influence how you answered the post-test question?
5. Since the start of Bio 1010, have you had any experiences <u>not</u> related to class that have influenced your scientific knowledge of macroevolution?

Acceptance

6. Have your views of evolution acceptance changed since the start of Bio 1010?
    a. How does this compare or add to your previous acceptance of evolutoin?
7. Think about what your professor did and talked about during class. Can you recall specific things about what you did or discussed that influenced your acceptance of evolution? *If so, explain why/how.*
8. Think about what you were assigned outside of class. Can you recall specific things about what you did that influenced your knowledge of macroevolution? *If so, explain why/how.*
9. Probe regarding changes in answers on the Measure of Acceptance of the Theory of Evolution (MATE), *Especially those with large change in Likert scale*
    a. The first time you took the survey, you selected this answer. However, on the second time, you selected this answer. Can you explain your reasoning for me?
    b. How do you think the Bio 1010 class influenced or did not influence how you responded the second time you took the survey?
10. Since the start of Bio 1010, have you had any experiences <u>not</u> related to class that have influenced your acceptance of evolution?

Students Must Reflect on Their Own Thinking (Metacognition) / Monitor Progress

1. During class, your professor used _______ (instructional technique used to help students' metacognition).
    a. What do you think of the ________ (instructional technique) used in class?
    b. How do you think the ________ (instructional technique) influenced your learning?
    c. When a ________ (instructional technique) occurs in/out of biology class, explain to me what you usually do.
    d. For formative assessments (i.e. clickers, in class assignments):
        i. How often do you know the answers to the _____ (formative assessment) questions?
        ii. What do you get a question wrong, what do you do?
2. Think about studying for this class and others you take.
    a. How do you know when a topic is easy or difficult for you?
    b. Were you aware which macroevolution topics in Bio 1010 were easy or difficult for you? How aware?
    c. Why do you think these macroevolution topics were easy or difficult?

i. *If applicable* - When _____ (given topic) was difficult for you, what do you do to remedy the problem?

3. Think about the unit exam.
    i. Which questions were difficult? Why?
    ii. Are these topics still difficult for you?

Is there anything else I should know about your learning of macroevolution and acceptance of evolution? **Thank you the time to interview you!**

Appendix F

Factor Loadings for Pilot Study, Pre-Test, and Post-Test Measure of Understanding of Macroevolution (MUM) Using Principle Components Analysis with Kaiser Normalization Method.

Question	Pilot Study MUM (3 Factors)			Pre-Test MUM (1 Factor)	Post-Test MUM (1 Factor)
	Factor 1: Evidence	Factor 2: Common ancestry	Factor 3: Change over time		
Q1	.128	.029	-.185	.031	.116
Q2	.314	.159	.357	.098	.070
Q3	.111	.218	-.212	-.038	.046
Q4	.082	.358	-.328	.687*	.719*
Q5	.403*	.073	.080	.622*	.670*
Q6	.112	-.042	.058	-.032	.079
Q7	.277	-.358	.088	.042	.434
Q8	.083	.235	-.169	.417*	.513*
Q9	.441*	.221	-.032	.313	.721*
Q10	.454*	-.037	.129	.513*	.306
Q11	.202	.274	-.176	-.020	.019
Q12	.095	.107	-.357	.145	.345
Q13	.127	.524*	.134	.375	.583*
Q14	.076	.351	.454*	.048	.001
Q15	.349	-.159	.263	.287	.573*
Q16	.248	-.205	-.289	.542*	.186
Q17	.518*	-.099	.210	.225	.010
Q18	.246	.210	-.169	.189	.389
Q19	.098	.130	.228	.131	.101
Q20	.360	-.091	.233	.162	.227
Q21	.190	.467*	-.118	-.075	.123
Q22	.334	.031	.236	.016	-.020
Q23	.556*	.080	.147	.430*	.274
Q24	-.344	.428*	.309	-.007	.513*
Q25	.541*	-.171	-.368	.125	.497*
Q26	.504*	-.232	-.146	.231	.213
Q27	-.168	-.284	.399*	-.029	.009

Note. * = Items factored together.

Appendix G

Alignment Between Final Exam Questions and Knowledge of Learners

---

Genetics and evolution test item.

60. What is the connection between genetics and evolution?

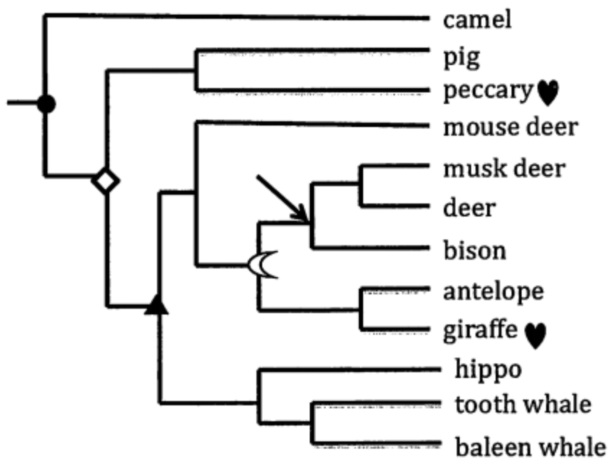
1. Evolution is a change in how common particular forms of a gene are.
2. Evolution requires that some individuals have more chromosomes than other individuals.
3. Evolution is a change in the alleles of an individual animal or plant.
4. The evolution of one species to another causes genetic changes.
5. Evolution causes genetic mutations to occur.

Tree thinking test item.

The question that follows is an example of a new phylogenetic tree which Dr. Wallace has the students interpret to determine the most recent common ancestor of giraffes and peccaries. It uses format of using symbols to highlight nodes of interest in the same fashion as used on the tree thinking in class activity.

> For the tree thinking skills, I give them a tree that they haven't seen before and ask them questions that are intended to test do they understand and interpret the tree? Who's related to who? Is this one evolved from this one? Do they understand the concept of common ancestors? (Interview 1, p. 14)

10. What happened at the point where the arrow is pointing?



1. deer evolved from bison
2. a species went extinct
3. two populations diverged from each other genetically
4. deer and musk deer hybridized to form bison
5. bison, deer, and musk deer all appeared simultaneously on the Earth

Evolution as a science.

No specific questions, did ask students to apply knowledge of theory and law, which is related but not given by Dr. Wallace as a misconception about evolution.

Human evolution.

What does it mean to say that humans and chimpanzees have a common ancestor?
1. Humans evolved from chimpanzees.
2. Chimpanzees are the most common ancestors of humans.
3. Chimpanzees evolved from humans.
4. Chimpanzees will eventually evolve into humans.
5. Both humans and chimpanzees evolved from the same species.

13. In the figures above, each letter represents a different species. Letter A is a species that lived soon after our most recent common ancestor with chimps. Homo sapiens are modern humans. Which figure is a more accurate representation of human evolution?

Appendix H

Qualitative Summaries to Support MATE Data

Participant	MATE Pre	Qualitative Pre	MATE Post	Summary	Nothing evolves	Humans do not evolve
Adrian	44	Unsure what I believe in.	70	Convinced by the evidence, science and religion can work together		X
Amelia	61	I wouldn't have believed evolution, Everything comes from God	70	I accept evolution because of the evidence, I know Bible says otherwise		Undecided
Ashley	34	You can't observe evolution; I don't think it's real	65	Cites evidence as to why she knows it doesn't take as long for some things to evolve as she thought; Evolution is real.		X
Beverly	58	I didn't really think about it that much, but it was just something that I learned in school.	73	Like I mean I believe in my religion first. I know why, evolution does have a	X	X

				good evidence, but I'll always go with my religion.		
Bridget	45	Everything was created at one time by God and nothing has changed	61	Earth is old but Bible says otherwise. I'm still undecided but both could be correct.		--
Brooke	65	Neutral, I didn't have any knowledge about it	78	I was pretty much convinced by the evidence.		--
Mary	26	Didn't believe it, cites counterevidence	29	Recognizes evidence but prioritizes religion	X	X
Megan	62	God made everything	60	I can't ignore the evidence but I still believe God created the Earth. I see both views.	X	Unsure
Millie	63	I didn't really understand it before	61	We need more evidence, nobody was alive back then; but I think it is valid		--

Nancy	64	I didn't have any <thoughts>. So they weren't like negative or I believe this or I don't believe that.	64	I believe in the Bible then after learning all this information, it kind of makes me think twice.	X	Unsure
Nathan	69	It was a little sketchy, I didn't believe it but thought it could be true - I was open to whatever.	58	I know there is evidence but it doesn't sound right	X	X
Nicholas	26	I believe in creationism but know things evolve, cites counterevidence	26	I believe in creationism but know things evolve		Humans are special but may evolve

Appendix I

Participants' Pre and Post-MATE and MUM scores, Overall Grade, and Attendance during the Macroevolution Unit as Indicated by Clicker Score (%). Abbreviations. Measure of Understanding of Macroevolution (MUM); Measure of Acceptance of the Theory of Evolution (MATE)

Pseudonym	Pre-MUM	Post-MUM	Pre-MATE	Post-MATE	Overall Grade	Unit Attendance
Bridget	7	20	45	61	93.2%	90.0%
Brooke	4	12	65	78	95.7%	83.3%
Beverly	8	16	58	73	69.3%	86.7%
Amelia	17	19	61	70	90.1%	93.3%
Ashley	14	13	34	65	74.4%	96.7%
Adrian	16	15	44	70	89.7%	90.0%
Mary	10	17	26	29	94.2%	100.0%
Millie	3	10	63	61	60.6%	100.0%
Megan	5	15	62	60	79.5%	96.7%
Nicholas	12	8	26	26	88.0%	80.0%
Nathan	7	5	69	58	82.5%	80.0%
Nancy	11	5	64	64	59.5%	73.3%
M	9.50	12.92	51.42	59.58	81.40%	89.17%
SD	4.62	5.05	15.74	16.11	12.82%	8.66%

Appendix J

Tree Thinking In Class Activity

10. Apr

Name (printed):______________________________ Student no.: ______________

Name (signature):______________________________

1. Are rhesus macaques more closely related to lion-tailed macaques or to stump-tailed macaques?

stump-tail

2. Circle the most recent common ancestor of siamangs and humans.

3. Draw an arrow pointing to the last common ancestor of all species in the tree.

4. Are orangutans more closely related to chimps or to gorillas (or neither)?

neither

5. True or false: the species indicated by the asterisk (*) was a chimpanzee.

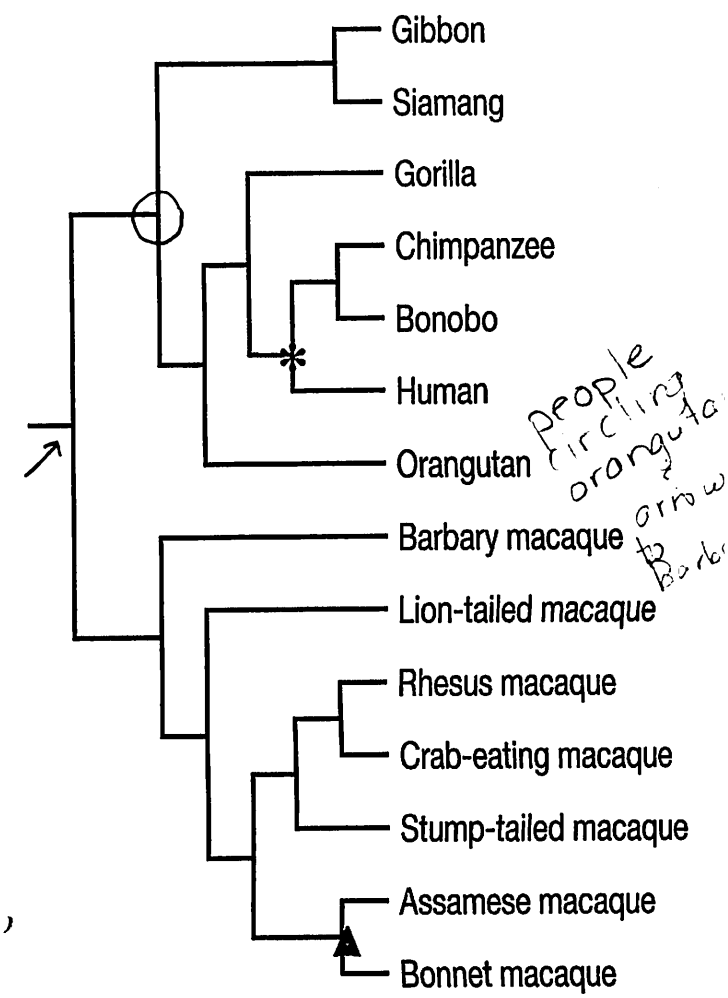
False

6. True or false: the species indicated by the asterisk (*) was a human.

False

7. Did humans evolve from chimpanzees? Explain.

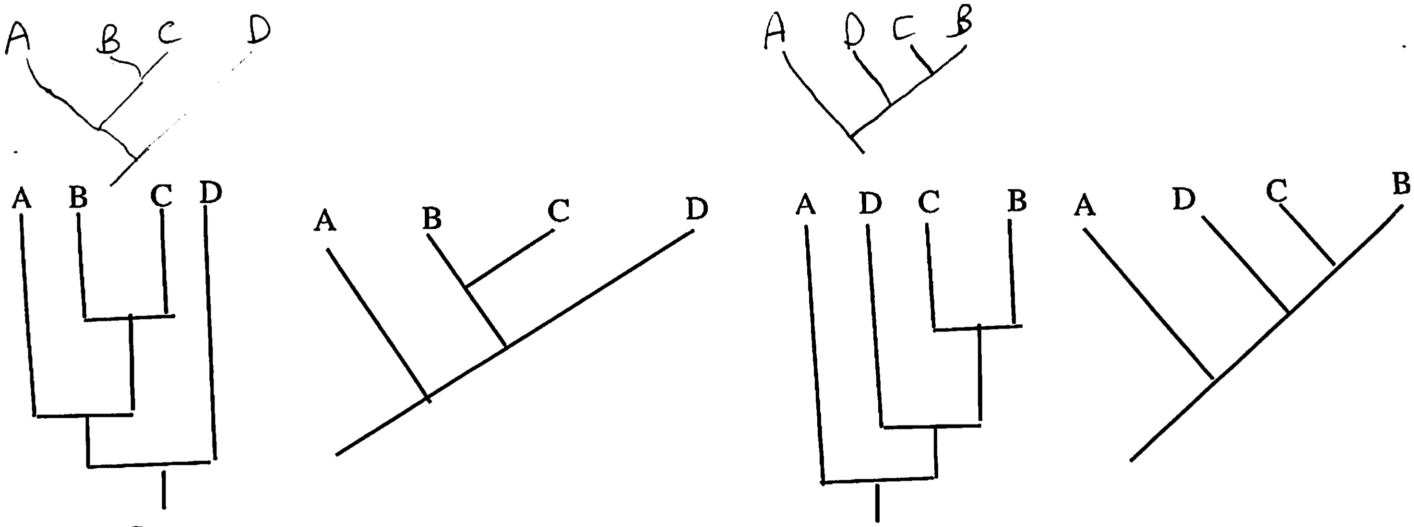
No, an ancester of humans, chimps and bonobos.



8. Explain what happened at the node marked by the triangle.

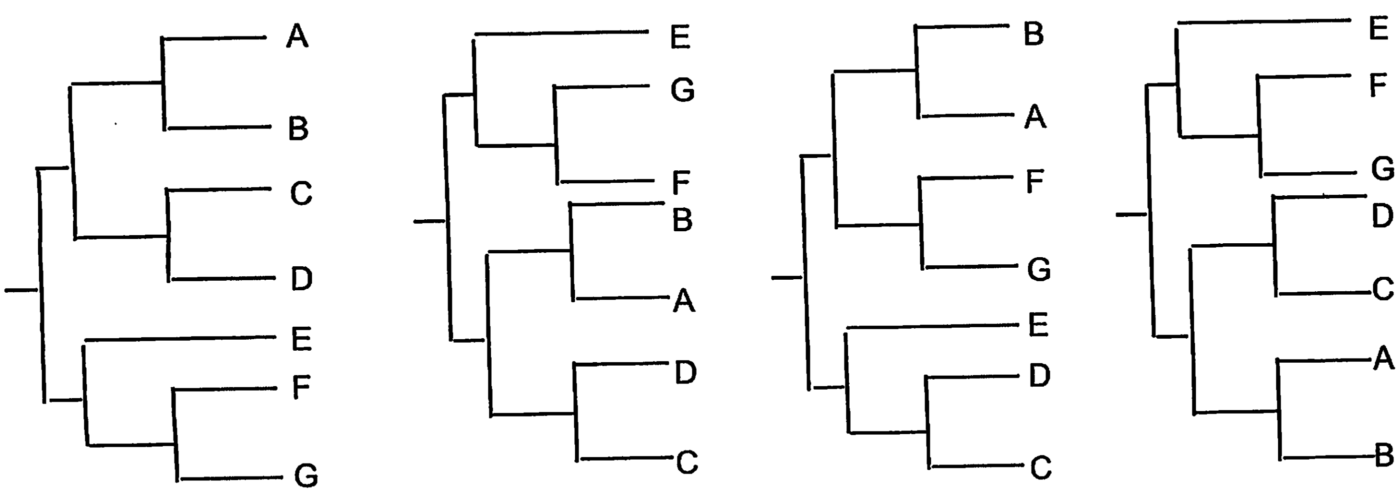
student guess: "they evolved?"

Speciation event – population split in two and diverged into two distinct macaque species



1 2 3 4

9. Three of the trees above show the same evolutionary relationship among the species. Which one is different?



1 ✓ 2 ✓ 3 4 ✓

10. Three of the trees above show the same evolutionary relationship among the species. Which one is different?

Appendix K

Copy of the final exam from Dr. Wallace's course. Includes summative assessment questions for macroevolution.

SP12 Bio 1010 Exams 4&5 Version A. Read each question carefully, choose the best answer, and fill in the corresponding circle on your Scantron.

1. Which of the following statements about human evolution is correct?

77

1. All living humans (*Homo sapiens*) can ultimately trace their ancestry to Africa.
2. Back when *Homo sapiens* evolved, there was only one enormous continent on the planet; as that continent split up, humans became isolated in different parts of the world.
3. The cave paintings in France indicate that western Europe was the birthplace of *Homo sapiens*.
4. The high population density in Asia indicates that humans first arose in what is now China and southeast Asia.
5. The fossil record is too sparse to provide much information about the geographical origin of *Homo sapiens*.

2. How does the fossil record provide evidence of evolution?

96

1. Fossils demonstrate that organisms lived and died a long time ago.
2. Fossils demonstrate that sometimes when an animal dies, it gets buried before it decomposes.
3. Fossils demonstrate that organisms on Earth have changed over time.
4. Fossils demonstrate that animals living in dry habitats are more likely to fossilize than animals living in humid habitats.
5. Fossils demonstrate that animals with hard body parts are more often preserved than animals that lack hard body parts.

3. Jason went to a Cinco de Mayo celebration last week and ate 2 tacos. Where is the majority of the energy that was contained in those tacos located now?

49

1. It's stored as fat around his waist-line.
2. It's in his blood.
3. It was destroyed by his body.
4. It has dissipated out of his body and into the atmosphere.
5. It was converted to matter, according to the formula E=mc2.

4. What does it mean to say that humans and chimpanzees have a common ancestor?

94

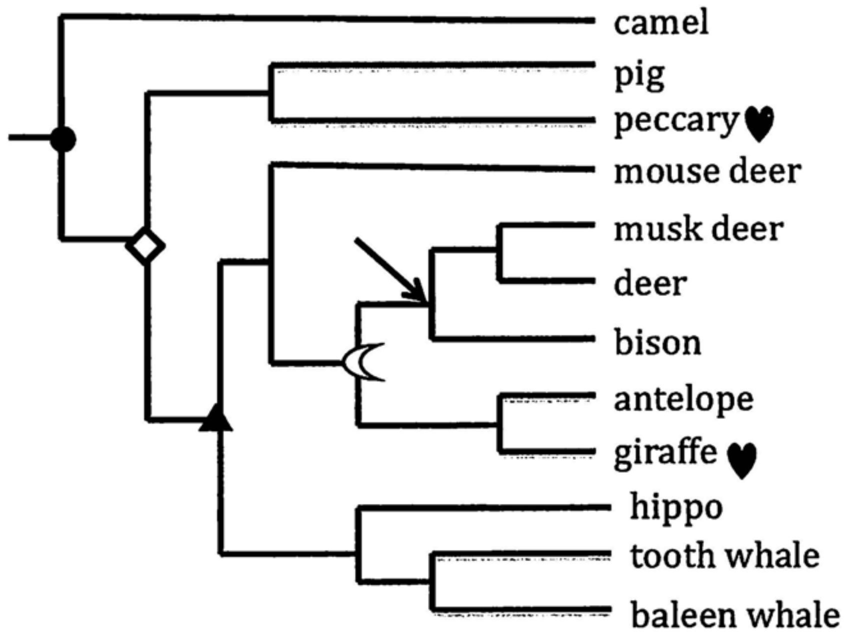
1. Humans evolved from chimpanzees.
2. Chimpanzees are the most common ancestors of humans.
3. Chimpanzees evolved from humans.
4. Chimpanzees will eventually evolve into humans.
5. Both humans and chimpanzees evolved from the same species.

5. Lynn Margulis, a biologist who presented evidence for the endosymbiont hypothesis back in the 1970s, suggested that this hypothesis could explain the evolutionary origin of a variety of cellular organelles including the flagellum (or tail) of sperm cells. Given your understanding of the endosymbiont hypothesis, what did Dr. Margulis think the flagellum arose from?

72

1. an eel
2. a hair
3. a stem cell
4. a bacteria cell

Questions 6-11: Refer to the tree to the right.



6. Of the following pairs of species, which ones are likely to have the greatest similarity in their sequence of DNA bases?

92

1. peccaries and mouse deer
2. mouse deer and musk deer
3. musk deer and deer
4. deer and bison
5. bison and antelope

7. The whales are classified with a group of animals called even-toed ungulates. Whales have been classified as part of this group along with their closest relative the hippo because:

97

1. Whales and hippos are big, heavy, and have large bodies with round mouths.
2. Whales and hippos have similar diets and need to live in the water.
3. The fossil record indicates that whales evolved from hippos.
4. Whales and hippos share similar social and parenting behaviors.
5. Whales share a more recent common ancestor with hippos than with the other species shown.

8. The evolutionary tree above indicates that:

73

1. baleen whales are not related to camels
2. tooth whales are more closely related to giraffes than to bison
3. deer evolved from bison
4. whales are more closely related to deer than to pigs
5. mouse deer are more closely related to antelope than to musk deer

9. Suppose you are drawing the evolutionary tree shown above and you accidentally swap the names of two species. Which of the following swaps would alter the evolutionary relationships shown in the tree?

91

1. giraffes and antelopes
2. pigs and peccaries
3. mouse deer and musk deer
4. tooth whale and baleen whale
5. all of the above 'swaps' would alter the information in the tree

10. What happened at the point where the arrow is pointing?

78

1. deer evolved from bison
2. a species went extinct
3. two populations diverged from each other genetically
4. deer and musk deer hybridized to form bison
5. bison, deer, and musk deer all appeared simultaneously on the earth

11. Which symbol represents the most recent common ancestor of giraffes and peccaries?
(Use the tree on the previous page.)

98

1. ♥
2. ☾
3. ●
4. ▲
5. ◇

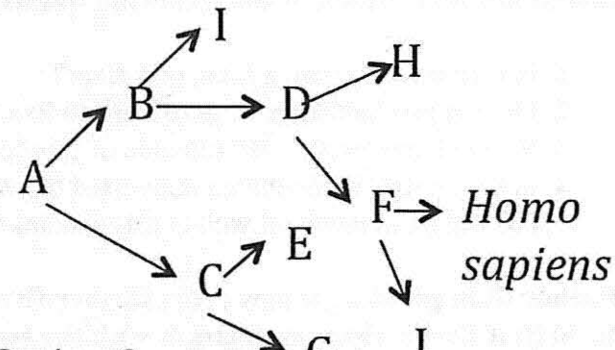
12. You unearth the 50-million year old fossil of a small mammal and you want to know whether it was a primate or a rodent. Which of the following is the most useful question to ask?

66

1. How many bones did it have in its ears?
2. How many different types of teeth did it have?
3. Could it hang from its tail?
4. How were its eyes positioned on its head?
5. Did it walk on two legs?

A → B → C → D → E → *Homo sapiens*

Option 1



Option 2

13. In the figures above, each letter represents a different species. Letter A is a species that lived soon after our most recent common ancestor with chimps. *Homo sapiens* are modern humans. Which figure is a more accurate representation of human evolution?

77

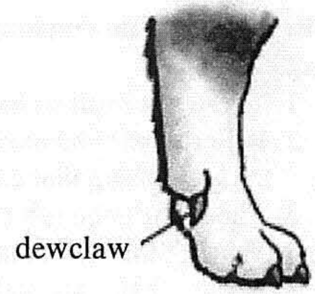
1. Option 1
2. Option 2
3. It's impossible to say, given the number of gaps in the fossil record.
4. Although there are plenty of fossils, whether they are best arranged according to option 1 or option 2 is hotly debated, with no broad consensus among evolutionary biologists.

Questions 14-15. A dewclaw is a claw that grows on the inside leg of dogs. In most breeds, the dewclaw on the hind leg does not touch the ground when the dog walks, is not firmly attached to underlying bones, and serves no purpose. Evolutionarily, the dewclaw moved into this position when the ancestors of modern dogs reduced the number of toes on their hind feet from five to four; the dewclaw emerges from the remains of the fifth toe bone.

14. Based on this information, the dewclaw is an example of:

94

1. the randomness of natural selection
2. genetic drift
3. the universality of the genetic code
4. natural selection in action
5. a vestigial structure



15. Humans, unlike dogs, have retained all five toes they inherited from their ancestors, including the tough keratin (i.e. nail or claw) that grows from the tips of toes and fingers. Given this information, which of the following statements about dewclaws and human toenails is correct?

1. The toenail of our big toe is homologous to the dewclaw of dogs.
2. Our toenail is likely to become a dewclaw sometime in the future.
3. The dewclaw on dogs is evolving into a form similar to a human toenail.
4. Humans and dogs evolved their toenails/claws independently of each other.
5. Evolution gave dogs a dewclaw because they needed them.

53

16. Susan is pregnant and wants to minimize the exposure of her developing fetus to toxic chemicals including mercury, which is subject to biomagnification. When choosing which type of fish to include in her diet, which of the following questions is most useful to ask?

1. Is it from an ocean, a lake, or a river?
2. Does it produce eggs or give birth to live young?
3. What characteristics do females of this species prefer when searching for a mate?
4. Is the energy it consumes converted to heat and released into the surrounding water?
5. How high in the food web is this species of fish?

86

17. Rather than planting a new crop, farmer Brown plants his field with clover this spring. Bacteria that live in close association with the roots of clover plants will perform chemical reactions that help to increase the availability of which nutrient in the soil?

1. carbon
2. phosphorus
3. nitrogen
4. oxygen
5. magnesium

50

Questions 18-19. A food chain consists of killer whales feeding on seals, which feed on big fish, which feed on little fish, which feed on aquatic plants.

18. What trophic level is occupied by the seals in this food chain?

1. producers
2. quaternary consumers
3. detritivores
4. secondary consumers
5. tertiary consumers

87

19. Why are there no consumers feeding on the killer whales?

90

1. There is a limit to how large animals can evolve to be, and killer whales are at the maximum.
2. Killer whales have evolved a mechanism to store toxic chemicals in their fat, which would kill anything that eats a killer whale.
3. There isn't enough energy available to support an additional level.
4. Whale blubber is tough and rubbery; nothing can digest it.
5. Killer whales are so fierce that nothing could possibly eat them.

20. Evaluate the following statements:

A. Chemicals that dissolve in fat are more likely to exhibit biomagnification than chemicals that dissolve in water.
B. Chemicals that dissolve in fat are rapidly excreted back into the environment, and therefore cycle through the ecosystem faster than chemicals that dissolve in water.

1. A is true and B is false.
2. B is true and A is false.
3. Both A and B are true, and B provides a valid explanation of A.
4. Both A and B are true, but B does not provide a valid explanation of A.
5. Both A and B are false.

73

21. Triceratops and Tyrannosaurus rex were two species of large dinosaurs that lived at the same time and in the same locations. Even though their size and physiology were similar, Triceratops were much more abundant than T. rex. Which of the following statements about the two species probably best explains their difference in numbers?

1. Triceratops had a bony frill on its neck, whereas T. rex had no bony frill.
2. Triceratops walked on four legs, whereas T. rex walked on two legs.
3. Triceratops had a relatively small brain compared with T. rex, even though the body size was similar.
4. Triceratops ate plants, whereas T. rex was a predator.
5. Triceratops had 4 fingers on its forelimbs, whereas T. rex had only 2 fingers.

95

22. The Majorcan midwife toad is found on the Mediterranean island of Majorca, 120 miles off the coast of Spain. There are two other species of midwife toads in the world. They resemble in many respects the Majorcan midwife toad, but they exhibit differences in body shape and egg number that reflect adaptations to a different type of habitat. According to your understanding of biogeography, where are these other species of midwife toads most likely found?

1. in Spain
2. in the Caribbean Islands
3. in the Amazonian rain forest
4. Someplace with the same type of habitat as Majorca.
5. The distribution of species on Earth is random, so it's impossible to say.

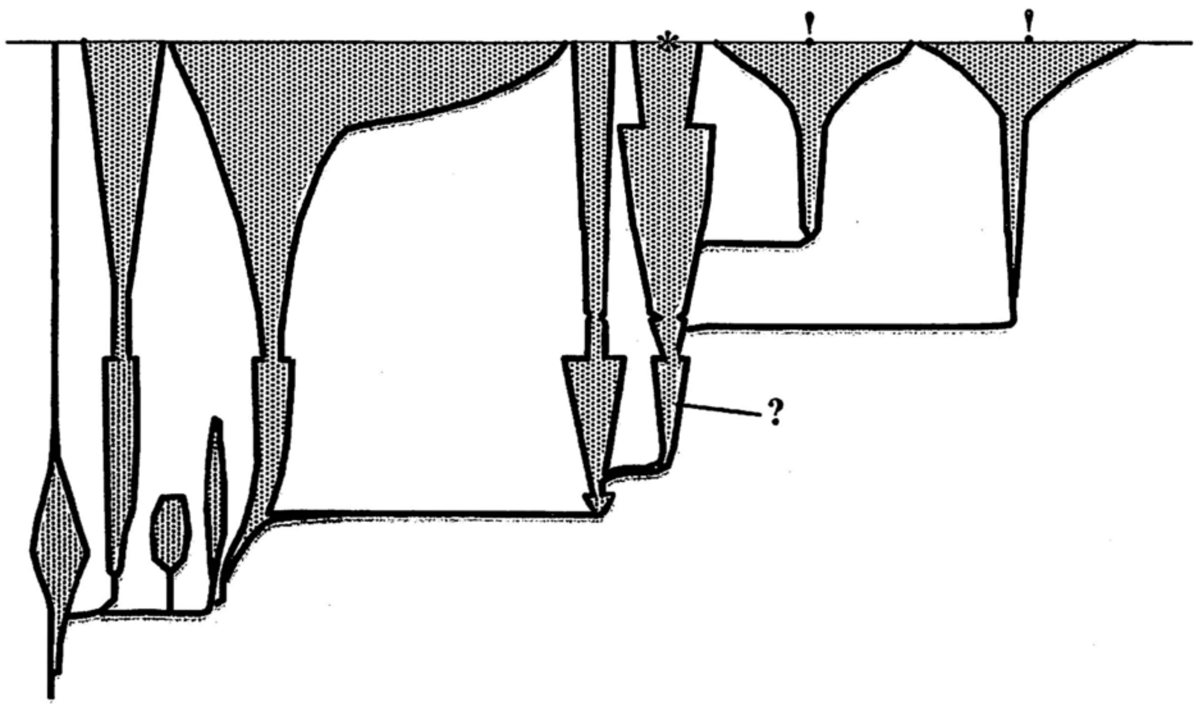
76

23. Which of the following statements is a valid reason to exercise caution when purchasing or using herbal remedies?

1. In addition to the 'active ingredient,' herbs contain a variety of other chemicals, some of which may have harmful effects on the body.
2. Herbal remedies may contain powerful medications that can profoundly alter your physiological responses if taken frequently or in high doses.
3. There is little government oversight to verify that the dosage of an herb is consistent over time in the same product and consistent with the stated dosage on the packaging.
4. Manufacturers of herbal remedies are not required to demonstrate that their products produce the advertised effects.
5. All of the above are valid reasons to exercise caution when purchasing or using herbal remedies.

87

Questions 24-26. The figure below shows the evolutionary history of the vertebrates (animals with backbones).



24. The asterisk (*) indicates modern reptiles (snakes, turtles, lizards, crocodilians). What types of animals are represented by the question mark?

1. They are the same species of reptiles as occur at the asterisk.
2. They are extinct reptiles that are the ancestors of modern reptiles.
65
3. They are fish.
4. They are birds.

25. The two groups of animals represented by the exclamation points (!) are:

1. prokaryotes and eukaryotes
2. reptiles and amphibians
48
3. bony fish and lamprey
4. mammal-like reptiles and feathered dinosaurs
5. birds and mammals

26. Which of the following statements best describes the evolutionary pattern of life on Earth?

1. Today's living organisms are the current representatives of repeated speciation and extinction events that have taken place over the past 3.6 billion years.
91
2. The fossil record shows us that most living organisms are the same species as were present on the Earth a billion years ago; speciation and extinction are both rare events that have had only a minor impact on the diversity of life on Earth.
3. The diversity of life on Earth was greatest about 3.6 billion years ago. Living organisms represent the relatively few survivors of the series of extinction events that have gradually whittled away the number of organisms on the planet over the past 3.6 billion years.
4. The fossil record shows us that life on Earth has remained pretty much the same over time; each species alive today is the same as it was when it appeared on the planet a few thousand years ago.

27. Suppose you are examining a new fossil that belongs to the group called mammal-like reptiles. You want to know whether this species was more similar to reptiles or to mammals. All of the following are useful questions to ask EXCEPT:

1. Did it squat with its legs out to the sides, or stand upright with its legs under its body?
2. How many different types of teeth did it have in its mouth?
3. Did its forelimbs ('arms') contain one upper bone and two lower bones?
4. How many bones made up its lower jaw?

25

28. Why can more people be supported as vegetarians than as carnivores?

1. Cows will go extinct if we eat vegetarian diets, leaving more plants for humans to eat.
2. Nutrients are lost as you move higher up the trophic levels.
3. Vegetarian diets contain less fat than carnivorous diets.
4. There is more energy available to support primary consumers than secondary consumers.
5. Humans can obtain more calories by eating vegetables than by eating meat.

81

29. From an evolutionary perspective, why is the trait 'physically attractive' ranked as high priority by men when choosing a partner? Because among our evolutionary ancestors __________

1. attractive women were likely to have beautiful daughters.
2. attractive women were likely to reproduce successfully.
3. pairing with an attractive woman was likely to confer a high social status to the man.
4. attractive women were better at inciting competition among males.
5. attractive women were likely to bring many material resources to the marriage.

84

30. What is the major difference between energy and nutrients with regard to their movement through an ecosystem?

1. Nutrients are continuously re-used; energy is not.
2. Nutrients are found in both the biotic and abiotic components of an ecosystem; energy is not.
3. Energy is passed up the trophic food web; nutrients are not.
4. Nutrients enter and then leave an ecosystem; energy does not.
5. Energy can be destroyed; nutrients cannot.

46

31. Imagine an inspector for the Environmental Protection Agency is examining alligators to determine whether or not they are safe to eat. Which of the following observations would suggest that biomagnification of mercury is occurring in these alligators?

1. Alligator flesh contains only trace amounts of mercury, although the concentration of mercury in the environment is high.
2. The quantity of energy found in alligators is higher than the quantity of energy in the animals they consume.
3. The lens of the alligator eye serves as a biological magnifier, focusing the light rays of the sun onto the back of the alligators' eyes.
4. The presence of the alligators is altering the water chemistry, causing mercury to dissolve out of the rocks and into the water, where other organisms are now exposed to it.
5. The concentration of mercury is much higher in the bodies of the alligators than in the water where they live.

73

32. Among our evolutionary ancestors, women may have been under selection pressure to choose mates based on their ability and willingness to provide resources such as food and shelter to their offspring. According to an evolutionary perspective on human mate choice, many modern women express this preference by looking for which characteristic in men?

85
1. youth
2. ability to earn money
3. physical attractiveness
4. kindness
5. high sperm count

33. A scientist who is interested in the evolution of the first bony jaws would look for fossils of:

46
1. early fish
2. early amphibians
3. early mammals
4. early multicellular animals
5. early eukaryotes

This is the end of Exam 4. The remainder of the questions constitute Exam 5.

34. What do all cancer patients have in common?

1. inherited tendencies to develop cancer
2. benign tumors somewhere in their bodies
3. an over-exposure to UV radiation
4. a loss of control over cell division
5. extra chromosomes in their cells

35. Dolly the sheep closely resembles the sheep who donated an udder cell, but not the sheep who donated the egg cell or the sheep who carried Dolly in her uterus. Why?

1. because the udder cell was the only eukaryotic cell involved in the process
2. because the udder cell contained the genetic material used to make Dolly.
3. because the sheep who donated the udder cell also donated the cytoplasm for the egg cell
4. because the sheep who donated the egg cell was a twin of the sheep who donated the udder cell
5. because the sheep who donated the udder cell also donated the sperm cell, containing DNA.

36. Among katydids here in Missouri, some individuals are green and others are brown, even though they belong to the same species. The color of the katydid is determined by its alleles. A graduate student at MU studied a population of katydids many years ago and reported that approximately 300 were green and 100 were brown. A new graduate student has re-examined the population.Which of the following counts would indicate that evolution has occurred?

1. 45 green, 15 brown
2. 500 green, 100 brown
3. 600 green, 200 brown
4. 90 green, 30 brown
5. All of the above counts indicate that evolution has occurred.

37. The function of all enzymes is best described as:

1. to break down molecules of food
2. to separate the strands of DNA
3. to specify which molecules are involved in a chemical reaction
4. to supply enough energy to cause two molecules to react
5. to increase the speed at which a chemical reaction occurs

38. In the process of Somatic Cell Nuclear Transfer (SCNT), what is transferred?

1. The nucleus of a diploid cell is transferred to an egg cell.
2. The genetic material in an egg cell is transferred to a body cell.
3. The DNA of one species is transferred into the nucleus of another species.
4. Amino acids are transferred to the ribosome to be put into protein molecules.
5. A cell of one species is transferred into the body of another species.

39. You have isolated a cell and you want to determine whether it is a prokaryote or a eukaryote. All of the following are appropriate questions to ask EXCEPT:

1. Does the cell contain organelles?
2. How large is the cell?
3. Does the cell contain DNA?
4. Does the cell have mitochondria?
5. Does the cell have a nucleus?

40. What is the difference between a gene and an allele?

1. Alleles are attached to genes.
2. A gene codes for the production of a protein; an allele does not.
3. An allele is a more specific way of describing a gene.
4. Genes are made out of DNA; alleles are not.
5. All of the above describe the difference between a gene and an allele.

41. The protein called keratin is found in your skin. The protein called hemoglobin is found in your blood. The two proteins serve different functions. How do they differ in structure?

1. They are made out of different nucleotide bases.
2. They are made out of different numbers of base-pairs.
3. They differ in their number of fatty acids.
4. They have different sequences of amino acids.
5. They contain different numbers of genes.

42. Genes contain the instructions for building proteins. Where are those instructions located?

1. in the bonds between complimentary bases
2. in the sugar and phosphate groups that are part of each nucleotide
3. in the order of the DNA bases
4. in the nuclear membrane
5. in the tRNA

43. What is a scientific theory?

1. an explanation that has been proved to be true
2. an observation that has been replicated by so many different people that very few people doubt that is valid
3. an idea that is purely hypothetical
4. a broad explanation that accounts for many different observations
5. a confounding variable in determining the history of life on Earth

44. What is the function of photosynthesis?

1. to release oxygen
2. to make glucose
3. to break apart water molecules
4. to use carbon dioxide
5. to absorb light energy

45. Papain is an enzyme extracted from papaya fruits. It is sold as a meat tenderizer because it helps to break down the proteins in muscle fiber. Suppose you add papain to a test tube containing a small piece of steak. Later you examine the contents of the test tube. What would you expect to find?

1. amino acids
2. ribosomes
3. nucleotides
4. fatty acids
5. simple sugars

46. Amylase is an enzyme used in commercial bread production. This enzyme breaks down starch into small sub-units. Given this information, which of the following molecules would you expect to find in abundance in bread dough that has been treated with amylase?

1. ATP
2. amino acids
3. nucleotides
4. glucose
5. fatty acids

47. Why does the male peacock have a long tail?

1. because it helps him fly, and so any individual with alleles coding for a long tail is likely to pass those alleles on to the next generation
2. because it enables him to hide from predators better, and so any individual with alleles coding for a long tail is likely to pass those alleles on to the next generation
3. because it helps him attract a female, and so any individual with alleles coding for a long tail is likely to pass those alleles on to the next generation
4. because it makes him more visible to predators, and so any individual with alleles coding for a long tail is likely to pass those alleles on to the next generation
5. because it scares away predators, and so any individual with alleles coding for a long tail is likely to pass those alleles on to the next generation

48. A particular segment of DNA has the base sequence CGGTTTGGG. What amino acids does it code for? Use the sample of the genetic code shown below to answer the question.

CGG = arginine
CCC = proline
GGG = glycine
GCC = alanine
CCU = proline
AAA = lysine
ACC = threonine
CCA = proline
UUU = phenylalanine

1. arginine-phenylalanine-proline
2. alanine-lysine-proline
3. arginine-lysine-glycine
4. alanine-proline-proline
5. proline-phenylalanine-alanine

49. Why do you have hair on your arms but not on the palms of your hands?

1. because the skin cells on the palm of the hand don't have the genes coding for hair
2. because the amino acids needed for building hair are only found in the arms, not in the palms
3. because genes coding for hair migrate out of our palm cells and into our arm cells during early development
4. because skin cells on our palms are unable to manufacture any proteins
5. because the genes coding for hair are expressed in the skin cells on the arm, but not in the skin cells on the palm

50. A scientist wants to engineer a bacteria cell to produce human growth hormone. What will she need to do?

1. put a copy of the human gene for growth hormone into the DNA of a bacteria cell
2. remove the DNA from a bacteria cell and insert it into human cells that produce the growth hormone
3. remove the nucleus from a human egg and insert a bacteria cell in its place
4. inject a bacteria cell with a small amount of human growth hormone
5. inject bacteria into the patient who needs the hormone

51. Dr. G has published a paper in which she argues that dietary supplements containing Enzyme Q10 have no effect on people, despite the claims of the pharmaceutical company that is promoting it's benefits. Can we expect her to ever change her mind?

1. No, because scientists are trained to adhere to their opinions for the good of science.
2. Yes, because scientists are trained to be fair, and it's only fair to support both sides of an argument.
3. Yes, if sufficient new evidence arises, demonstrating an effect of the supplement.
4. No, because science is about finding absolute truths, and absolute truths don't change.
5. Yes, if the supplement industry claims they are losing money from reduced sales.

52. What is the function of cellular respiration?

1. to make ATP
2. to make carbon dioxide
3. to get rid of pyruvic acid
4. to make water
5. to make glucose

53. The First Law of Thermodynamics states that energy is never created or destroyed. Why is this statement considered a law rather than a theory?

1. because it's been proven to be correct
2. because it explains how energy changes form
3. because it is a description of a natural phenomenon
4. because there is a lot of evidence supporting it
5. because the Science Legislature voted it into law.

54. Energy enters ecosystems in the form of ________ energy, moves from one organism to another in the form of __________energy, and leaves the ecosystem in the form of ______________ energy.

1. heat, chemical, light
2. light, chemical, heat
3. heat, radiant, chemical
4. potential, kinetic, radiant
5. light, heat, potential

55. Many mammals have small muscles behind the ears that enable them to point the ears in the direction of a sound. Humans have these muscles, although we are not able to use them. In humans, these muscles _______

1. are vestigial structures.
2. evolved through artificial selection.
3. must have evolved for a different purpose.
4. are examples of natural selection in action.
5. arose through genetic drift

56. Place the following structures in order of size, from smallest to largest:

DNA-molecule
chromosome
nucleotide
gene
nucleotide-base

1. gene, nucleotide base, nucleotide, DNA molecule, chromosome
2. nucleotide base, nucleotide, gene, DNA molecule, chromosome
3. DNA molecule, nucleotide base, nucleotide, chromosome, gene
4. gene, chromosome, nucleotide base, nucleotide, DNA molecule
5. nucleotide base, nucleotide, DNA molecule, chromosome, gene

47%

57. Evaluate the following statements:
A. Natural selection is a random process.
B. It is arbitrary which individuals of a generation survive to reproduce.

1. A is true and B is false.
2. B is true and A is false
3. Both A and B are true, and B provides a valid explanation of A.
4. Both A and B are true, but B does not provide a valid explanation of A.
5. Both A and B are false.

58. Through what process does energy enter a food chain?

1. nutrient cycling
2. ingestion
3. cellular respiration
4. photosynthesis
5. fermentation

59. What is the primary reason that cells need to make ATP?

1. to build glucose molecules in photosynthesis
2. to add phosphate groups to ADP
3. to make nucleic acids
4. to supply energy for chemical reactions that require it
5. to break down pyruvic acid

60. What is the connection between genetics and evolution?

1. Evolution is a change in how common particular forms of a gene are.
2. Evolution requires that some individuals have more chromosomes than other individuals.
3. Evolution is a change in the alleles of an individual animal or plant.
4. The evolution of one species to another causes genetic changes.
5. Evolution causes genetic mutations to occur.

61. The scientific method CANNOT be applied to which of the following questions:

1. Why does the body reject organs that have been transplanted from another person?
2. Given the scarcity of organ donors, is it ethical to use stem cells to grow new organs for people?
3. How does the immune system 'recognize' the proteins on the surface of cells?
4. Can identical twins donate organs to each other without organ-rejection?
5. Are transplanted livers rejected more often than transplanted kidneys?

62. Does a liver cell contain genes for eye color?

1. Yes
2. No - not all cells have genes.
3. No - all cells have genes, but only the genes they need.

Exam continues...

63. A population of rabbits experiences a change in climate, such that the habitat becomes much hotter and many individuals die due to over-heating. Which of the following best describes what may happen in this population?

1. The climate-change will cause a mutation in some rabbits. The mutation will give them longer ears that release body-heat out of the blood and into the air.
2. Rabbits will give birth to babies that have longer ears than their own parents, allowing excess heat to dissipate into the environment.
3. If a mutation occurs that reduces the thickness of fur, so that more heat can escape from the rabbits' bodies, then this mutation will probably become more common in the population in future generations.
4. It is arbitrary which individuals of a generation of rabbits will survive and reproduce. Therefore, the rabbits are likely to go extinct due to over-heating.
5. Natural selection will create a new allele that increases the amount of sweat produced by the rabbits, enabling them to cool their bodies more efficiently.

64. What is a stem cell?

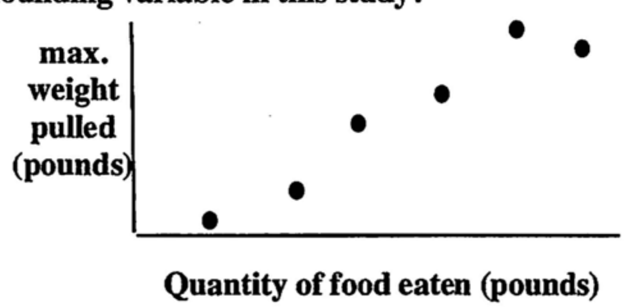
1. a cell that is committed to performing one specialized task
2. a cell that has been genetically engineered to produce human proteins
3. a cell that is fused with an egg cell to make a clone
4. a type of cell that is only found in embryos
5. a cell that is the source of different types of cells in the body

65. What do regulatory genes regulate?

1. the movement of genes into and out of the nucleus
2. the actions of other cells in the body
3. the movement of energy in the cell
4. whether or not other genes are turned on
5. the ability of a person to gain or lose weight over time

66. Zippy dog food company wants to demonstrate that their dog food makes dogs strong. Mr. Z performs an experiment in which he allows dogs to eat as much of the food as they want over the course of one day. The next day, he tests the strength of each dog by measuring the maximum weight that the dog can pull on a sled. <u>He finds that the more Zippy dog food a dog has eaten, the greater the weight he/she can pull the next day</u>. Mr. Z concludes that Zippy dog food makes dogs stronger. Which of the following is the most likely confounding variable in this study?

1. how much weight was added to the sleds
2. whether it was snowing during the sled trials
3. whether the dogs have tried Zippy dog food before
4. how much Zippy dog food the dogs ate
5. the size of the dogs



Turn in your scantron but take your exam paper with you. Have your ID ready. Stage 2 will be available from noon today until **noon** tomorrow. You may use your book, notes, our Blackboard site & discussions with **classmates** to complete stage 2. The questions in stage 2 will be in the same sequence as in stage 1, but the order of the answers may be different.

VITA

Emily Marie Walter (Mollman) was born on August 22, 1983 to Greg and Cindy Mollman of Urbandale, Iowa. She has two younger siblings, Kristin Nicole Koppes and Jacob Daniel Mollman. Emily has her Bachelor of Science degree in Biology from Iowa State University and her Master of Science degree in Biology from Western Illinois University. By completing this dissertation, Emily follows in the footsteps of her grandfather, Ronald Trenda Pflaum, who was a professor of chemistry at the University of Iowa, and her great-grandfather, Clarence Carl Pflaum, who was a professor of pathology at the University of Missouri School of Medicine.

Emily married her high school sweetheart, Clint Thomas Walter, in 2007 and they have two daughters, Lillian Elizabeth and Charlotte Kathryne. They will be residing in Kalamazoo, Michigan following graduation as Emily has accepted a two-year post-doctoral research position at Western Michigan University.