

INVESTIGATING THE DEVELOPMENT AND USE OF PHYLOGENETIC  
REPRESENTATIONS BY COLLEGE UNDERGRADUATES  
IN A PLANT SYSTEMATICS 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  
KRISTY LYNN HALVERSON

Dr. Sandra K. Abell and Dr. Patricia Friedrichsen, Dissertation Supervisors

JULY 2009

© Copyright by Kristy L. Halverson 2009

All Rights Reserved

The undersigned, appointed by the Dean of the Graduate School, have examined the  
dissertation entitled.

INVESTIGATING THE DEVELOPMENT AND USE OF PHYLOGENETIC  
REPRESENTATIONS IN COLLEGE UNDERGRADUATES

Presented by Kristy L. Halverson  
A candidate for the degree of Doctor of Philosophy.

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

---

Dr. Sandra Abell, Dissertation Co-Supervisor

---

Dr. Patricia Friedrichsen, Dissertation Co-Supervisor

---

Dr. Marcelle Seigel

---

Dr. J. Chris Pires

---

Dr. Gerald Summers

*In loving memory of my mother, my first science teacher.*

## ACKNOWLEDGEMENTS

The journey of becoming a science education researcher has taken me down a challenging path full of obstacles and inspiration. This dissertation is the result of support and encouragement from a vital community. First and foremost, I wish to thank my advisors, Sandi Abell and Patricia Friedrichsen. Both of whom helped motivate me when I hit rough patches and writers block. Sandi, thank you for constantly pushing me to think more deeply about my ideas and my professional goals. I feel as though you were bound and determined that I would find value in qualitative research. I have, and this has helped me become a better, passionate researcher. I appreciate your openness with me and your honesty in telling me what I needed to hear, even if it was not always what I wanted to hear. You have helped me become a stronger person. Pat, you have provided much needed emotional support and guidance when I needed it most, especially while I was collecting and analyzing data. I have always appreciated your open doors and shoulder. Through me research and teaching, you have been an important mentor. Thanks to you, I am now able to include “no” in my vocabulary. I cannot thank each of you enough for the support you have offered over the past four years.

I also extend my gratitude to my doctoral committee. Marcelle Siegel, you have helped me persevere as a researcher through all of our adventures together. You have also helped me understand the importance of communication and bringing food to research meetings. Chris Pires, you brought enthusiasm and excitement to every moment of data collection. What can I say, it is still fun and I will always appreciate your dedication to this project and the opportunities you provided. Gerry Summers, you

pushed me to maintain attention to detail in my work and provided me with invaluable teaching experiences. For this, I thank each of you.

There have also been many other instrumental people that have helped guide me along my journey. I could not have made this journey without support from my colleagues at the Science Education Center. Debi Hanuscin, I will always remember our conversations over coffee breaks and shoe shopping. Lloyd and Mark, you have given me new perspectives. Thank you to all of my fellow science education doctoral students. Your smiles and encouragement have meant a great deal to me. Michele Lee and Aaron Sickel, I do not know if I would have ever finished my writing without the encouragement and watchful eyes of my study buddies. I will miss you both dearly. Rená Smith, thank you for helping me maintain my sanity through our lunch outings and gossip sessions. Cathy Wissehr and Deanna Lankford, you gave me hope for the light at the end of the tunnel. Dominike Merle, I appreciated your role as a sounding board. Steve Witzig, you have helped me have fun with my work and not take things too seriously. Pat Brown, you helped so much by offering insights of experience and a willingness to answer all of my incessant questions. Bina Vanmali, I have known you for so long and in many ways I feel as though you have taken this journey with me. I wish to acknowledge all past and current members of ARG. I consider myself lucky to have been a part of this group and included in our invaluable conversations (or debates as some were). Through this group, I learned what it was to be a member of a community.

I would like to thank Megan Pallo, the members of the TREE working group, and the National Evolutionary Synthesis Center. I look forward to working with you again. I would also like to thank my participants for their openness with me during my study.

Last, but not least, I want to thank my friends and family. With whom, none of this would have been possible. My roommate, Whitney Spivey, you reminded me of the importance of laughter and taking a break from time to time (after I had met my deadlines of course). Janet Healy, your letters gave me motivation and helped me believe that I could do this. Brandy Nylund, you have always been a source of stability for me, encouraging me to continue and never allowing me to give up. Special thanks goes to my sister and brother-in-law, Tami and Eric Presley, my brother and sister-in-law, Lee and Debby Halverson, and my father, Scott Halverson. Thank you for your constant support of my efforts and belief in my ability to accomplish my goals -- I am finally "Doctor."

## TABLE OF CONTENTS

ACKNOWLEDGEMENTS .....	iii
LIST OF TABLES .....	x
LIST OF FIGURES .....	xii
ABSTRACT .....	xv
CHAPTER ONE: INTRODUCTION .....	1
Rationale .....	4
Research Questions .....	6
Theoretical Framework .....	7
<i>Knowledge Development</i> .....	7
<i>Representational Competence</i> .....	12
Significance of Study .....	19
CHAPTER TWO: REVIEW OF LITERATURE .....	21
Overview .....	21
Research on Representations in Education .....	22
Proposed Instructional Guidelines .....	29
Phylogenetic Trees as Biological Representations .....	30
<i>Tree Thinking</i> .....	33
<i>Pilot Study</i> .....	37
Gaps in the Literature .....	39
CHAPTER THREE: METHODOLOGY .....	41
Research Tradition .....	42
<i>Constructivism</i> .....	42
<i>Epistemological Assumptions</i> .....	43

<i>Onotological Assumptions</i> .....	44
Context of the Study .....	45
<i>Course Curriculum</i> .....	46
<i>Participants</i> .....	47
<i>Role of the Researcher</i> .....	48
Design of the Study .....	49
<i>Methodological Assumptions</i> .....	50
<i>Data Collection</i> .....	51
<i>Pre/Posttest</i> .....	53
<i>Online Reflective Journals</i> .....	53
<i>Interviews</i> .....	54
<i>Field Notes</i> .....	54
<i>Documents/Artifacts</i> .....	55
<i>Data Analysis</i> .....	56
Trustworthiness .....	58
CHAPTER FOUR: INTERPRETATIONS .....	60
Students' Incoming Ideas .....	60
<i>Interpretation of Phylogenies</i> .....	61
<i>Placement of Time</i> .....	71
<i>Comparing Representations</i> .....	72
<i>Generating Representations</i> .....	79
Students' Ideas at the End of the Course .....	92
<i>Interpretation of Phylogenies</i> .....	93
<i>Improvements</i> .....	100
<i>Placement of Time</i> .....	103

<i>Comparing Representations</i> .....	104
<i>Generated Representations</i> .....	105
Student Perceptions of Improvement from Instructional Interventions .....	115
<i>Student Perceptions of Improvement in Tree Thinking Skills</i> .....	116
<i>Pipe Cleaner Phylogeny</i> .....	116
<i>Pseudocot Fossil Activity</i> .....	121
<i>Whippo Activity</i> .....	125
<i>Summary</i> .....	128
Essential Tree Thinking Skills .....	129
<i>Tree Reading Core Skills</i> .....	130
<i>Tree Building Core Skills</i> .....	134
Summary of Interpretations .....	140
<i>Sub-Research Question 1: Students' Incoming Ideas</i> .....	140
<i>Sub-Research Question 2: Improvements in Students' Tree Thinking</i> .....	141
<i>Sub-Research Question 3: Students' Perceptions of Instructional Interventions</i> ...	141
<i>Sub-Research Question 4: Core Skills for Tree Thinking</i> .....	142
CHAPTER FIVE: DISCUSSION AND IMPLICATIONS .....	144
Contributions to the Literature .....	144
<i>Students' Tree Thinking Approaches</i> .....	145
<i>Tree Thinking Challenges and Instructional Interventions</i> .....	150
<i>Representational Competence Frameworks</i> .....	153
Implications for Teaching .....	162
Implications for Policy .....	165
Future Research Directions .....	165
Conclusions .....	167

REFERENCES .....	168
APPENDICES .....	182
APPENDIX A. PILOT STUDY .....	183
APPENDIX B. COURSE SYLLABUS .....	217
APPENDIX C. CONSENT FORM.....	227
APPENDIX D. PRETEST INSTRUMENT.....	230
APPENDIX E. POSTTEST INSTRUMENT.....	236
APPENDIX F. SELECTED WEEKLY REFLECTION QUESTIONS .....	243
APPENDIX G. INTERVIEW ONE PROTOCOL.....	248
APPENDIX H. INTERVIEW TWO PROTOCOL.....	250
APPENDIX I. PIPE CLEANER INSTRUCTIONAL INTERVENTION.....	253
APPENDIX J. PSEUDOCOT FOSSIL INSTRUCTIONAL INTERVENTION .....	254
APPENDIX K. WHIPPO INSTRUCTIONAL INTERVENTION .....	259
APPENDIX L. MODIFIED INSTRUCTIONAL INTERVENTIONS .....	267
<i>Pipe Cleaner Phylogeny Lesson Plan</i> .....	267
<i>Interpreting Pseudocots Lesson Plan</i> .....	276
VITA.....	292

## LIST OF TABLES

### Table

1. Representational competence levels in chemistry education (Kozma & Russell, 2005) .....	18
2. Identified novice-expert gradient of abilities and reasoning used to interpret and solve systematics problems.....	38
3. Participant demographics.....	48
4. Data matrix with primary and secondary data sources .....	52
5. Data sources attributed to research questions .....	57
6. Student responses to the multiple choice portion of pretest questions involving interpretation of relationships represented on a phylogenetic tree .....	62
7. Student approaches in interpreting phylogenetic representations at the beginning of the plant systematics course .....	63
8. Student perceptions of time on a diagonal phylogenetic representation at the beginning of the plant systematics course .....	72
9. Criteria used to compare phylogenetic representations at the beginning of the plant systematics course.....	74
10. Types of representations generated by students at the beginning of the course ....	81
11. Student responses to the multiple choice portion of posttest questions involving interpretation of relationships represented on a phylogenetic tree .....	95
12. Student approaches in interpreting phylogenetic representations upon completion of the course.....	96
13. Student perceptions of time on a diagonal phylogenetic representation upon completion of the plant systematics course .....	103
14. Reasoning types used to compare phylogenetic representations at the end of the course .....	104
15. Types of representations generated by students at the end of the course .....	106
16. Representational competence levels in chemistry education (Kozma & Russell, 2005) .....	154

17. Levels of representational competence associated with tree thinking .....	156
18. Levels of representational competence exhibited by participants .....	161

## LIST OF FIGURES

### Figure

1. An example of a phylogenetic tree of the Brodiaea and Milla complex within the Themidaceae flowering plant family (Pires & Sytsma, 2002).....3
2. Phylogenetic tree representation illustrating key features .....30
3. Phylogenetic tree illustrating monophyletic groups .....32
4. Two trees with equivalent topology retrieved from Baum et al. (2005).....34
5. Two trees illustrating opposing hypotheses about the evolutionary history of whales (Image taken from BioQUEST Curriculum Consortium (2006)).....55
6. Is the seal more closely related to the horse, the whale, or equally related to both? The scientific interpretation is that the seal is equally related to both.....64
7. Is the crocodile more closely related to the lizard, the bird, or equally related to both? The scientific interpretation is that the crocodile is more closely related to the bird .....64
8. Is the crocodile more closely related to the lizard, the bird, or equally related to both? The scientific interpretation is that the crocodile is more closely related to the bird .....68
9. Is the seal more closely related to the horse, the whale, or equally related to both? Bob measured time vertically from the most basal node and interpreted the tree as representing the seal more closely related to the horse. The scientifically accurate interpretation is the seal is equally related to the horse and whale. ....69
10. Phylogenetic tree with alternative orientations of time indicated by arrows. The scientifically accurate representation of time is indicated by the vertical, labeled arrow. ....71
11. Which of the following four evolutionary trees depicts a different pattern of relationships than the others? Provide an explanation for how the tree you chose is different from the others.....73
12. Although sea urchins and humans appear to have little in common, scientists recently found new evidence that relates sea urchins (B) with humans (E) and other vertebrates (D). This finding also suggests that sea urchins are not as closely related to beetles (C) and clams (G). Which tree below does not represent this new evidence? The scientifically accurate response would be to select tree a,

because it shows urchins (B) as being equally related to beetles (C), humans (E), and other vertebrates (D) .....	76
13. Two examples of scientifically accurate phylogenetic trees representing the relationships among 16 selected organisms. The second of these trees is an example of how a scientist can use consensus nodes when exact relationships are uncertain.....	80
14. Jamie’s dichotomous key .....	82
15. Jeremy’s dichotomous key that organized species based on ecological role (e.g., producers or consumers) and taxonomic characteristics .....	82
16. Chad generated three representations to illustrate relationships among the organisms by using a folk taxonomy style of categorization.....	83
17. Tim’s ladderized representation with organisms diverging in order of implied progression .....	84
18. Aimee generated a progressive tree placing humans at the point she considered most advanced.....	85
19. Mitch generated two separate trees segregating plants and fungi from animals ...	86
20. Randy generated a flow chart to illustrate how the organisms were related to one another.....	87
21. Lauren generated a flow chart to illustrate how the organisms were related to one another.....	88
22. Peter indicated taxa along the branches of a diagonal tree .....	89
23. Bob drew a diagonal representation illustrating character stated, secondary branching structures, and common ancestry. However the relationships represented are not scientifically accurate .....	90
24. Krystal generated a written list of animals .....	90
25. Aaron illustrated relationships among organisms by drawing images of each species and describing the ecological interactions connecting each organism.....	91
26. Representations used in the three tree interpretation questions were replaced for the posttest. Each new representation illustrated the same pattern of relationships as previously indicated. Tree A replaced the former tree used for tree interpretation question one and illustrates the salamander as equally related to the turtle and whale. Tree B replaced the former representation for tree interpretation question two and illustrated the lizard more closely related to the rabbit than the frog. Tree C replaced the former representation for tree interpretation question	

27. Amiee explained her response to the first tree interpretation question by illustrating how the monophyletic group, turtle, lizard, kangaroo, and whale, was represented on the phylogenetic tree.....	97
28. Emily inaccurately illustrated branches rotated around a node .....	98
29. Tim generated a scientifically accurate, species-poor phylogenetic representation at the end of the plant systematics course.....	107
30. Aimee generated a phylogenetic diagram using apomorphies to define monophyletic groups of taxa.....	108
31. Jared generated a ladder tree progressing from mushrooms to humans .....	109
32. Mitch generated a progressive rectangular tree based on his perception of the age of the taxa.....	110
33. Jeremy generated a dichotomous key that organized species based on ecological roles (e.g., autotrophic, heterotrophic) and taxonomic classifications rather than phylogenetic evidence.....	111
34. Jamie generated two separate trees segregating plants and fungi from animals..	112
35. Krystal generated three separate lists -- plants, almost plants, and animals -- to group how she thought the given taxa were related to one another.....	113
36. This is an example of a pipe cleaner model with one full lineage (from root to tip) indicated by a dashed line. This depicts the smallest inclusive monophyletic group and most recent node for this lineage .....	118
37. Pseudocot fossil record .....	122
38. Proposed Whippo hypothesis.....	126
39. Explain how these two attached trees are the same or different .....	132
40. Brandt's representation at the beginning of the course.....	137

INVESTIGATING THE DEVELOPMENT AND USE OF PHYLOGENETIC  
REPRESENTATIONS BY COLLEGE UNDERGRADUATES  
IN A PLANT SYSTEMATICS COURSE

Kristy L. Halverson

Dr. Sandra K. Abell & Dr. Patricia M. Friedrichsen, Dissertation Co-Advisors

ABSTRACT

Representations are critical tools for visualizing complex scientific knowledge. However, there is limited research investigating how students gain representational competence in biology, specifically in evolution. In evolutionary biology, phylogenetic trees are representations generated to express understandings of evolutionary relationships among taxa. Unfortunately, these trees are not well understood by students. In this study, I used open-ended student responses from pre/posttests, interviews, weekly reflective journal entries, field notes from course observations, and course assessments to learn how 27 upper-level undergraduate students enrolled in a plant systematics course used phylogenetic trees and developed tree thinking skills. I identified a) 10 approaches students used to interpret phylogenetic trees and 5 criteria used to compare representations; b) 8 alternative representations students generated and that some students were not able to generate any type of representation to illustrate a given phylogenetic scenario; and c) improvements in students' overall tree thinking, with greater improvement in tree reading than tree building. During the course, students were exposed to three instructional interventions to improve their tree thinking skills which they responded to with various levels of success. I identified 16 core skills necessary for

students to develop competence in tree reading and tree building. I proposed 7 levels of representational competence (Levels 0-6) based on these core skills. This empirical framework for representational competence in tree thinking will inform the design of evolution curriculum and maximize the instructional potential of using phylogenetic representations.

## CHAPTER ONE: INTRODUCTION

The major goal of science education is to develop science literacy (National Research Council, 1996; Rutherford & Ahlgren, 1990). One component of science literacy is the ability to use common representations of phenomena, such as molecular models (Ferk, Vrtacnik, Blejec, & Gril, 2003), abstract physics diagrams (Chi, Feltovich, & Glaser, 1981), Punnett squares (Cavallo, 1996), genetic structures, such as DNA diagrams (Patrick, Carter, & Wiebe, 2005; Takayama, 2005), pedigrees (Hackling & Lawrence, 1988), and phylogenetic trees (Matuk, 2007). Representations affect multiple aspects of science learning including: reasoning through problems and phenomena, developing deeper understandings of the relationships among phenomena, and improving creativity (Peterson, 1994). Thus, it is imperative that representations are designed appropriately and included in science instruction in ways that facilitate optimal learning experiences. Recently, college level instructors have incorporated phylogenetic trees into the biology curriculum to promote conceptual learning of evolutionary principles. Unfortunately, these trees are not well understood by students (Baum, Smith, & Donovan, 2005; Gregory, 2008; Halverson, Pires, & Abell, 2008; Meir, Perry, Herron, & Kingsolver, 2007; Omland, Cook, & Crisp, 2008). Thus, students often fail to achieve the intended learning outcomes.

Just as every geographer needs to know how to read a map, every biologist needs to know how to read a phylogenetic tree (O'Hara, 1998). Evolutionary biologists see biology through the perspective of phylogeny, or evolutionary history. They think about biological phenomena in terms of how observations fit within the branching structure of

genealogical relationships among species (Baum et al., 2005; Cooper, 2002). Often biologists generate phylogenetic representations to express their understandings of the relationships they are investigating (e.g., Figure 1). In systematics biology, where biological information is organized using phylogenetics, “evolutionary trees serve not only as tools for biological researchers across disciplines but also as the main framework within which evidence for evolution is evaluated” (Baum et al., 2005, p. 979). Specifically, phylogenetic trees are used to represent the “inferred evolutionary relationship among set of species” by mapping descent from common ancestry (Baum & Offner, 2008, p. 222). Phylogenetic trees offer more integrated information about evolutionary processes than just phylogenetic definitions (e.g., common ancestors) or analogies (e.g., genetic bottlenecks).

Researchers have argued that understanding phylogenetic trees as representations of evolutionary relatedness is a cognitively complex task, given the numerous misconceptions that students commonly hold (e.g., Baum et al., 2005; Gendron, 2000; Gregory, 2008; Halverson et al., 2008). Developing phylogenetic thinking involves understanding evolutionary mechanisms, inheritance and genomics, using phylogenetic tools, and organizing evolutionary relationships through tree thinking. Furthermore, tree thinking is generally inconsistent with everyday thinking about biological groups and their relationships (Cobern, Gibson, & Underwood, 1999). Our intuitive folk taxonomy is based on overall similarity, whereas modern phylogenetic classifications define monophyletic groups (clades) by shared derived characters. For example, birds and crocodiles belong to the same clade; however, these organisms are often grouped into two separate categories when a person is using folk taxonomy.

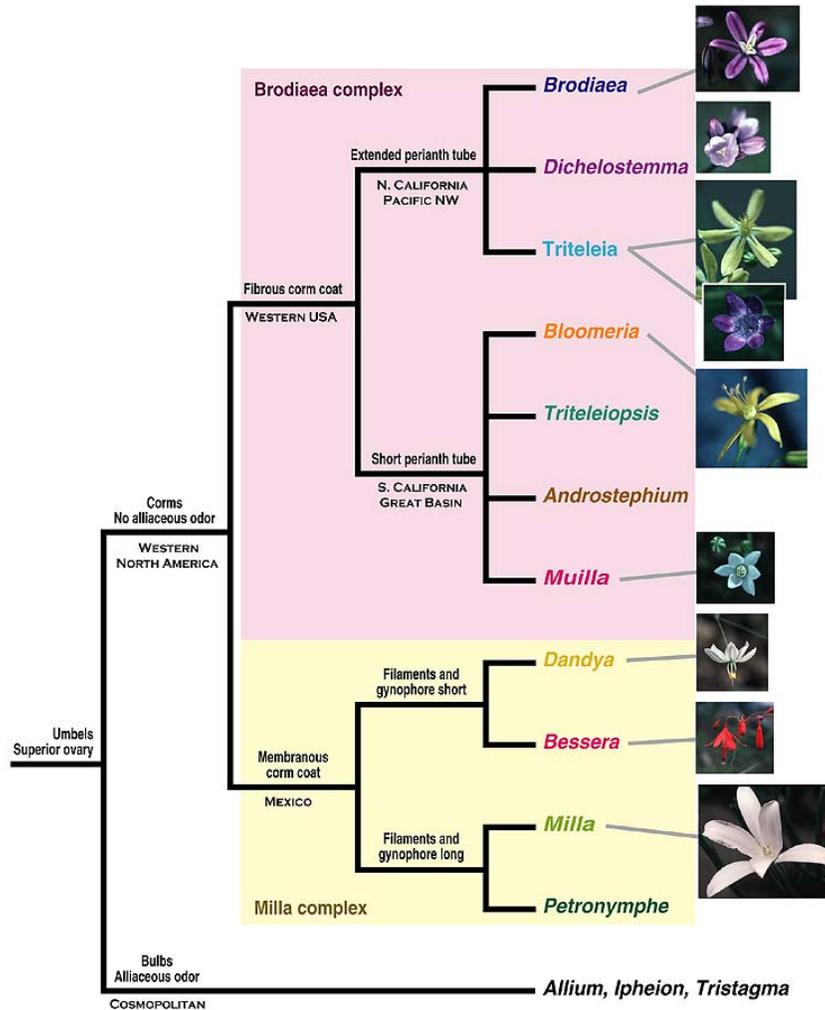


Figure 1. An example of a phylogenetic tree of the Brodiaea and Milla complex within the *Themidaceae* flowering plant family (Pires & Sytsma, 2002).

Much of the current college biology curriculum is driven by the use of phylogenetic trees (Novick & Catley, 2008). However, it is clear that most students do not interpret trees in the same manner as evolutionary biologists (Baum et al., 2005; Gregory, 2008; Halverson et al., 2008; Meir et al., 2007). The biology curriculum must be revised to address alternative student reasoning types in order to effectively promote understanding and development toward expertise. In particular, this is true when considering the role of prior knowledge and the detrimental effect misconceptions can have on student learning. The type of reasoning students use can cause them to generate

a variety of responses when interpreting and using phylogenetic trees. Current quantitative assessment instruments (e.g., Baum et al., 2005) may uncover categories of student errors, such as those described by Gregory (2008), but they do not uncover the underlying reasoning patterns.

While research has shown multiple areas in which interpreting phylogenetic trees is difficult for students, few studies have focused on why students misinterpret trees or how students can overcome these misconceptions to develop internalized tree thinking skills. The purpose of this study was to examine undergraduates' understandings of visual representations and how students developed and used phylogenetic trees during a plant systematics course. By investigating student understanding of visual biological representations throughout an entire course, this study will begin building knowledge on how students develop scientific literacy in systematics.

#### Rationale

We use representations to explain how we make sense of things on a daily basis. External representations can take many forms: gestures, visual aids, verbal metaphors. Representations are critical for communicating abstract science concepts (Gilbert, 2005a). In science, visual representations are used to display data, organize complex information, and promote a shared understanding of scientific phenomena (Kozma & Russell, 2005; Roth, Bowen, & McGinn, 1999). These representations are often used to present multiple relationships and processes that are difficult to describe or observe. Although student learning with representations is well documented in chemistry, physics, and geography (e.g., Chi et al., 1981; Ferk et al., 2003; Kozma & Russell, 2005; Peterson, 1994), little research has been conducted in biology education (see Gilbert, 2005b).

Phylogenetics is a central tool in biology, yet little is known about how students understand and use this tool.

In a previous study (Halverson et al., 2008), we investigated how students understood and used tree thinking during a plant systematics course. We found that the reasoning used to interpret trees influenced how students applied tree thinking to new systematics problems. Students were resistant to solving problems using abstract tools such as phylogenetic trees. Although the course emphasized tree thinking throughout, no students made reference to tree thinking when explaining their responses to questions that did not refer explicitly to a tree. While students attempted to make sense of unknown organisms and interpret trees, they did not attempt to use tree thinking to help make sense of new systematics problems. And, although students were able to interpret representations similar to those presented within the course, they were unable to transfer that knowledge to interpret or generate novel representations. The results illustrate the need to understand how students develop representational competence in evolution education across time, particularly with phylogenetic trees.

After identifying that students did not transfer phylogenetic tree thinking to novel systematics problems, I focused my research questions for the present study on students' use of representations in a plant systematics course. I reviewed a model of representational competence in chemistry education and used this study to test its application to biology education. To understand students' representational competence in a plant systematics course, I specifically wanted to investigate how students interpreted representations presented in the course, how students transferred their understandings to multiple styles of representations (e.g., diagonal, rectangular, or circular), and what types

of representations students generated to explain their ideas at different points in time. Thus, the research questions center on identifying students' skill developments as they became tree readers and tree builders.

### Research Questions

The overarching question guiding this study was: How do undergraduate college biology majors use phylogenetic representations in a plant systematics course and develop tree thinking? From this overarching question I developed the following sub-questions:

1. What is the status of undergraduate students' phylogenetic conceptual understanding and representational competence when they enter a plant systematics course?
  - a. How do students interpret phylogenetic representations (e.g., key features, evolutionary relationships, reasoning schemes, limitations of the representation)?
  - b. What sense do students make of different phylogenetic representations? What do the students acknowledge as similar/different in the representations?
  - c. What types of representations do students use or generate to solve problems? How do they justify the representation?
2. In what ways do students show improvement in their phylogenetic conceptual understandings and representational competence upon completion of the plant systematics course?

3. How do students perceive improvements in their tree thinking related to three instructional interventions?
4. What are the core skills essential for students to develop competence in tree thinking?

## Theoretical Framework

### *Knowledge Development*

Learning is acknowledged as the process of developing expertise within a discipline. Bransford, Brown, & Cocking (2000) claim that, “the study of expertise shows what the results of successful learning look like” (p. 31). Posner, Strike, Hewson, and Gertzog (1982) suggest that learning is a cognitive activity that can be defined as the comprehension and acceptance of new ideas, or concepts, because they are intelligible and rational. Similarly, Niedderer and Goldberg (1994) described learning as a progression of change from the learner's prior naive conceptions to intermediate conceptions, to scientific conceptions. Alexander, Schallert, and Hare (1991) explained that knowledge construction occurs when outside information is combined with (or constructed with) conceptual and metacognitive knowledge in an attempt to make new information a part of existing knowledge structures. Content knowledge can be understood at varying levels: concept (e.g., science), domain (e.g., biology), and discipline knowledge (e.g., phylogenetics). All of these descriptions of learning view the individual as able to construct personal meaning by interpreting new information through a lens of prior knowledge; in other words, knowledge builds upon prior knowledge (Bransford et al., 2000).

Knowledge development consists of at least two phases, first understanding the descriptive, or observable, concepts and later building upon that knowledge to make sense of theoretical concepts, or imagined explanations of events (Lawson, Alkhoury, Benford, Clark, & Falconer, 2000). For example, Darwin noticed that many species shared similar features and wondered why. He first described the observable similarities or phenotypes, the descriptive concept, before he began developing his model of natural selection and evolutionary relatedness, the theoretical concept. In other words, a scientist does not invent an explanation involving unseen theoretical entities (e.g., genes) until he/she has some unexplained observations to resolve (e.g., why do organisms share so many similarities?). Thus, in order for learners, particularly college students, to begin constructing theoretical concepts in a new topic and achieving expertise, the descriptive conceptual foundation must, at least, be partially in place.

Experts can be defined as people who have “acquired extensive knowledge that affects what they notice and how they organize, represent, and interpret information in their environment. This, in turn, affects their abilities to remember, reason, and solve problems,” (Bransford et al., 2000, p. 31). Expert knowledge allows learners to chunk information into meaningful patterns and to transfer what they have learned to think through new problems (Bransford et al., 2000). Novice learners, on the other hand, are often incapable of seeing patterns in information (Bransford et al., 2000). In order for learners to develop expertise in a science discipline, they must, (a) have a deep foundation of usable knowledge, (b) understand facts in the context of a conceptual framework, and (c) be able to organize that knowledge in ways that facilitate retrieval and application (Bransford et al., 2000). In addition to revisiting the conditions that lead

toward developing expertise, Bransford (2000) assembled a list of six characteristics that experts share:

1. Experts notice features and meaningful patterns of information that are not noticed by novices.
2. Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter.
3. Experts' knowledge cannot be reduced to sets of isolated facts or propositions but, instead, reflects contexts of applicability; that is, the knowledge is "conditionalized" on a set of circumstances.
4. Experts are able to flexibly retrieve important aspects of their knowledge with little attentional effort.
5. Though experts know their disciplines thoroughly, this does not guarantee that they are able to teach others.
6. Experts have varying levels of flexibility in their approach to new situations (p. 31).

These characteristics allow experts to engage in deep thinking about domain problems and motivate them to reinvest efforts towards more complex problems in the domain (Beck & McKeown, 2001; Bereiter & Scardamalia, 1993; Fullan & Steigelbauer, 1991).

Students, who are novices in the discipline often come to the science classroom with alternative preconceptions about how the world works. If their initial knowledge is inaccurate, they may fail to grasp new concepts and information that are presented (Bransford et al., 2000; Chi & Roscoe, 2002). Vosniadou (2003) argued that while prior alternative ideas stem from naïve experiences, these experiences form a coherent whole not just fragmentations. To further this idea, Vosniadou (2003) viewed learning as a process that enables students to synthesize models in their minds, beginning with their existing explanatory frameworks. Researchers (e.g., Bransford et al., 2000; Lewis, Leach, & Wood-Robinson, 2000) also found that students are not always capable of making connections between new concepts and their existing understandings. Thus, students often fail to see inconsistencies between the scientific information presented and

their personal central concepts. Even when confronted with a new, scientifically acceptable idea, students may choose not to accept the scientific explanation because they do not understand the abstract concept. Students resist altering their ideas because they often develop their personal observations into cohesive theories that seem plausible to them (Posner et al., 1982). Central concepts in the domain must make sense to the individual in order to be accepted and these conceptual understandings are often constructed to be consistent with everyday experiences (Driver, Squires, Rushworth, & Woods-Robinson, 1994; Duit & Treagust, 2003; Pearsall, Skipper, & Mintzes, 1997; Wandersee, Mintzes, & Novak, 1994). Therefore, the students see no practical reason to refine their central conceptual understanding. Even if students do accept a new, scientific concept into their knowledge structure, their initial alternative ideas are not necessarily extinguished. Rather, students might hold both the scientific concept and their alternative conception concurrently (Chinn & Brewer, 1993; Tyson, Venville, Harrison, & Treagust, 1997). Furthermore, Duit and Treagust (2003) found that students' conceptions after instruction tend to remain limited and inaccurate when their prior alternative ideas were not directly addressed.

When teachers do not consider students' prior knowledge, instruction can lead to unintended learning outcomes, thus initiating a cycle of misconception development. Thus, prior knowledge plays an important role in knowledge construction. In addition, constructing an accurate, solid cognitive foundation is necessary to begin developing expertise in a discipline. Development of mental procedural structures occurs gradually over time and involves more than just overcoming misconceptions. "According to developmental theory, descriptive and theoretical concept construction is linked to

intellectual development because the process depends in part on procedural or operational knowledge structures (i.e. reasoning patterns) as well as prior declarative knowledge structures” (Lawson et al., 2000, p. 997).

Developing expertise within a discipline includes overcoming alternative prior ideas and learning to use common representations of phenomena within that discipline (e.g., in biology, Punnett squares, Hardy-Weinburg equation). In cognitive science, representations can refer either to internal cognitive representations or external representations (e.g., graphs, maps, and phylogenetic trees), that are tools for shared reasoning within a subject matter domain (Palmer, 1978). Understanding the nature and role of external representations in subject matter areas is important when thinking about issues concerning learning since external representational systems are often the focus of a primary reasoning component within a domain (e.g., Anderson & Leinhardt, 2002; Simon, Larkin, McDermott, & Simon, 1989; Tabachneck, Leonardo, & Simon, 1994). External representations are used to visualize concepts that only exist in the mind. However, novices tend to focus on superficial features of representations rather than the underlying conceptual meanings and they tend to treat representations as concrete rather than flexible hypotheses (Caravita, 2001). These tendencies limit the effectiveness of using representations in knowledge development. Additionally, Anderson and Leinhardt (2002) found that “experts use representations as a tool to reason about real-life objects and events, whereas novices tend to reason within the representation itself and have more difficulty in moving back and forth between the representation and the real-world objects represented” (p. 285).

Experts in systematics are identified by their ability to comprehend phylogenetic trees as representations of species relatedness and are able to use trees as reasoning tools when solving systematics problems. They use phylogenetic representations to interpret and illustrate patterns among the evolutionary histories of different species lineages. Thus, understanding phylogenetic trees involves overcoming prior naïve ideas about species and interpreting relations based on the branching patterns of the tree. It is imperative that biology students are able to interpret and recognize patterns when manipulating or building evolutionary trees. If students cannot recognize patterns within phylogenetic trees, then they will not be able to accurately interpret the intended meaning nor test the hypothesis presented.

I used these ideas about developing expertise through knowledge construction to help guide my data collection, analysis, and frame implications from my study. I collected data on students' prior ideas about phylogenetic and evolution concepts, because I assume that knowledge builds upon existing knowledge. By gathering these data, I was able to assess how students overcame or built upon foundational understandings to develop essential skills for tree thinking. The idea of knowledge construction supports assertions of essential core skills and a developmental trajectory associated with becoming an expert tree thinker. Additionally, understanding how knowledge is constructed provided a framework for me to design effective instructional interventions based on the findings of my study.

### *Representational Competence*

Traditional science classrooms emphasize verbal teaching of concrete and abstract concepts. However, according to Haber (1970), linguistic memory is distinct from visual

memory. Gardner (1983) expanded upon this idea and classified eight different types of intelligence, including spatial intelligence and logical-mathematical intelligence. These two intelligences allow learners to be able to detect patterns, reason deductively, and “perceive the visual world accurately, to perform transformations and modifications [based] upon one’s visual experience,” (Gardner, 1983, p. 173). Thus, when teaching scientific concepts, instructors must utilize non-verbal representations, not just verbal descriptions, to help better relate abstract content through simplified images or ideas students can more easily comprehend. The use of non-verbal representations in science education has grown increasingly important over the past few years. Researchers are interested in investigating how visual representations affect understanding and how students evaluate and interact with visual representations (Ferk et al., 2003).

Representations provide a different way of presenting information rather than through verbal lectures and are critical for communicating abstract science concepts (Gilbert, 2005a; Mathewson, 1999; Patrick et al., 2005). More specifically, visual representations enhance learning from texts, improve problem solving, and facilitate developing connections between new knowledge and prior knowledge (Cook, 2006; Roth et al., 1999). In science, graphic representations are used to display data, organize complex information, and promote a shared understanding of scientific phenomena (Kozma & Russell, 2005; Roth et al., 1999). These graphics are often used to present multiple relationships and processes that are difficult to describe. Although their importance in science areas such as chemistry, physics, and geography is well documented in the literature (e.g., Anderson & Leinhardt, 2002; Chi et al., 1981; Kozma & Russell, 2005; Larkin, McDermott, Simon, & Simon, 1980; Luisi & Thomas, 1990), little research has

been conducted on the role of visual representations in science instruction (Cook, 2006) or investigating representations in biology education (see Gilbert, 2005b), especially when considering phylogenetic problem solving.

There are two primary types of representations: external and internal (Gilbert, 2005a). External representations are visually perceivable models while internal representations result from perceptions that remain inside the mind. The distinction between these representation types is sometimes blurred by the assumption that the focus of cognitive research is ultimately on internal representations. The classification of pictorial and verbal representations constructed by students can be used as an assessment tool to help represent, internal representations or mental models held and used by students (Driver et al., 1994; Reiss & Tunnicliffe, 2001). All the same, understanding the nature and role of external representations in content areas is important when investigating instruction and learning, because external representations themselves can be a significant component of reasoning within that domain. For example, within the scientific community, phylogenetic trees are critical for communicating hypotheses about species relatedness (Baum et al., 2005; Gendron, 2000; O'Hara, 1998; Staub, Pauw, & Pauw, 2006). For the purpose of this dissertation, I shall use the term *representation* in reference only to external representations, unless otherwise noted.

When approaching representations, there are five modes of expression: concrete, verbal, symbolic, visual, and gestural (Gilbert, 2005a). The concrete mode, or material mode, is a three dimensional structure made of physical materials, such as a ball and stick model of a double helix DNA molecule or using plastic links to represent polymers. The verbal mode consists of spoken descriptions of the entities and relationships represented.

This mode would include a lecturer describing the differences in frog mating calls. The symbolic mode refers to chemical symbols or formula equations like Hardy Weinberg. The visual mode uses graphs, diagrams, charts, and other two-dimensional structures, examples include geographic maps and images of atoms illustrating electron clouds. This visual mode also incorporates virtual three-dimensional models generated by computer programs, often used to portray molecular structures. Lastly, the gestural mode takes place when the representation is generated by using body parts or movements, such as when students role-play the orbit of planets and moons or use charades to represent an animal's behavior. These modes can be combined; for instance, the verbal and visual mode are combined when using a verbal description of the "flipping" ability of branches on a visual representation of a two dimensional phylogenetic tree. For the purposes of this dissertation, I have focused on the visual mode of representations. I use the term *visualization* to refer to Tufte's (2001) definition that visualizations are visual modes of external representations since they refer to the visual display of information in the form of tables, diagrams, and graphs.

Visualizations affect multiple aspects of learning (Peterson, 1994). Reasoning through problems and phenomena can be affected by recombining features of existing images to generate new images and create visual analogies. Comprehension of verbal descriptions is aided both by accompanying visualizations and when learners generate visualizations from a series of descriptive statements. These types of visualizations help develop a deeper understanding of the relationships among phenomena. Creativity is also affected by visualizations, through the ability to reinterpret meaning or change perceptions within set images. Thus, it is imperative that visualizations are included in

instruction and are designed appropriately to help facilitate optimal learning experiences. The primary importance of using such visual tools to facilitate learning is that the visualization itself, animated or still, should explain not merely show content. In addition, students must learn how to use representations to construct meaning through interpretations of underlying ideas rather than rely primarily on the surface features of representation to derive meaning (Chi et al., 1981). Wu and Shah (2004) outlined five principles of how to design and facilitate learning to utilize visualizations. First, multiple representations and accompanying descriptions should be used to help students make connections between the content and the image as well as make connections among visualizations. Second, it is imperative that key informative features are visible in the representation. Third, visualizations should represent the interactive nature of the phenomena. Fourth, learners should actively investigate the transformation between two dimensional and three dimensional models. And lastly, the visualization should help reduce the cognitive load by making information explicit and integrate information for learners. Incorporating these five principles allows students the opportunity to develop essential core skills (described below) for appropriately interacting with visualizations.

Kozma and Russell (2005), in the context of chemical representations, proposed a set of seven core skills that must be developed in order to achieve competence in the use of representations. An individual must be able to:

- use representations to describe observable phenomena in terms of the underlying entities and processes;
- generate or select an appropriate representation and explain why it is best suited;
- in the case of non-verbal modes, use words to identify and analyze features of the representation;

- describe how different representations can illustrate the same idea in different ways and how one representation might illustrate something different or something that cannot be said by another, because of differences in limitations;
- make connections across different representations, to transfer features of one type of representation onto those of another and explain relationships between the features;
- accept that representations are depictions of phenomena or concepts but are distinct from the actual phenomena; and
- use representations and associated features as evidence to support claims, draw inferences, and make predictions.

Once these skills are developed, a learner should be able to effectively use a variety of representations, thereby achieving representational competence. Although Kozma and Russell (2005) proposed this list of core skills for chemistry education, this list of skills has not been empirically tested in or beyond chemistry. Additionally, Kozma and Russell claimed that a student can achieve multiple levels of competence. They proposed five levels of representational competence related to how students utilize these core skills and interact with representations (Table 1). These levels correspond to a progressive developmental gradient moving from the use of surface features to defining phenomena to the metaphoric or reflective use of representations (Chi et al., 1981; Kozma & Russell, 1997). When a learner achieves representational competence, he/she can begin shifting the external representation into an internal representation, or a mental image that can be manipulated (e.g., scanned and rotated) to improve performance on visual tasks, memory tasks, and cognitive problem solving (Botzer & Reiner, 2005; Clement, Zietsman, & Monaghan, 2005; Gilbert, 2005a).

Table 1

*Representational competence levels in chemistry education (Kozma & Russell, 2005)*

---

***Level 1: Representation as Depiction***

Representations are generated or interpreted solely on physical features

---

***Level 2: Early Symbolic Skills***

Representations are based on physical features and some symbolic elements to accommodate limitations of the medium, but are still interpreted literally

---

***Level 3: Syntactic use of Formal Representations***

Representations take into account both observed physical features and unobserved features, underlying entities or processes. However, these representations may not be scientifically accurate and interpretations are based upon the accompanying description rather than the underlying meaning. In addition, similarities between representations are still only based on surface features.

---

***Level 4: Semantic use of Formal Representations***

Representations utilize a symbol system to representation unobservable entities and processes. Interpretations are based on syntactic rules and the underlying meaning that it represents. At this stage the representation can be used to solve a problem, explain a phenomenon, or make predictions. In addition, multiple representations can be compared based upon meaning.

---

***Level 5: Reflective use of Representations***

Multiple representations are used to explain relationships between physical properties and the underlying entities and processes of a phenomenon. The learner constructs appropriate representations and can explain why a particular representation is more appropriate than another. In addition, the learner accepts representations as substitutions for phenomena that can only be understood through a representation.

---

This model of representational competence does not account for students who choose to ignore the representation when reasoning through problems. Most studies of phylogenetic reasoning were based upon the assumption that students use representations to make meaning when presented with associated problems (e.g., Baum et al., 2005; Meir et al., 2007). However, Halverson et al. (2008) found that students' prior knowledge about taxa interfered with the process of gaining representational competence. When students were familiar with the organisms on the phylogenetic tree, they used their prior knowledge of physical and ecological similarities rather than the information represented

in the phylogenetic tree. This study demonstrated that some students who approach a problem may not even be at Level 1 of competence.

This representational competence framework guided data collection and analysis during this study. I designed my research questions to investigate essential core skills associated with tree thinking. I accomplished this by exploring the ways students interpreted, compared, and built phylogenetic representations throughout an entire course focused on plant systematics. I used an inductive approach in my analysis to search for themes in the data and test the competence levels proposed by Kozma and Russell (2005). Furthermore, I compared essential core skills I uncovered for tree thinking with the skills Kozma and Russell presented for chemistry education.

#### Significance of Study

Representations can refer either to internal cognitive representations or external representations (e.g., graphs, maps, and phylogenetic trees), that are tools for shared reasoning within a subject matter domain (Palmer, 1978). Understanding the nature and role of external representations in subject matter areas is important when thinking about issues concerning student learning. Phylogenetics is a growing area of research in biology, particularly because research investigators are gaining better, easier, and cheaper access to genome sequencing facilities. This improved access allows researchers to gather critical evidence necessary to address phylogenetic questions. This evidence was previously inaccessible or too expensive to reasonably obtain. Because of the growth of this discipline, phylogenetic representations play a prominent role in evolution curriculum, but very little is known about the core skills needed for students to make sense of them. When students are being expected to interpret, use, and build

phylogenetic trees without a good understanding of the needed skills, etc., it is difficult to design effective instruction. In addition to identifying and targeting misconceptions about tree interpretations, students must be given opportunities to explore systematics problems in ways that utilize phylogenetic trees. Explicit direction on how to utilize tree thinking is necessary to help students move from a novice to an expert problem solver. Researchers (e.g., Baum et al., 2005; Halverson et al., 2008; Omland et al., 2008) have investigated misconceptions and faulty reasoning associated with phylogenetic trees. However, no one has investigated how students develop representational competence with phylogenetic trees over time. There is a need to develop a model for phylogenetic tree thinking as a framework to guide such studies. Understanding phylogenetics involves interpreting and building multiple versions of the same representations. Thus, there is a need to investigate how students gain representational competence with phylogenetic trees to maximize the potential of evolution education and improve science literacy. This study provides insights into how undergraduate biology majors develop representational competence in tree thinking. The results of this study contribute to the development of a cohesive, empirically based representational competence model and inform the design of evolutionary biology curriculum.

## CHAPTER TWO: REVIEW OF LITERATURE

### Overview

In this chapter, I elaborate on the literature related to the research questions. Research on the role of representations in learning has been extensively conducted in mathematics (e.g., Cuoco, 2001; Tabachneck et al., 1994; Trouche, 2005; Tufte, 2001; Zbiek, Heid, Blume, & Dick, 2007), geography (e.g., Anderson & Leinhardt, 2002; Peterson, 1994; Reynolds et al., 2005), and the physical sciences (Botzer & Reiner, 2005; M. Briggs & Bodner, 2005; Chi et al., 1981; Dori & Belcher, 2005; Ferik et al., 2003; Gilbert & Treagust, 2009; Larkin et al., 1980; Luisi & Thomas, 1990; Mach, 1976; Mammino, 2008; Reiner & Gilbert, 2008; Russell & Kozma, 2005). This previous research has addressed both how representations are used and how they are learned. However, less research has been conducted on biological representations (e.g., Cavallo, 1996; Hildebrand, 1986; Kindfield, 1994; Patrick et al., 2005; Reiss & Tunnicliffe, 2001; Rogers, 2008; Takayama, 2005), with only a few studies specifically addressing phylogenetic trees (e.g., Baum & Offner, 2008; Baum et al., 2005; Cooper, 2002; Halverson et al., 2008; Omland et al., 2008). In this chapter I review the literature on student learning with external visual representations. Additionally, I examine what is currently understood about student learning with representations in biology, particularly with phylogenetic trees. Other literature exists on student learning with mental models, computer-based animations, and simulations. However, because this literature base is not directly connected to the research questions for this study, I have excluded these areas from this review.

## Research on Representations in Education

Representations play a key role in mathematics, geography, and science (Cuoco, 2001; Gilbert, 2005b). Researchers (Friedlander & Tabach, 2001; Lamon, 2001; Peterson, 1994) have drawn strong connections between representations students use and their content understanding. “Furthermore, representations are often considered as a means to form conceptual understanding. The ability to move smoothly between various representations of the same concept is seen as an indication of conceptual understanding and also as a goal for instruction” (Zazkis & Liljedahl, 2004, p. 167). Therefore, representations play a key role in science education. Representations are tools based on real data and are modified when new evidence is presented; they represent our interpretations and understandings (Van Fraassen, 2008). For scientific representations to be used for their intended purpose, they must be similar to the object or phenomena represented. Gilbert (2005b) stated that representations bridge scientific theory and the natural world in two ways: acting as simplified depictions of phenomena, to which abstract theory can be applied, or as idealizations of abstract theory and comparable to observations of phenomena in the natural world.

Representations enhance learning from texts, improve problem solving, and facilitate connections between new knowledge and prior knowledge (Cook, 2006). For example, researchers (Meyer, 2001; Woleck, 2001) have shown how middle school children use and develop mathematic, symbolic representations to build content knowledge. In geology, Peterson (1994) investigated cartography misconceptions and identified a strong connection between visual representations and advanced thinking processes. He found that symbolization expertise helped provide a cognitive context for

geographic visualization development and content understanding. In physics education learners take part in thought experiments, where they internalize visual representations and use mental simulations to run scenarios in their minds to construct new knowledge (Gilbert & Reiner, 2000; Lakoff, 1987; Mach, 1976; Reiner & Gilbert, 2008). These thought experiments would not be possible without representations. Likewise in mathematics, Richard Feynman described how he used an internal visual representation to test the validity of a mathematical theorem:

I had a scheme, which I still use today when someone is explaining something that I'm trying to understand: I keep making up examples. For instance, the mathematicians would come in with a terrific theorem, and they're all excited. As they are telling me the conditions of the theorem, I construct something which fits all the conditions. You know, you have a set (one ball)—disjoint (two balls). Then the balls turn colors, grow hairs, or whatever, in my head as they put more conditions on. Finally, they state the theorem, which is some dumb thing about the ball which isn't true for my hairy green ball, so I say, "False!" (Feynman in Cuoco, 2001, p. ix).

Mathematicians (Tabachneck et al., 1994; Trouche, 2005; Tufte, 2001) also have studied the role of external representations, specifically graphs, tables, and diagrams, in student learning.

In mathematics, educators investigate student learning with external representations because they strive to help students develop representational fluency. Representational fluency can be defined as a student having "meaningful and fluent interaction with representations" (Zbiek et al., 2007, p. 1196). Students who have representational fluency have "the ability to translate across representations, the ability to draw meaning about a mathematical entity from different representations of that mathematics entity, and the ability to generalize across different representations can be examined as they affect mathematical ability" (Zbiek et al., 2007, p. 1194). This fluency

can be investigated as an outcome, condition, or developmental stage with students' understanding of mathematical entities based on their interactions with representations. In science, the National Research Council (1996) outlined the following objectives for students working with representations. Students should be able to:

- Describe and represent relationships with visual representations;
- Analyze relationships and explain how a change in an entity affects another;
- Systematically collect, organize, and describe data;
- Describe and compare phenomena;
- Construct, read, and interpret representations;
- Support hypotheses and argument with data;
- Evaluate arguments based on data presented;
- Represent situations with multiple external visual representations and explore the inter-relationship of these representations; and
- Analyze representations to identify properties and relationships.

Students' representational fluency can change with the difficulty of the task.

Barnea (2000) identified three skills necessary for understanding representations in chemistry education. These skills correspond to varying difficulty levels of tasks: spatial visualization, spatial orientation, and spatial relations. Students are expected to be able to understand, rotate, and invert two dimensional (2D) representations in three dimensions (3D) when they have representational fluency. Courses in geology and chemistry emphasize these skills associated with transitioning between 2D representations.

Research in these courses, such as the study by Ferk et al. (2003), explored how primary, secondary, and university students interpreted 2D and 3D representational structures in chemistry. Ferk et al. (2003) reported that in order to accurately interpret 3D structures students needed to be able to apply mental rotation and spatial manipulation techniques as described by Barnea.

Researchers (Gabel, 1999; Hinton & Nakhleh, 1999; Johnstone, 1993; Treagust, Chittleborough, & Mamiala, 2003) proposed there are different levels and types of representations, as well as transitions among these different representations that are difficult for students. For example, students associate more scientifically accurate meanings with concrete representations (e.g., three-dimensional models and photographs) than abstract types (e.g., schematic representations and stereochemical formulas) (Ferk et al., 2003). Furthermore, it has been documented in mathematics education that curricula using concrete representations in conjunction with realistic problems promote representational fluency more so than abstract problems and representations (Zbiek et al., 2007).

In addition to having difficulties interpreting, using, and transitioning among representations, students have difficulties understanding what approaches are appropriate for making sense of representations. Sometimes, the way students make sense of a representation may lead to correct responses, but this does not mean that the students have used appropriate approaches (Tabachneck et al., 1994; Trouche, 2005). For example, Cavallo (1996) investigated the relationships among meaningful learning orientations, reasoning ability, understandings about genetics, and problem solving abilities. She reported that students were able to successfully solve genetics problems when using Punnett square representations as a tool. She also reported that students with meaningful learning orientations were best able to understand genetics topics, such as meiosis. Meaningful learning orientations were defined as when students were able to formulate relationships between ideas and respond to novel problems by using self-questioning and elaborating upon ideas. However, this orientation could not be used to predict problem

solving with representations, nor could the use of representations predict understanding of concepts. For students to become experts with representations, they must interpret representations correctly and use them as a reasoning tool when investigating problems.

Another aspect of learning to read and to construct representations involves determining which features are pertinent and which are not pertinent (Van Fraassen, 2008). When representations are accurately understood, they can provide depictions of phenomena that cannot be illustrated through other approaches. Visual representations are the dominant way of thinking in chemistry (Bailer-Jones, 1999; Gilbert, 2005a; Luisi & Thomas, 1990). “Historically, advances in chemistry took place as new representational tools became more available which supported more insightful visualizations” (Gilbert, 2005b, p. 2). Chemists use visual representations of molecular structures to interpret and predict physical properties of the entity or process represented. While representations are designed to illustrate reality, they can never become reality, therefore representations can only offer limited understandings about natural phenomena or entities (Luisi & Thomas, 1990). In some cases, representations can also be misleading, such as statistics and manipulative visual imagery, and create additional difficulties with interpretation (Tufte, 2001; Zbiek et al., 2007). This is often the case when students use representations as a literal depiction of the phenomenon (Anderson & Leinhardt, 2002). For example, Reiss and Tunnicliffe (2001) investigated how children’s drawn images related to their mental models of anatomical structure. They found that, although representational depictions grew to include more content over time, students continued to view some symbolic references as reality, such as the use of a valentine style heart.

One reason students struggle with making accurate associations between science content and abstract representations is because they tend to rely upon superficial features rather than use representations as analytical tools (Anderson & Leinhardt, 2002; Chi et al., 1981; Larkin et al., 1980). For example, Chi et al. (1981) investigated students' interactions with simplified representations of abstract physics principles. This study reported that undergraduates relied upon superficial features of representations and had difficulties in moving back and forth between representations and the problem. In another study, Larkin et al. (1980) compared pattern recognition in chess to how people solve physics problems. Experts are able to organize knowledge from visual representations into patterns that inform actions and strategies, while novice students rely upon superficial knowledge of equations and representations rather than patterns to generate solutions. Anderson and Leinhardt (2002) investigated how differing levels of expertise affect interpretation and problem solving ability related to reading maps. They reported that experts explained their solutions by including references to internal representations generated from past experiences with similar external representations and focused on underlying similarities. Novices did not understand or recognize deeper meaning in the geographic representations and only applied superficial explanations when framing their solutions. In biology education, Patrick et al. (2005) investigated how middle school girls focused upon two dimensional and three dimensional visualizations of DNA and the replication process. They found that purely visual characteristics such as color, shape, and complexity were important components the girls used to make sense of the images. However, not all of these visual characters provided

informative meaning about the phenomena and many students had difficulty distinguishing between relevant and irrelevant information.

### *Summary*

Various forms of representations can support an understanding of different, yet overlapping, aspects of a phenomenon or entity. The studies highlighted focus on student learning with multiple representations. Investigators have focused primarily on how students interpret, utilize, and internalize representations rather than the types of external representations students generate. Educators agree that the use of representations enhance learning (e.g., Cook, 2006; Meyer, 2001; Peterson, 1994; Reiner & Gilbert, 2008; Woleck, 2001). “External visualizations provide support for all perception, including that in science,” (Gilbert, 2005b, p. 4). They also agree that students have difficulties understanding and interacting with representations (Anderson & Leinhardt, 2002; Ferk et al., 2003; Reiss & Tunnicliffe, 2001; Tufte, 2001; Zbiek et al., 2007). Challenges include: identifying key structures of representations, interpreting and using representations, transitioning among different modes of representations, and relating abstract representations to content knowledge. However, skills such as transitioning between different modes of representations (e.g., 2D and 3D models) are a vital part of becoming an expert. Because of these identified challenges, there is a need to help students develop the same level of representational skills as practitioners or expert scientists, developing representational competence or fluency (Barnea, 2000; Kozma & Russell, 2005; National Research Council, 1996; Zbiek et al., 2007).

## Proposed Instructional Guidelines

To facilitate students' abilities to overcome difficulties associated with learning using representations, researchers Christopherson (1997) Gilbert (2005b), and Tufte (2001) have proposed several instructional guidelines. Instructors should begin by “starting any sequence of representations with the most regular, geometrically simple forms available. This will enable students to ‘get their eye in’” (Gilbert, 2005a, p. 21). Gilbert, Boutler, and Rutherford (2000) separated representations into different categories of models: scientific models, curricular models, and teaching models. Scientific models are developed by scientists working in a given subject area (e.g., Schrodinger model of the atom or the Watson-Crick model of DNA). Simplified versions of scientific models are called curricular models and those used to provide classroom instruction are teaching models. As students begin learning with representations or teaching models, “too many forms of representation hindered, rather than supported, visualization” (Gilbert, 2005b, p. 4). Tufte (2001) also supported the recommendation that visualizations should be represented in their simplest form because complexities in images clutter the intended meaning and minimize recognition of key informative features. Additionally, maximizing the salience of shapes, edges, shadings, and patterns within representations enables students to better distinguish the structure of the representation (Christopherson, 1997). By understanding the structure of a representation, students are less likely to rely upon uninformative superficial features when make meaning of the representation.

Students are better able to gain representational competence when they are given the opportunity to interact with concrete representations involving realistic problems (Ferk et al., 2003; Zbiek et al., 2007). Still, over time, students should be deliberately,

systematically, and steadily introduced to more complex and abstract representations until a full range of representations is explored (Gilbert, 2005b). This approach allows students to learn how to relate common features across representations, compare and interpret multiple representations, and understand that different modes of representations are more appropriate for different situations, thus building representational competence. As students gain representational competence, exposure to a broader range of representations facilitates their conceptual learning in both chemistry and in the other sciences (Gilbert, 2005b).

### Phylogenetic Trees as Biological Representations

Genomics is a new and developing field of science which examines the full genomes of organisms. Gilbert (2005b) stated, “The rapid increase in the number of genomes that are being sequenced means that students have to develop a general capacity to understand any example that they may encounter,” (p. 4). This leads to a need for suitable representations for gene structure, gene orientation and organization, gene relationships, genome structure, and their integration into an overview. One way to present an overview of genomic relationships is by illustrating patterns in evolutionary histories of organisms such as those represented in phylogenetic trees (Figure 2).

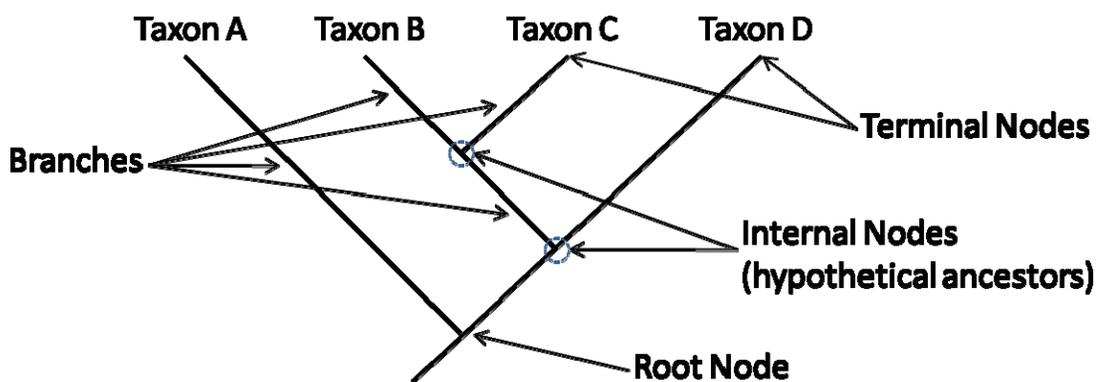
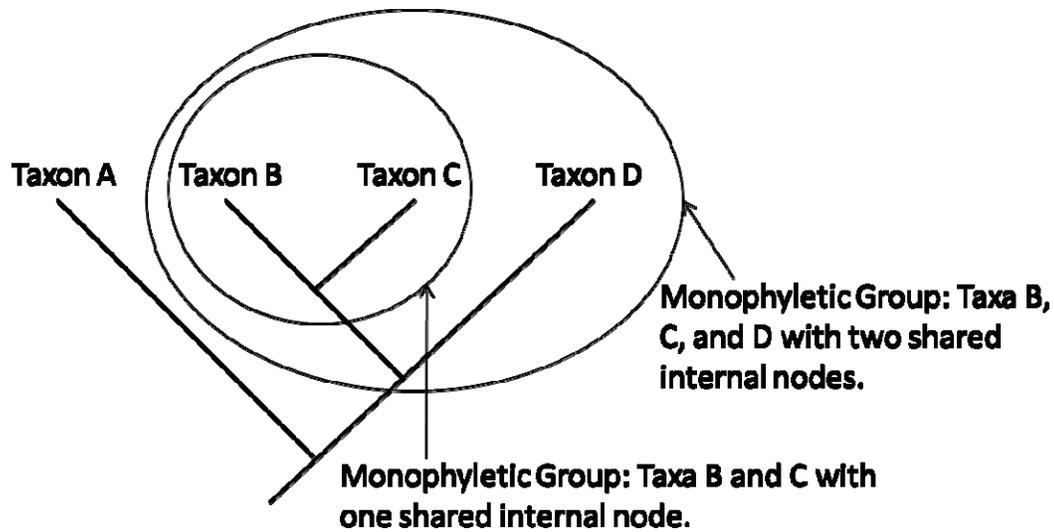


Figure 2. Phylogenetic tree representation illustrating key features.

The use of phylogenetic trees in systematics, the science discipline that classifies relationships among organisms with respect to evolutionary histories, allows students the opportunity to interact with the proposed hypotheses illustrated by the branching patterns. Any given tree can be manipulated and reconstructed in different formats, yet offer the same information. Phylogenetic trees can also be verbally explained to assist with interpretation. However, it is difficult to represent relationships among organisms at the same level of detail without a visual aid. Within the image of a phylogenetic tree, nodes and branches have significant meaning. A node symbolizes a hypothetical common ancestor and a branch symbolizes a historic evolutionary lineage of a taxon. Visualizing this meaning takes less cognitive energy to detect than representing the same information using a different mode. In addition, due to differences between verbal and visual knowledge (Haber, 1970), the reasoning process involved with visual-spatial reasoning offers an understanding of phylogenetic concepts that cannot be represented any other way, not even through verbal descriptions of the 'tree of life' or through the definitions of synapomorphies (shared character states). For example, patterns of monophyletic groups (a common ancestor and all descended lineages, also referred to as a clade) and genetic algorithms (evolutionary computations used to identify optimality) cannot be identified without a visual or symbolic image (Figure 3). Also, phylogenetic trees are used as evidence for evolutionary relatedness; without visual trees the methods by which we test and support evolutionary relationships are nullified. Global optima of phylogenetic hypotheses cannot be determined without first generating a tree. For example, parsimony, a key concept in evolution used to select best fit explanations or optimal trees, is based upon the length of a visually depicted tree. A parsimonious tree is a

representation that indicates the fewest number of derived character states that still accounts for all of the available data.



*Figure 3.* Phylogenetic tree illustrating monophyletic groups.

Systematists recognize the roles of descent from common ancestry and evolutionary adaptation in establishing patterns of similarity and difference among groups of organisms. Boster and Johnson (1989) investigated differences in how experts and novices approached a systematics problem about the evolutionary relationships among different fish lineages. They reported that experts vary more in their conclusions about evolutionary similarities among different fish species than novices because they have more knowledge to judge similarity. In addition, they found that experts tend to look at multiple levels of similarity (both morphological and functionality), versus novice learners who tended to only look at one level of similarity (only morphology) among the fish. Identifying accurate evolutionary similarities is essential for developing visual phylogenetic representations. Visualization of genotype and phenotype data simultaneously is crucial to biological research and facilitating communication across disciplines. Mabee (2006) argued that understanding the interaction between

developmental and phylogenetic constraints in evolution is an overarching goal of the field of evolution and development. As this field has refined the ability to compare developmental morphology, it has become necessary to situate findings within a phylogenetic framework. Phylogenetic tools connect evolutionary development with directionality and timing of evolutionary change by identifying patterns in homology.

### *Tree Thinking*

Phylogenetic tree representations are generated to express understandings of evolutionary relationships among taxa. Researchers have argued that understanding phylogenetic trees as representations of evolutionary relatedness is a cognitively complex task that requires explicit instruction given the numerous misconceptions associated with reading phylogenetic trees (e.g., Baum et al., 2005; Gendron, 2000; Gregory, 2008; Meir et al., 2005). Experts in systematics are identified by their ability to comprehend phylogenetic trees as representations of species relatedness and to use trees as one type of reasoning tool when solving systematics problems. However, novices reason only within the tree itself. Interpreting visual representations often depends more on pattern recognition than on conceptual understanding.

There are three different types of assumptions about the nature of species as represented on phylogenetic trees; but only one of these assumptions is accurate (Donovan, 2004). The accurate scientific assumption emphasizes both the historical relationships among species and their non-linear, or branching, divergence from multiple evolutionary events. The intermediate assumption is that species make up different steps along a single evolutionary (developmental) pathway, much like an evolutionary ladder. For example, the popular, flawed cartoon, *March of Progress* (Howell, 1970),

showing the progression of apes into humans, implies that apes evolved into humans rather than both species evolving independently but shared a common, ancient ancestor (Matuk, 2007). The naïve assumption considers species as fixed, non-related entities and is most consistent with what we experience in our everyday interactions with organisms. Tree thinking involves being able to incorporate the scientific assumption into one's biological sense making (Cooper, 2002), using a phylogenetic representation. Baum et al. (2005) reported that students commonly make inaccurate assumptions causing trees to be misunderstood due to flawed reasoning associating species relatedness with proximity of branches regardless of common ancestry. For example, given the two trees in Figure 4, Baum et al. (2005) predicted that students would indicate frog as more closely related to fish than human in the tree on the left, and more closely related to human in the tree on the right. This prediction is based on students claiming relatedness due to proximity of organisms to one another along the terminal tips of the representation. However, these two trees are equivalent in their topology and represent the same relationships – frog is more closely related to human than fish.

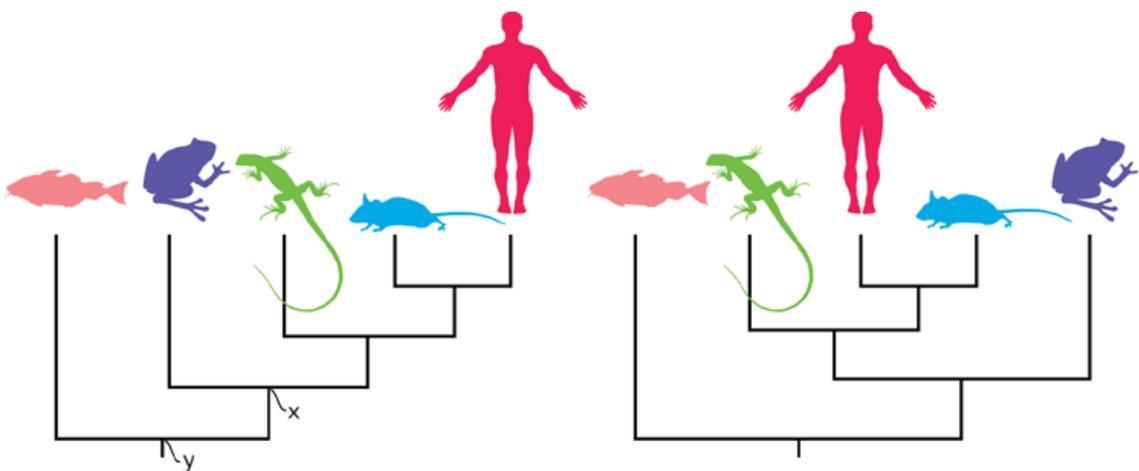


Figure 4. Two trees with equivalent topology retrieved from Baum et al. (2005).

Achieving expert understanding about species relatedness when reading phylogenetic trees involves understanding multiple biological concepts. Evolutionary biologists recognize relationships among species by using foundational concepts such as inheritance, the four forces of evolution (natural selection, genetic drift, gene flow, and random mutation), and parsimony to develop hypotheses and build phylogenetic trees. However, many researchers (e.g. Baum et al., 2005; Brumby, 1979; Driver et al., 1994) have reported that students often struggle with accommodating foundational concepts involved in evolution, thus hindering their ability to interpret evolutionary trees. Brumby (1979), Driver et al. (1994), Williams and Tolmie (2000), and Moore, Mitchell, Bally, Inglis, Day, and Jacobs (2002) reported many students share Lamarckian views and believe acquired traits can be passed down to offspring, basing their assumptions on environmental explanations. Students also think that natural selection occurs with purposeful intent and organisms deliberately select traits for survival (Driver et al., 1994; Moore et al., 2002). Brumby (1979) reported that students believed evolution can alter an individual during its lifetime, and evolution progressively improves organisms toward perfection. Lord and Marino (1993) reported that many students believed humans directly evolved from monkeys. They also reported that some students believed species were static, thus evolution does not occur.

To date, the literature in tree thinking has focused on alternative conceptions within a phylogenetic framework, such as “reading across the tips” (basing relatedness on proximity of organisms along terminal tips) and “more intervening nodes equals more distantly related” (basing relatedness on the number of nodes between species, more nodes equals less closely related) (see Baum et al., 2005; Gregory, 2008; Meir et al.,

2007). Baum et al. (2005) and Sandvik (2008) reported that trees are commonly misunderstood by students, leading to confusion about the concept of common ancestry. These researchers inferred that students misinterpret trees because of flawed reasoning, associating species proximity to each other as relatedness. Gregory (2008) compiled a collection of ten common misconceptions that interfere with students' abilities to interpret phylogenetic trees:

- Higher and Lower
- Main Line and Side Tracks
- Reading across the Tips
- Similarity versus Relatedness
- Sibling versus Ancestor
- Long Branch Implies no Change
- Different Lineage Ages for Modern Species
- Backwards Time Axes
- More Intervening Nodes Equal More Distantly Related
- Change only at Nodes

However, physical location and representation attributes do not explain all student difficulties with tree thinking. In a pilot study (Halverson et al., 2008), we found that students incorporate foundational misconceptions about evolution into tree thinking and these ideas complicated tree interpretations. One issue is that some students do not use the information presented in a tree to make sense of a presented problem. Instead these students rely on their prior ideas about the organisms; for example, they consider what they know about habitat or morphological similarities. In the next section I describe the pilot study in more detail.

### *Pilot Study*

In a pilot study, (Halverson et al., 2008), we used pre/post tests and interviews of upper-level college biology students to investigate how students understood and used tree thinking to make sense of plant systematics. We classified students' problem solving skills on a novice-expert gradient based upon the expert skills identified by Bransford et al. (2000). How students interpreted phylogenetic trees influenced how they applied trees to solve systematics problems. We grouped students into three different representation-based skill levels: expert, intermediate, and novice. The students used nine alternative reasoning processes when making sense of phylogenetic trees, eight of which hindered their transition from novice to expertise tree thinking (Table 2).

Although we identified misconceptions in tree thinking consistent with those identified previously (such as reading across the tips, main lines and side tracks, similarity versus relatedness, and more intervening nodes equals more distantly related) (Baum et al., 2005; Gregory, 2008), we also found conceptual misconceptions unrelated to misreading the topology of phylogenetic trees. Our findings revealed that students interpreted trees based upon fundamental inaccuracies in their conceptual understandings about phylogenetics. Many students did not consider phylogenetic trees as containing information needed to solve systematics problems. Therefore, they relied upon prior knowledge of the organisms, such as ecological characteristics, to supplement or overturn phylogenetic reasoning.

Table 2

*Identified novice-expert gradient of abilities and reasoning used to interpret and solve systematics problems*

<i>Expertise Gradient</i>	<i>Representation-Based Thinking Ability</i>	<i>Type of Reasoning Used</i>	<i>Student Emphasizes</i>
Novice	Inability to recognize and/or solve systematics problems	Inconsistent	Uncertainty; lack of confidence; no emphasis on tree thinking
Intermediate 	Use of disconnected knowledge to attempt or partially solve systematics problems	Reliance on Expert Knowledge	Knowledge gained from an expert, text, or reliable source
		Ecological	Habitat; where an organism lives; what an organism eats
		Morphological <ul style="list-style-type: none"> <li>• Categorizing</li> <li>• Elimination</li> </ul>	Similarities in physical appearance; differences in physical appearance
		Branch-Influenced	Proximity and order of branch location
		Tree Shape-Influenced	Physical nature of tree's appearance
		Node-Influenced	Number and location of nodes
		Quasi-scientific	Correct conclusion, but limited/faulty explanation
Expert	Use of expertise knowledge to solve systematics problems	Phylogenetic	Scientifically acceptable conclusions and explanations

Baum et al. (2005) investigated how the topology of phylogenetic trees caused students to fail to see patterns of evolutionary relatedness. Their quantitative findings based on multiple choice items inferred that branch proximity was the core reason students failed to interpret relationship patterns illustrated in the trees. However, a multiple choice instrument does not reveal student thinking behind their response. By using a qualitative approach and having students explain rationales for their responses, Halverson et al. (2008) found that while branch proximity did interfere with some students' reasoning, this was not the only, or primary, challenge associated with tree-thinking. Student reasoning was also based on other alternative ideas such as the style of the representation, similarities or differences in physical appearance of the taxa represented, and the number/location of nodes. This pilot study provided new insights into how college biology students interpret and use phylogenetic trees, going beyond the work of identifying misconceptions. (The full paper of this study is available in Appendix A.)

### Gaps in the Literature

While very little research about biological representations, studies in chemistry and physics provide guidance for instruction and future research on representations (Gilbert, 2005b). These studies highlight the importance of both content knowledge mastery as well as spatial reasoning. The lack of literature in this area leads to the need for research on the role that representations play in learning biology, particularly with phylogenetic trees. By better understanding the core skills needed for students to develop representational competence with phylogenetic trees, we will be able to design an informed curriculum that enhances meaningful learning in evolutionary biology.

We need to investigate how students learn from representations. Phylogenetic trees play a prominent role in biology textbooks, but very little is known about how students make sense of them. Current research on students' interpretations of these trees describes difficulties students have describing relationships between groups, relating biological concepts (e.g. homology) to visualizations, and ancestral misconceptions derived from vernacular descriptions of trees (Baum et al., 2005; Crisp & Cook, 2005). However, these studies are limited in scope and methods; most employ quantitative analyses of static moments, such as pre and posttests (e.g., Baum et al., 2005). This type of approach overlooks changes in student thinking over time and makes assumptions about students' tree thinking ideas. We need to better understand how students make sense of phylogenetic trees, how they develop the necessary skills to become proficient tree thinkers, and how they use information about the historical relationships between species to reason about patterns in biological data. More specifically, we need to investigate how students translate information between verbal and visual models across time and to what extent external representations reflect internal representations (Reiss & Tunnicliffe, 2001). In addition, Cook (2006) identified a need for exploring the developmental continuum of representational competence as a way to help maximize the potential of visual representations. This study uses a qualitative approach investigating how students develop tree thinking throughout an entire course on plant systematics.

## CHAPTER THREE: METHODOLOGY

The purpose of this study was to investigate how undergraduate college biology majors use phylogenetic representations in a plant systematics course and develop tree thinking. In order to address this idea, I focused on the following questions:

1. What is the status of undergraduate students' phylogenetic conceptual understanding and representational competence when they enter a plant systematics course?
  - a. How do students interpret phylogenetic representations (e.g., key features, evolutionary relationships, reasoning schemes, limitations of the representation)?
  - b. What sense do students make of different phylogenetic representations? What do the students acknowledge as similar/different in the representations?
  - c. What types of representations do students use or generate to solve problems? How do they justify the representation?
2. In what ways do students show improvement in their phylogenetic conceptual understandings and representational competence upon completion of the plant systematics course?
3. How do students perceive improvements in their tree thinking related to three instructional interventions?
4. What are the core skills essential for students to develop competence in tree thinking?

These research questions were directed toward gaining insights into the developmental process involved in undergraduate learning of primary aspects of tree thinking: tree reading and tree building. I used a constructivist qualitative research tradition to guide the design and implementation of this study.

## Research Tradition

### *Constructivism*

A constructivist research tradition allows researchers to investigate the nature, reality, and truth of knowledge. Researchers who use a constructivist perspective assume that learners construct knowledge about reality, and they cannot study reality itself (Patton, 2002). By using this tradition, I assume all knowledge about the natural world is filtered through existing, individual knowledge (Briggs, 2007; Ferguson, 2007). Because all individuals have unique histories, knowledge is constructed differently by individuals allowing multiple realities to exist that suit each knower (Denzin & Lincoln, 2005; Patton, 2002). According to Denzin and Lincoln (2000) this tradition identifies that “understanding is interpretation” (p. 194). Knowledge is developed through “individual reconstructions coalescing around consensus” (Denzin & Lincoln, 2000, p. 170). Thus, when using this constructivist tradition to guide research, the researcher believes that knowledge is co-constructed between the researcher and research participants. This suggests that knowledge or the constructed truth about reality that one understands is relative to the individual (Ferguson, 2007; Patton, 2002). Constructivists do not seek a singular and universal “truth.” Rather, constructivists aim is to describe knowledge and look for patterns.

This tradition is best suited for understanding individuals' beliefs and knowledge (Ferguson, 2007). Central questions that researchers within this tradition investigate include: "How have the people in this setting constructed reality? What are their reported perceptions, 'truths,' explanations, beliefs, and worldview? What are the consequences of their constructions for their behaviors and for those with whom they interact?" (Patton, 2002, p. 132). The constructivist tradition is based on the following set of epistemological and ontological assumptions.

#### *Epistemological Assumptions*

Knowledge is never transmitted directly from participants to the researcher (Ferguson, 2007). The constructivist research tradition assumes that researchers actively construct knowledge through interacting with their environment and others with respect to their existing understandings (Denzin & Lincoln, 2005). Briggs (2007) suggested that researchers create models or representations to make sense of information and these models are connected to the unique structure of their existing knowledge. Additionally, these models or representations are only understood within the particular context of the experience. Guba and Lincoln (1989) described the epistemological assumption of constructivism as knowledge being dependent upon information and context available to those involved with constructing assertions about reality or truth (i.e., researchers). In this study, I focused on the representations students generated in a plant systematics course. I interpreted student knowledge by collecting data from multiple sources over time. I asked students to reflect upon phylogenetic ideas and tree thinking problems to understand their constructed representations. I clarified my interpretations of their

understandings by asking questions during interviews and observing participants' activities and involvement in the course.

### *Ontological Assumptions*

The constructivist researcher believes that knowledge is subjective and we cannot identify one absolute 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). Although individuals technically live in the same world, each of their perceptions of the world is unique. 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). This means that knowledge is relative to each individual and is embedded in the context of the experience. Because I am utilizing a constructivist framework to guide my research study, I assume that students' prior ideas interact with new knowledge as they interpret new representations. Each student constructs his/her own reality with respect to his/her own experiences and knowledge expands as learners encounter more experiences and evidence.

Even though all of the participants of this study were enrolled in the same plant systematics course, their background experiences with evolution and phylogenetic trees varied greatly. Thus students could construct multiple representations to make sense of the same concept. By using the constructivist perspective, I was able to make sense of individual student knowledge and the representations they generated as well as patterns in knowledge across individuals. Given that each student creates his/her own meaning of

phylogenetic representations, I searched for consistencies across students to understand the knowledge students develop regarding tree thinking.

### Context of the Study

This study took place in the lecture section of an upper-level, plant systematics course (Biological Sciences 3210) at a Midwestern research extensive university during the Spring 2008 semester. The course included a lecture and mandatory laboratory section and was designed for undergraduate science majors. As a prerequisite, students who enrolled in this course had completed at least eight credits of Biological Sciences with a grade of C- or better.

The instructor, Dr. J. Chris Pires, is an assistant professor in the Division of Biological Sciences and an expert plant phylogeneticist. Dr. Pires has published extensively in his field -- 22 publications (20 peer-reviewed articles and 2 book chapters) related to phylogenetics in the past 10 years (since 1999). Additionally, he teaches a graduate level course in phylogenetics. Dr. Pires transformed a traditional plant taxonomy course into this plant systematics course and designed the course to focus on tree thinking. The former taxonomy course focused only on the identification, nomenclature and classification of flowering plants. He shifted the course content to a systematics approach that integrated taxonomy, evolution, and phylogenetics. This revised course focused on plant diversity, speciation, reproductive biology, adaptation, convergence, biogeography, phonetics, cladistics, and historical perspectives of systematics, in addition to traditional taxonomy. This study took place during the second year of course transformation. One of the instructor's course goals was to help students develop tree thinking skills while investigating plant systematics, rather than memorize

taxonomy associated with plant families. Students were engaged in interpreting and building phylogenies in addition to learning about plant systematics.

### *Course Curriculum*

The plant systematics course was organized primarily around phylogenetic tree thinking. The lecture portion of the course used the textbook *Plant Systematics* (Simpson, 2006) and focused on: 1) how systematists discover, describe, and classify plant diversity; 2) the major features and evolutionary origins of vascular plants; and 3) the analytical and experimental tools used to understand organismal diversity. The emphasis in the lecture and associated readings was on both locally occurring and globally important plant families. (The full course syllabus is available in Appendix B.) By the end of the course, students were expected to understand key morphological characters used to identify plants in a phylogenetic context, in addition to processes that led to speciation and diversity. Specific course objectives stated that students would be able to complete the following tasks by the end of the course:

- state, define, and give examples of the components of taxonomy: description, identification, nomenclature, and classification.
- describe a plant, using the descriptive terminology of plant morphology and reproductive biology.
- draw phylogenetic relationships of the major lineages of plants, indicating their classification and significance of major evolutionary changes.
- name, classify, and diagnose several of the major families of flowering plants.
- collect, identify, and record field data; create herbarium specimens.
- state the principles and rules of plant nomenclature, including how to publish a new taxon name, and know how to use and apply botanical names.
- describe the basics of the theory and methodology of phylogenetic systematics and how it is applied in systematic research.
- design and implement a project in plant systematic research.

- use the major literature sources in plant systematics, including bibliographic surveys (Appendix B).

The professor assessed his students' progress toward achieving these objectives through online weekly reflections administered via BlackBoard, in-class activities and discussions, and exams and quizzes throughout the semester.

### *Participants*

I limited recruitment of participants to undergraduates enrolled in the plant systematics course during the Spring 2008 semester. After I introduced this study during the first day of class, I invited students to participate at one of three levels (Level 1: participate through class activities only; Level 2: participate through class activities and an interview series; or Level 3: no participation) and to sign a consent form (Appendix C). This study (project number--1080077) was approved by University of Missouri-Columbia (MU) Campus Institutional Review Board (IRB) prior to any data collection procedure. Under the guidelines of MU Campus IRB, only students who gave permission to access their responses were included as participants of the study<sup>1</sup>. Whether or not students participated in the study did not influence their course grades and students were allowed to drop out of the study at any point without penalty. Among the 30 students in the class, 30 students granted access to use their responses and scores, and 14 students volunteered for the interview series. Among these volunteers, I selected 27 participants and 13 key informants, removing three participants who were not full time students at the university. I categorized key informants as students who volunteered for the 2-part interview series. All of the selected participants were full time students at the university

---

<sup>1</sup> All consent forms, digital audio files, and digital video files from the data set will be kept in a locked file cabinet or password protected digital file for a minimum of three years following completion of this study.

and were majoring in a science field (Table 3). Most of the students had limited previous experience with phylogenetic trees during their introductory biology course. Four students, Tim, Chip, Jared, and Darren, had direct instruction on tree thinking and used phylogenetic trees during a past semester when they were enrolled in Ichthyology.

Table 3

*Participant demographics*

		Percentage (n = 27)	Pseudonym
Gender	Male	59%	
	Female	41%	
Grade Level	Senior	59%	
	Junior	30%	
	Sophomore	11%	
Major	Biology	44%	Brenda <sup>*</sup> , Roger <sup>*</sup> , Chad <sup>*</sup> , Kathryn <sup>*</sup> , Krystal, Maggie, Mitch, Aaron, Emily, Bob, Cameron, and Karen
	Fisheries and Wildlife	33%	Darren <sup>*</sup> , Jared <sup>*</sup> , Sally <sup>*</sup> , Chip <sup>*</sup> , Miranda <sup>*</sup> , Abe, Jamie, Tim, and Lauren
	Secondary Education - Unified Science/Biology	11%	Jeremy <sup>*</sup> , Brandt <sup>*</sup> , and Peter
	Forestry	4%	Aimee <sup>*</sup>
	Chemistry	4%	Kristen <sup>*</sup>
	Interdisciplinary – Science	4%	Randy

<sup>\*</sup> = Key Informants

*Role of the Researcher*

My role as researcher began during a pilot study conducted in the first semester the course was offered. During this pilot study, I was responsible for assisting with course design, data collection, and data analysis. The findings from the pilot study highlighted a need to revise the course curriculum and design of the study. The instructor and I collaborated on restructuring the course to help students reason through

phylogenetic problems by using tree representations rather than relying on prior ideas. The course revisions included three major changes. First, we added evolution content at the beginning of the course to make connections between the course content and tree representations. Previously, during the initial course offering, evolution was not included in the curriculum until the end of the semester. Second, we presented multiple styles of phylogenetic representations throughout the course. Previously, diagonal trees were used as the primary phylogenetic representation. Third, using results from the pilot study, I designed plant oriented activities that targeted alternative ideas about phylogenetic trees to provide scaffolds for students to become tree thinkers.

In this study, my roles included assisting with curriculum design, designing instructional interventions, developing data collection instruments, administering interviews, and attending course lecture meetings to take field notes. According to Lincoln and Guba (1985) it is important to build and maintain trust with research participants. Trust facilitates a safe environment for students to talk openly with the researcher. I built participant trust by explaining my research goals and clarifying my role as a researcher as well as working with the participants on coursework issues so that they felt comfortable sharing their ideas with me. My role as a non-participant observer (Patton, 2002) was made evident to the students throughout the project.

#### Design of the Study

This constructivist-guided study employed a qualitative research design to examine undergraduate plant systematics students' understanding and use of phylogenetic trees. As a constructivist, I believe that students create personal meaning of representations based upon prior ideas, and that individuals can possess different levels of

representational competence (Kozma & Russell, 2005). Due to the relative nature of representational competence, students who demonstrate fewer core tree thinking skills and less representational competence may perceive and construct representations of evolutionary relationships differently from those who show more advanced representational competence and have developed more core tree thinking skills. Thus, I assume that while people might have similar conceptual knowledge, they may still construct unique meanings of phylogenetic trees. Moreover, some students may have difficulties using or building phylogenetic trees to make sense of systematics problems, thus hindering learning.

#### *Methodological Assumptions*

Hermeneutic-dialecticism has been attributed as a constructivist methodological assumption (Guba & Lincoln, 1989). This assumption presumes that the researcher investigates and reconciles the realities of both the researcher and participants. Initially, the researcher attempts to assess the constructed reality of the participants, then the researcher and the participants engage in a dialog to co-construct the meaning of the experience. Interpretations of student responses are dependent on the content in which a response was created and the researcher's understandings (Patton, 2002). This methodological assumption leads to the necessity of using persistent observation, member checks, and other methods to ensure trustworthiness.

In my study, I observed students' interactions with phylogenetic trees during each course period across 15 weeks. Student explanations about phylogenetic trees provided information about how they organized, related, and integrated biology concepts to phylogenetic representations. I interpreted these responses to understand how students

made personal sense of representations. The participants and I co-constructed the meanings of student- and scientist-generated representations as we engaged in dialog during individual interview series. During these interviews I also completed simple member checks by asking students to verify that my interpretations of their comments were accurate. Furthermore, I gathered additional evidence of students' understandings and skills by collecting student assignments and observing student interactions with phylogenetic trees during the course.

### *Data Collection*

I collected data throughout the entire semester of the lecture section of the plant systematics course. I utilized several methods of data collection to gain an understanding of how students develop phylogenetic thinking over the course of the semester. Data came from student responses on two-tiered diagnostic pre/posttests (Treagust, 1988) (see Appendix D & E), online reflective student journals (see Appendix F), semi-structured interviews (Patton, 2002) to probe students' ideas about phylogenetics (see Appendix G & H), field notes, and document/artifact analysis from coursework (e.g., in-class assignments, homework, and exams). By using multiple data sources, I increased the validity of my research by being able to triangulate my findings.

To elicit students' ideas about phylogenetic representations and challenges they face when developing tree thinking, I used multiple open-ended data sources (Patton, 2002). The primary data sources I used were students' reflective journal entries, responses to the pre/posttest, and semi-structured interviews with key informants. The secondary data sources for this study included written documents/artifacts, and field notes (see Table 4).

Table 4

*Data matrix with primary and secondary data sources*

Research Question: How do undergraduate college biology majors use phylogenetic representations in a plant systematics course and develop tree thinking?					
Sub-Questions	Tree Thinking Pre/Post-test	Coursework (Homework/Exams)	Student Interviews	Reflective Journals	Field Notes
What is the status of undergraduate students' phylogenetic conceptual understanding and representational competence when they enter a plant systematics course?	P		S		
<ul style="list-style-type: none"> <li>How do students interpret phylogenetic representations (e.g., key features, evolutionary relationships, reasoning schemes, limitations of the representation)?</li> </ul>	P	S	S	S	
<ul style="list-style-type: none"> <li>What sense do students make of different phylogenetic representations? What do the students acknowledge as similar/different in representations?</li> </ul>	P		S	S	
<ul style="list-style-type: none"> <li>What types of representations do students use or generate to solve problems? How do they justify the representation?</li> </ul>	P	S	S	S	
In what ways do students show improvement in their phylogenetic conceptual understandings and representational competence upon completion of the plant systematics course?	P	S		S	
How do students perceive improvements in their tree thinking related to three instructional interventions?		S	S	P	S
What are the core skills essential for students to develop competence in tree thinking?	P	S	P	P	S

P = Primary data source, S = Secondary data source.

### *Pre/Posttest*

During the first week of class, I administered a pretest (Appendix D) highlighting areas of student difficulty identified in the tree thinking literature. I administered a slightly altered posttest (Appendix E) during the last week of the course, to assess students' understandings at the close of the semester. The posttest was altered to include more technical terminology and an additional four questions to assess students' ideas about evolution. I designed open-ended assessments targeting students' ideas about phylogenetics and evolution including co-evolution, heritability, informative evidence, and problem solving. Two-tiered questions asking students to interpret phylogenetic trees were modified from Baum et al. (2005) by adding a prompt for students to explain their reasoning for their selected answers. I used the pretest explanations to customize the interview protocols which allowed me to probe more deeply into individual student's ideas.

### *Online Reflective Journals*

I administered online reflective prompts via Blackboard on a weekly basis (Appendix F). These questions ranged from assessing content knowledge and tree thinking abilities to eliciting reflections upon instructional strategies. Each week's questions were designed to have students reflect on discussions and experiences from the previous week. For example, I designed reflection questions that were administered after students participated in a group activity targeted at developing tree reading skills to elicit how students thought the activity and group interaction affected their understanding of phylogenetic trees. More specifically these prompts were designed so that I could identify the core skills students needed to become effective tree thinkers; I also used the

prompts to recognize shifts in students' phylogenetic understanding and how students perceived instructional interventions supported their learning.

### *Interviews*

I selected 13 student volunteers to act as key informants and participate in an interview series consisting of two 1.5 hour semi-structured interviews (Patton, 2002). Selection was determined based on student consent to be interviewed. Each key informant scheduled individual interviews with me during the second and fourth month of the semester. Each interview explored plant-based tree thinking tasks. Interview 1 (Appendix G) was a series of questions that probed students' reasoning as expressed on the pretest in addition to assessing tree reading skills and how students compared multiple phylogenetic representations. Interview two (Appendix H) focused on having students reflect upon the semester and included a series of three think aloud tasks: building a phylogenetic tree, interpreting a phylogenetic tree, and comparing phylogenetic trees. All of the questions and activities were designed to elicit students' ontological perspectives, explanations, and use of tree thinking. I videotaped and audio recorded each interview to capture a holistic account of their responses. I also interviewed the instructor prior to the course so I could compare his expert responses to the students' responses. During this interview, the instructor engaged in and responded to the same tasks and prompts as the students. I transcribed each interview verbatim and reviewed each transcript for accuracy.

### *Field Notes*

I observed all lecture meetings for the plant systematics course (30 meeting dates of 90 minutes each). During the observations, I recorded field notes about instructional

supports used to teach tree thinking skills, student involvement in the class, comments and questions presented about phylogenetics, and student strategies for solving systematics problems during in-class activities.

When students interacted in small group activities, I observed the two groups that included key informants. I used my field notes from these group observations to inform my observations of the entire class for that period. This data source was used as a secondary source to triangulate my findings (see Table 4).

*Documents/Artifacts*

I collected student responses from homework and exam questions designed to elicit explanatory responses about phylogenetic thinking components. For example, participants completed an activity debating the evolutionary ancestry of hippos and whales (BioQUEST Curriculum Consortium, 2006). Students were presented the scenario presented in Figure 5:

Scientists have compiled multiple data sources and developed two arguing hypotheses about the evolutionary relationships among the whales and various ungulates. Examine the following two trees (Figure 5). In your own words what are the evolutionary relationships illustrated between Cetacea (Whales and Dolphins) and Artiodactyls (Even-Toed Ungulates)

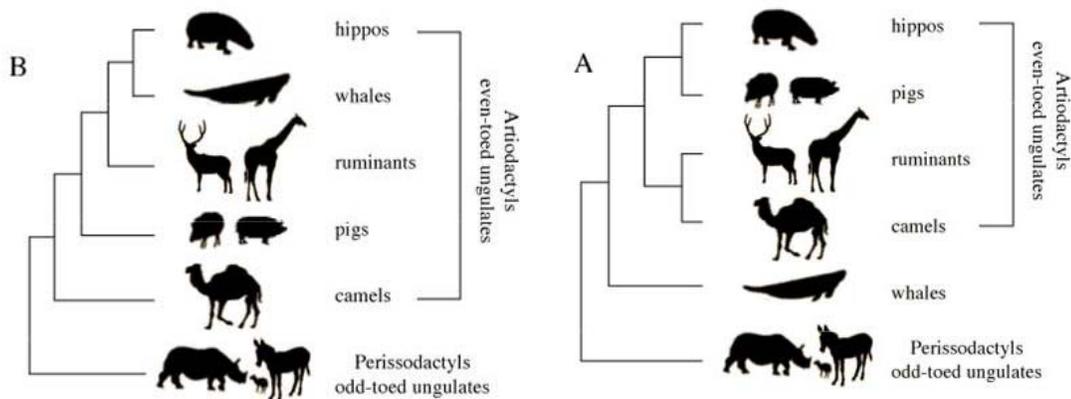


Figure 5. Two trees illustrating opposing hypotheses about the evolutionary history of whales (Image taken from BioQUEST Curriculum Consortium (2006)).

This assignment had students review a consensus hypothesis and compare it to multiple trees generated from single data sources (e.g.  $\alpha$ -hemoglobin, cytochrome b, and skeletal/dental) in search of nodal support. Students responded to questions such as, “Is it possible to have support for a more basal clade if a more recent clade is not supported? Explain how or why not?” Student responses to these questions provided insights into their thinking periodically throughout the entire semester. The classroom documents and artifacts served as a secondary data source.

### *Data Analysis*

I utilized all transcripts, field notes, expanded observation notes, and documents in data analysis. I organized data sources by relevance to research questions and removed uninformative data from the data set (see Table 5). Then I reviewed the full “selected” data set for each student. Starting with the key informants, I wrote a profile describing each student’s reasoning and tree thinking abilities. These profiles included interesting quotes, defined as when the student described his/her rationale for a response that deviated from the instructor’s expert explanation. Throughout the construction of each student profile, I returned to the data sources to test my interpretations of student responses and find additional supporting evidence.

Table 5

*Data sources attributed to research questions*

Research Question	Data Source	Questions/Tasks
1. What is the status of undergraduate students' phylogenetic conceptual understanding and representational competence when they enter and complete a plant systematics course?	Pretest	# 1-10, 13, 14
	Interview 1	# 1, 2, 6
a) How do students interpret phylogenetic representations (e.g., key features, evolutionary relationships, reasoning schemes, limitations of the representation)?	Pretest	# 4, 5, 6, 9
	Posttest	# 4, 5, 6, 9, 15
	Reflective Journal	Wk2-1; Wk3-1, 4; Wk7-1, 2; Wk13-1
	Interview 1	# 7
	Interview 2	Interpret task
b) What sense do students make of different phylogenetic representations? What do the students acknowledge as similar/different in the representations?	Pretest	# 7, 10, 13
	Posttest	# 7, 10, 13
	Reflective Journal	Wk3-2; Wk4-2; Wk8-4; Wk11-1
	Interview 1	# 5, 8
	Interview 2	Comparison task
c) What types of representations do students use or generate to solve problems? How do they justify the representation?	Pretest	# 14
	Posttest	# 14
	Reflective Journal	Wk4-4; Wk7-4; Wk13-2
	Interview 1	# 4, 6, 9
	Interview 2	Building task
2. In what ways do students show improvement in their phylogenetic conceptual understandings and representational competence upon completion of the plant systematics course?	Posttest	# 1-10, 13-18
3. How do students perceive improvements in their tree thinking related to three instructional interventions?	Reflective Journal	Wk2-3, 4; Wk3-3; Wk4-3; Wk8-2, 5; Wk12-1
	Interview 1	# 3, 6
	Interview 2	Reflection task
	Field Notes	
	Documents/Artifacts	
4. What are the core skills essential for students to develop competence in tree thinking?		All selected data

Rather than approach the data with predetermined themes in mind, I used an inductive approach and let the data lead me to identify meanings that the students created. I inductively coded the profiles to identify reasoning used by students when interpreting, comparing, and building phylogenetic trees. Some of the codes I developed included: a main branch exists, when branches are flipped the tree meaning is altered, branch length illustrates time, relationships are related to tip proximity, and relationships are dependent on the number of nodal events. These codes allowed me to compare the reasoning processes and tree thinking abilities within students among data sources and across students. I compared the coded student profiles to identify themes. Once the themes were identified, I triangulated the findings using my secondary data sources, field notes and student documents/artifacts, to ensure the research findings represented accurate interpretations of the data. Upon identification of themes, I generated frequency counts of student tree reading and tree building responses to support my interpretations of the data. I wrote rich descriptions of students' tree thinking skills and documented themes that emerged from the data about students' representational competence.

#### Trustworthiness

As in any study, the findings are limited by the context of the study. However, I have taken multiple steps to ensure trustworthiness of my results. According to Lincoln and Guba (1985), trustworthiness is developed by fulfilling four criteria: credibility, transferability, dependability, and confirmability. To enhance the credibility of my study I used multiple data sources (pre/posttest, reflective journals, interviews, field notes, and course documents/artifacts) to triangulate my findings, and used persistent observation of student activities and informal member checks during interviews. As a further step, I

asked a colleague to engage in peer debriefing to ensure that I remained honest to my research questions and corroborated my findings, increasing the credibility and dependability of my study (Patton, 2002). She helped review and triangulate data sources. She provided her own interpretation of the data based on her own understanding. Then, we compared our interpretations by looking for similarities and differences. As differences arose, we discussed the data until we reached consensus. A peer debriefer was used to reduce the bias associated with a single individual analyzing data (Patton, 2002). Furthermore, I conducted member checks of the core skills I identified with two key informants from the course to ensure my interpretations were consistent with how students reflected upon their own learning of tree thinking.

The rich, or thick, descriptions I presented improve the transferability (Lincoln & Guba, 1985) of my findings, allowing other researchers to see similarities to their own situations as well as consider how my findings could fit into their investigations beyond the context of my study (e.g., ideas connected to general biology and zoological systematics courses). I improved the dependability and confirmability of my study by using my doctoral advisors to ensure I used the most appropriate and analytic methodologies. They also assisted by checking that my data merited my interpretations (Denzin & Lincoln, 2005). Finally, I confirmed any similar findings from this research to those cited in the literature.

## CHAPTER FOUR: INTERPRETATIONS

The interpretations of this study are rich descriptions about how undergraduate college students developed and used phylogenetic representations in a plant systematics course. (Participants' names are pseudonyms to ensure confidentiality of their responses.) I have organized the interpretations of this study around the research questions. The first section describes students' incoming ideas about how to interpret phylogenetic representations and the types of representations they generated to explain a phylogenetic scenario. The second section of this chapter describes students' ideas at the end of the course. The third section of this chapter describes how students perceived improvements in their tree thinking in response to three instructional interventions targeted at improving tree thinking abilities. The final section of this chapter describes specific core skills for tree thinking that emerged from the data.

### Students' Incoming Ideas

The first research question I investigated was: "What is the status of undergraduates' phylogenetic conceptual understanding and representational competence when they enter a plant systematics course?" I organized this section around the four categories of phylogenetic understanding assessed by the pretest at the beginning of the course: 1) Interpretation of individual phylogenetic trees; 2) Placement of time on simple, diagonal phylogenetic representations; 3) Comparison of phylogenetic representations (both similar and differing tree styles); and 4) Types of representations generated to illustrate a phylogenetic problem. Next, I present themes that emerged from the data regarding these areas of phylogenetic understanding.

### *Interpretation of Phylogenies*

Evolutionary biologists interpret phylogenetic trees in accordance with how they illustrate evolutionary histories or inferred evolutionary relationships among a set of organisms. Scientists interpret patterns in phylogenetic representations using an approach that involves mapping descent from common ancestry in order to identify the most recent common ancestor and isolate monophyletic groups, or clades, of species. I administered a pretest at the beginning of the course with three questions directed toward having students interpret relationships represented on a phylogenetic tree. Table 6 details the accuracy of responses students provided to the multiple choice portion of these questions.

On the pretest, each multiple choice question included a prompt asking students to explain their reasoning for their selection. Seven approaches to interpreting phylogenetic trees emerged from the data at the beginning of the plant systematics course: main branch, proximity of terminal tips, common ancestry, knowledge of organisms, nodal emphasis, unidirectional reading, and physical measurements (Table 7). Students used one or more of these approaches to make sense of individual phylogenetic representations. Next, I describe each of these seven interpretation approaches, with common ancestry being the only scientifically accurate approach which was used by 19% of students at the beginning of the course.

Table 6

*Student responses to the multiple choice portion of pretest questions involving interpretation of relationships represented on a phylogenetic tree*

Tree Interpretation Question	Response	Number of Students	Percentage
Question 1 (Figure 6)	A: <i>Seal</i> is more closely related to <i>Horse</i> than <i>Whale</i>	20	74%
	B: <i>Seal</i> is more closely related to <i>Whale</i> than <i>Horse</i>	3	11%
	* C: <i>Seal</i> is equally related to <i>Horse</i> & <i>Whale</i>	4	15%
	D: <i>Seal</i> is related to <i>Whale</i> , but not to <i>Horse</i>	0	0%
Question 2 (Figure 7)	A: <i>Crocodile</i> is more closely related to <i>Lizard</i> than <i>Bird</i>	19	70%
	* B: <i>Crocodile</i> is more closely related to <i>Bird</i> than <i>Lizard</i>	7	26%
	C: <i>Crocodile</i> is equally related to <i>Lizard</i> & <i>Bird</i>	1	4%
	D: <i>Crocodile</i> is related to <i>Lizard</i> , but not to <i>Bird</i>	0	0%
Question 3 (Figure 8)	A: <i>Crocodile</i> is more closely related to <i>Lizard</i> than <i>Bird</i>	0	0%
	* B: <i>Crocodile</i> is more closely related to <i>Bird</i> than <i>Lizard</i>	23	85%
	C: <i>Crocodile</i> is equally related to <i>Lizard</i> & <i>Bird</i>	4	15%
	D: <i>Crocodile</i> is related to <i>Lizard</i> , but not to <i>Bird</i>	0	0%

Note. \*Denotes a scientifically accurate selection

Table 7

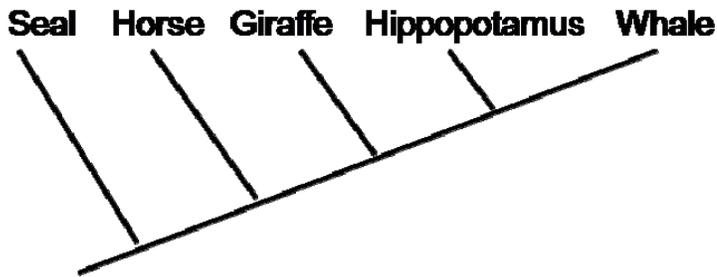
*Students' approaches in interpreting phylogenetic representations at the beginning of the plant systematics course*

Approach	Number of Students*	Percentage
Main Branch	11	41%
Proximity of Terminal Tips	10	37%
Common Ancestry	5	19%
Knowledge of Organisms	4	15%
Nodal Emphasis	4	15%
Unidirectional Reading	2	7%
Physical Measurements	2	7%

*Note.* \*Total equals more than 27 students because some students used more than one approach when interpreting phylogenetic representations.

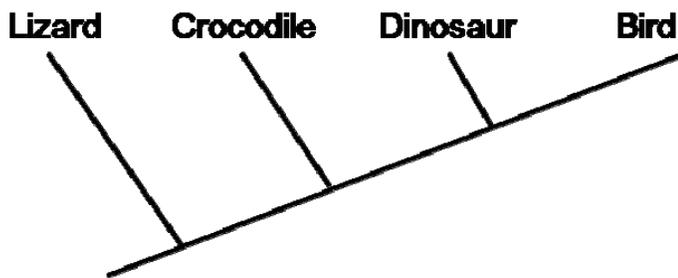
### *Main Branch*

Using references to a main branch was the most common interpretation of phylogenetic representations at the beginning of the plant systematics course. Particularly with the diagonal representations, students commonly interpreted relationships in phylogenetic representations in comparison to a “main branch” or primary structure that existed for taxa to “branch off from.” For example, Peter claimed “a horse is the next evolution out of a seal, therefore a horse is more closely related to a seal than a whale.” Scientists would conclude that the seal is represented as equally related to the horse and whale (see Figure 6). Mitch also used the main branch approach to interpret this representation. He stated that “the seal lineage branches directly off the whale lineage,” implying the most direct branch from the root to the left most terminal tips represented only the whale lineage rather than the shared evolutionary history of multiple organisms.



*Figure 6.* Is the seal more closely related to the horse, the whale, or equally related to both? The scientific interpretation is that the seal is equally related to both.

Mitch further used this reasoning to interpret a second question regarding the relationships illustrated among a lizard, crocodile, and bird. The representation depicted the crocodile being most closely related to the bird (see Figure 7). While Mitch selected the scientifically appropriate answer, his rationale did not follow conventions in systematics. He stated that the two were more closely related because “the crocodile lineage branches directly off the bird branch.” Darren also gave a flawed explanation for this question. He stated that a crocodile was more closely related to a bird than to a lizard because “it diverged from the bird lineage directly.” These explanations indicate that these students interpreted phylogenetic representations as patterns in which species branch off from a main line rather than showing shared lineages among taxa. Scientifically, it is accepted that species do not branch “off of” one another, rather taxa diverge from a hypothetical common ancestor.



*Figure 7.* Is the crocodile more closely related to the lizard, the bird, or equally related to both? The scientific interpretation is that the crocodile is more closely related to the bird.

### *Proximity of Terminal Tips*

At the beginning of the course, over one third of the students (37%) interpreted representations based upon proximity of the taxa represented at the terminal tips without utilizing the rest of the representation. Using this scientifically inaccurate interpretation approach, taxa that appear closer together along the tips of the representation are considered more closely related than taxa that are further apart. Students using this approach used explanations such as Chad's statement, "They are closer together in the cladogram," and Emily's statement, "Because of proximity!" For example, Brenda inaccurately claimed that a crocodile would be more closely related to a lizard than to a bird "because [the crocodile] is closer to a lizard on the graph." Likewise Cameron interpreted the phylogenetic tree to show the same inaccurate relationship between the crocodile and lizard because "in relation to the crocodile the lizard is closer than the bird."

### *Common Ancestry*

At the beginning of the plant systematics course, some students (19%) relied upon scientifically accurate explanations of common ancestry to deduce appropriate interpretations of phylogenetic representations. Most recent common ancestry refers to the last common ancestor two or more organisms shared, represented by the point at which the common lineage of the two species split. Jeremy used scientifically appropriate phylogenetic thinking to interpret relationships presented in a phylogenetic tree. He selected appropriate answers and provided appropriate explanations for his selections. "The crocodile and bird have a more recent common ancestor, meaning it could have evolved more traits similar to a bird." Chip also understood how to read phylogenetic

trees scientifically. He provided in-depth explanations of phylogenies, “I think of it as a continually growing tree. The lizards branched off first leaving a group of organisms who have yet to branch. Therefore, they are more closely related to each other (when they do branch) than one is to the lizards.” By relying on common ancestry, Jeremy and Chip were able to consistently use hypothetical ancestry represented by nodal patterns to determine relationships. The only students who used this interpretation approach at the beginning of the course had past experiences with tree reading in other biology courses.

#### *Knowledge of Organisms*

A small portion (15%) of students interpreted phylogenetic relationships by relying upon prior knowledge of the taxa present on the representation rather than the relationships illustrated within the tree itself. For example, Aaron based his interpretation of relationships on the idea that “both are reptiles” referring to the lizard and crocodile presented in one tree, rather than the common ancestry indicated between the crocodile and bird. Likewise, Emily argued that the relationship between the lizard and crocodile is closer than the crocodile and bird because, “physical characteristics, behavior, etc. are more alike between lizard & crocodile.” In each of these cases, students ignored the branching structures of the representation and interpreted the phylogenetic tree based upon their prior knowledge of the organisms.

#### *Nodal Emphasis*

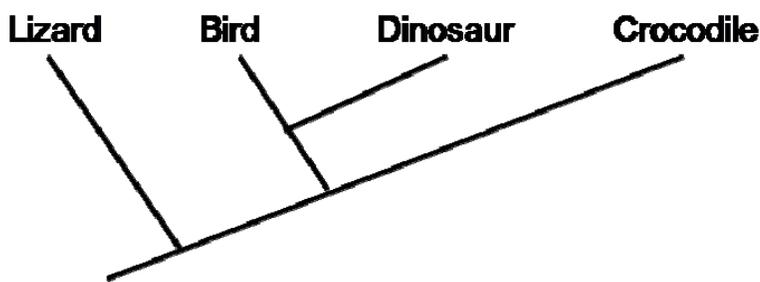
Students using this approach (15%) considered the number and distance between nodes as highly informative factors to interpret relationships among species. In instances where students counted the number of nodes between species, they equated more nodes between taxa with being more distantly related. For example, Brandt stated, “The

divergence on the lineage that led to the horse is only one up from the seal.” In another example, Kathryn considered that each nodal event signified a single change between organisms when she stated, “I think a croc is more closely related to a bird because there is only one apomorphy between lizard and bird.” Rather than simply counting the nodes in the representation, Jamie focused on the placement and location of nodes. She stated that the crocodile is more closely related to a lizard than a bird “because the cladogram shows degree of relationships and the node for the lizard is closer to crocodile than bird.” Likewise, Tim stated, “There is less time and fewer changes between where the ancestors of lizards and crocodiles differentiate and where the crocodiles and birds differentiate.” By thinking that closer nodes represent closer relationships, students using this interpretation approach inaccurately drew conclusions about the relationships illustrated in phylogenetic tree.

#### *Unidirectional Reading*

Students using this approach (7%) did not focus on clades, but instead on direction. These students believed that trees could only be read in one direction, either top to bottom or bottom to top, but not both. Thus, when using this approach, students reasoned that an organism must come after the other taxa in question to determine relationships on a phylogenetic tree. For example, Aimee was able to select the appropriate response regarding relationships presented in a phylogenetic tree. However, her explanation of her interpretation was flawed, “Genetic similarity is projected upward because there are traits shared by all three (crocodile, dinosaur, and bird) in which a lizard does not have.” By using this interpretation approach, Aimee was not able to consistently select scientifically appropriate responses. When asked to interpret a

phylogenetic tree illustrating equal relationships among the species in question, she responded “Seals and horses have similar traits because of the sequencing of the evolutionary split.” Furthermore, Aimee’s unidirectional reading of phylogenetic representations stemmed from a notion that evolution is progressive. For the problem in Figure 8, she stated, “In this phylogenetic tree, a crocodile is the most evolutionarily advanced organism.” This approach implies that phylogenetic representations are immobile and depicts a Lamarkian view of evolutionary relationships. These students thought that primitive organisms evolved into more advanced organisms; thus, the tree represented a progressive evolutionary ladder.



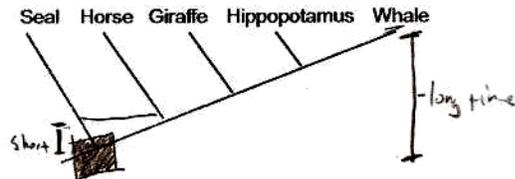
*Figure 8.* Is the crocodile more closely related to the lizard, the bird, or equally related to both? The scientific interpretation is that the crocodile is more closely related to the bird.

### *Physical Measurements*

Some students (7%) measured distances based on how they perceived time as an approach to interpreting phylogenetic relationships. They transposed time on the representation and then based their conclusion on the measured distance between speciation events. For example, Bob used his perception of time to measure the distance from the root of the tree to the most recent point of divergence as a way of determining relationships illustrated on a phylogenetic tree (Figure 9). He stated, “The length of time between seals and horses having a common ancestor and diverging into two species is much shorter than that for the seal and whale.” Sally also interpreted relationships based

on when the organisms diverged using a sense of evolutionary time. For example, she stated, “Much like the crocodile and lizard, the seal and horse are closer together on the evolution time scale.”

5. Using the image below, which of the following is an accurate statement?



- a) A seal is more closely related to a horse than to a whale
- b) A seal is more closely related to a whale than to a horse
- c) A seal is equally related to a horse and a whale
- d) A seal is related to a whale, but is not related to a horse

Provide an explanation for why you chose your answer:

The length of time b/c seals + horses have a common ancestor + diverging into 2 species is much shorter than that for the seal + whale

Figure 9. Is the seal more closely related to the horse, the whale, or equally related to both? Bob measured time vertically from the most basal node and interpreted the tree as representing the seal more closely related to the horse. The scientifically accurate interpretation is the seal is equally related to the horse and whale.

### Summary

Being able to interpret phylogenetic trees correctly is a critical skill in developing tree thinking. However, at the beginning of the plant systematics course, students used seven different approaches when interpreting phylogenetic trees, only one of which, common ancestry, was aligned with scientifically accurate interpretations. These approaches were not mutually exclusive -- students used one or more interpretation approaches to make sense of the phylogenetic representations. Moreover, an accurate response on the multiple choice portion of each question was not an indicator of scientific thinking when interpreting a phylogenetic tree. Most students (85%) selected an

incorrect response to the multiple choice portion of the first tree interpretation question. Of the 15% of students selecting the scientifically accurate response, only three used a scientific approach to interpret the phylogenetic tree. While Miranda selected the appropriate response, she came to this conclusion by using an alternative interpretation approach involving the organisms' positions in relation to a main branch. Miranda justified her answer by stating, "All are coming off from the same main branch."

In the second tree interpretation question, 26% of students selected the scientifically accurate response that the crocodile was represented as more closely related to the bird than the lizard. However, only four of these students used a scientific interpretation approach. The remaining students used an alternative approach to arrive at their response. For example, Mitch and Darren selected the accurate response. However, their interpretations of the relationships were based on the inaccurate idea of a phylogenetic representation having a main branch.

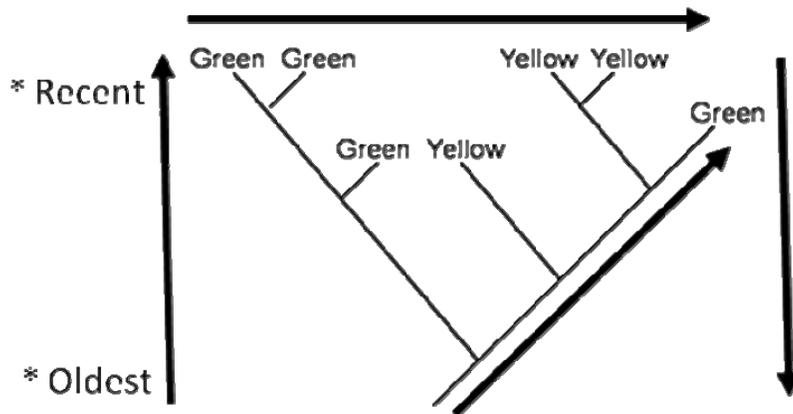
The majority of students (85%) selected an accurate response to the third tree interpretation question (see Figure 8). However, after investigating the approaches students used to interpret this representation, only five of those students provided a scientifically accurate explanation for their answer. For example, Emily explained her response using a scientific explanation, "Crocodile and bird are monophyletic with one common ancestor." However, the remainder of the students selecting the accurate response used alternative explanations to support their response. For example, Chad and Randy based their interpretations of the relationships on the inaccurate notion that organisms closer together on the representation are more closely related. Randy stated

that the crocodile was more closely related to the bird than the lizard because, “The crocodile is closer to the bird on the line and therefore more similar.”

Only two students (7%) interpreted all of the individual phylogenetic representations using the scientifically accurate common ancestry approach at the beginning of the plant systematics course. The remainder of the students relied upon the alternative approaches to make sense of phylogenetic representations: main branch, proximity of terminal tips, knowledge of organisms, nodal emphasis, unidirectional reading, and physical measurements.

### *Placement of Time*

One factor involved with interpreting phylogenetic trees accurately is the ability to identify key features represented by the tree, such as time. Phylogenies are the estimation of evolutionary histories through time. An implied time scale is an essential feature of phylogenetic representations identified by scientists. Scientists understand that phylogenetic representations denote directional time, with the root of the tree symbolizing the oldest event and the terminal tips symbolizing most recent events (see Figure 10).



*Figure 10.* Phylogenetic tree with alternative orientations of time indicated by arrows. The scientifically accurate representation of time is indicated by the vertical, labeled arrow.

As indicated by Table 8, the majority of students (63%) accurately transferred time vertically upwards onto the diagonal phylogenetic representation at the beginning of the course. However, many students (37%) inaccurately transposed time onto the representation. These students placed the direction of time on a diagonal angle, inverted vertical time, or indicated time as progressing horizontally, left to right (see Figure 10).

Table 8

*Student perceptions of time on diagonal phylogenetic representations at the beginning of the plant systematics course*

Direction of Time	Number of Students	Percentage
Vertical (↑)	17	63%
Diagonal (↗)	8	29%
Vertical (↓)	1	4%
Horizontal (→)	1	4%
Total Students	27	100%

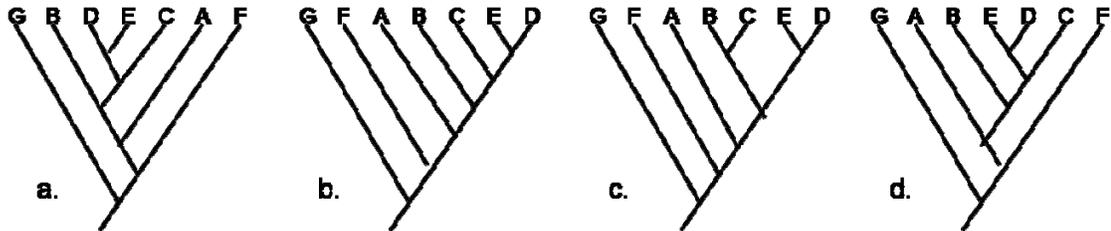
The manner in which individuals identify time on phylogenetic representations can impact interpretations regarding the location of most recent common ancestors. When students misplaced time directionality, as did 37% of the students at the beginning of the course, they consistently used an alternative approach when interpreting individual phylogenetic trees. Additionally, these students used alternative criteria when comparing multiple phylogenetic representations. For example, Karen indentified time as one directional or diagonal. She also interpreted trees from a main branch perspective and compared trees based on physical branching patterns

#### *Comparing Representations*

Scientists often compare phylogenetic representations in search of similar patterns to provide support for hypothesized relationships among taxa. They find similarities by comparing monophyletic groups across representations. Equivalent phylogenetic trees

will have identical topologies illustrating consistent evolutionary histories and common ancestry. For example, students were asked to compare the four trees in Figure 11.

When these trees are compared accurately, tree *c* illustrates a different pattern of relationships than the other three trees. In this tree, taxa *B* is shown as most closely related to *C*, however in the other trees, *B* is shown as equally related to *C*, *D*, and *E*.



*Figure 11.* Which of the following four evolutionary trees depicts a different pattern of relationships than the others? Provide an explanation for how the tree you chose is different from the others.

At the beginning of the course, I asked students to compare relationships shown on phylogenetic representations (see Figure 11 and 12). Students compared like styles of phylogenetic trees (e.g., comparing multiple diagonal trees) as well as different styles of phylogenetic trees (e.g., comparing diagonal trees to rectangular and/or circular trees). Students used one or more of five criteria when asked to compare similar and/or different styles of phylogenetic representations. These criteria included: physical branching patterns, style of representation, clade comparison, branch length similarities/differences, and/or patterns in tip proximity (see Table 9). I describe each of these criteria in the rest of this section.

Table 9

*Criteria used to compare phylogenetic representations at the beginning of the plant systematics course*

Comparison Criteria	Number of Students*	Percentage
Physical Branching Patterns	11	41%
Style of Representation	7	26%
Clade Comparison <sup>o</sup>	5	19%
Branch Length Similarities/Differences	3	11%
Patterns in Tip Proximity	3	11%

*Note.* \*Total equals more than 27 students because some students used more than one criterion when comparing phylogenetic representations.

<sup>o</sup>Clade Comparison represents a scientifically accurate comparison criterion.

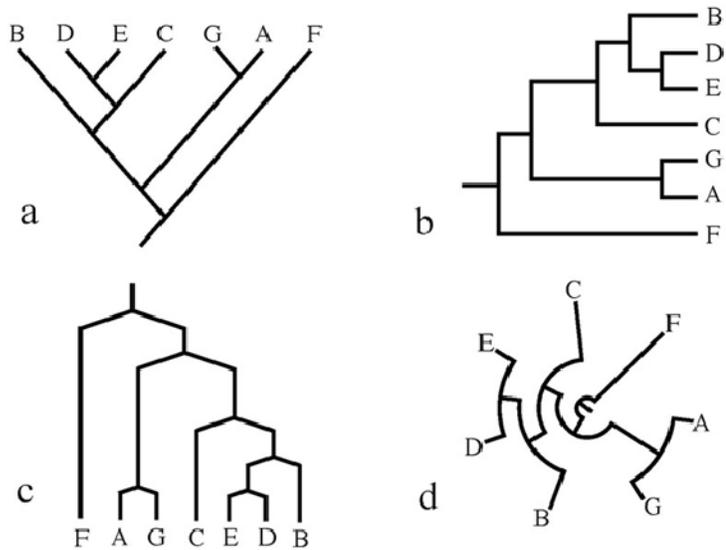
### *Physical Branching Patterns*

Students using this criterion compared phylogenetic representations based on the presence of primary and/or hierarchical divergence events within the representations. These students interpreted ladderized representations, only showing primary branches, as illustrating different relationships than the same representations rotated to show hierarchical branching structures. For example, students using this criterion to compare representations often selected tree *b* as showing a different pattern of relationships than the others (see Figure 11). Roger picked tree *b* because in this representation “each taxon is on its own lineage while the others have at least one or more branching off one lineage.” Likewise, Miranda selected tree *b* as illustrating a different pattern of relationships because in this representation the lettered tips “are branching off from one thing unlike the others which have branches branching off from those that branched off from the one thing.” Jeremy also commented on the different appearances of the branching patterns among the trees. Jeremy stated, “Each group is independently evolving where the other trees show groups breaking off into groups.” Students using

this criterion compared phylogenetic representations by looking at patterns in the superficial structure of the branches rather than overall topology.

### *Style of Representation*

Students were asked to compare different styles of phylogenetic trees and identify the tree that did not represent the same pattern of relationships as shown in the other trees (see Figure 12). The scientifically accurate response would be to select tree *a*, because it shows urchins (B) as being equally related to beetles (C), humans (E), and other vertebrates (D). However, the style of phylogenetic representation presented to students influenced how some (26%) students interpreted the evolutionary relationships among the taxa. Students using this criterion assumed that the style of tree drawn influenced the relationships depicted. Often, these students were unable to compare patterns of phylogenetic relationships among diagonal, rectangular, and circular representations (see Figure 12). For example, Jamie selected the circular diagram as the phylogenetic tree representing different relationships because, “This graph just looks different.” The circular representations were consistently most problematic for students who used this criterion. Jared selected the circular tree as the representation showing a different pattern of relationships, “Because I don’t understand it.” Kristen also had problems understanding circular trees. “The other three appear to be equal. I am not sure where you would start on this circular diagram.” Furthermore, Karen selected the circular diagram because she had no previous experience with this style of representation. “I have never seen this [type of] image before. So it seemed like the best answer.” This criterion, style of representation, was only used when students compared different styles of representations.



*Figure 12.* Although sea urchins and humans appear to have little in common, scientists recently found new evidence that relates sea urchins (B) with humans (E) and other vertebrates (D). This finding also suggests that sea urchins are not as closely related to beetles (C) and clams (G). Which tree below does *not* represent this new evidence? The scientifically accurate response would be to select tree *a*, because it shows urchins (B) as being equally related to beetles (C), humans (E), and other vertebrates (D).

### *Clade Comparison*

Only 19% of students compared patterns of clades across phylogenetic trees (similar to how scientists make comparisons) in at least one of the two questions in which students compared multiple tree representations. Chip was the only student who compared clades scientifically in each question. When comparing similar styles of trees (see Figure 11), Chip explained that tree *c* represented different relationships than the other tree because, “Tree *c* shows that B and C are more closely related than B is to E, D, and C, which is what the other trees say: that B is equally related to C, D, and E.” Likewise, when Chip compared different styles of representations (see Figure 12), he stated that tree *a* represented different relationships than the other trees because, “In tree *a*, it shows that B is related the same amount to D, E, and C which does not meet the

parameters of the question.” These explanations are consistent with how a scientist would respond to these questions.

The other students who used the clade comparison criterion only used it to explain their responses in one of the two tree comparison questions or had inaccuracies in their responses. For example, when Karen compared similar styles of tree (see Figure 11), she based her accurate response on the difference in relationships represented in tree *c*. She stated, “In graph *a*, *b*, and *d*, D branches off C. This is not the case in evolutionary tree *c*.” However, when she compared different styles of phylogenetic representations (see Figure 12), she reverted from using a scientific explanation to basing her explanation on alternative ideas regarding the style of each representation. In another example, Aimee used the scientific idea of comparing phylogenetic trees based on patterns of clades represented. However, there were inaccuracies in her explanation. “B and C are unique compared to tree options *a*, *b*, and *d*. This is because tree option *c* projects D and E being more closely related to B while the other options project D and E being more closely related to C.” Scientific interpretations of the relationships represented in tree *c* state that D and E are equally related to both B and C.

#### *Branch Length Similarities/Differences*

Some students considered that representations were the same when all of the branches appeared to be the same length. For example, students who used this criterion to compare representations may consider branch D longest in tree *b* and *c* and shortest in tree *d* (Figure 11). Darren stated, “All the trees appear different because of differences in divergence and lengths of lineages. Only ‘G’ remains consistent at least in its lineage length.” Rather than interpreting each branch as a lineage that extended from the root of

the tree to the terminal tip, Darren interpreted each branch length as extending from the terminal tip to the point of the most recent bend. Thus, when tree branches were swiveled upon a node, he viewed the new appearance as representing new relationships, because the branches now appeared to be different lengths than the original. He also compared different styles of phylogenetic representations based on similarities in branch lengths. Darren stated, “The separate lineages are not accurately represented through time in *d* [the circular tree] because the lineages aren’t as long.” However, in cladograms, branch lengths do not have meaning with regards to the relationships represented. Thus this criterion for comparing phylogenetic trees is not a scientific comparison.

#### *Patterns in Tip Proximity*

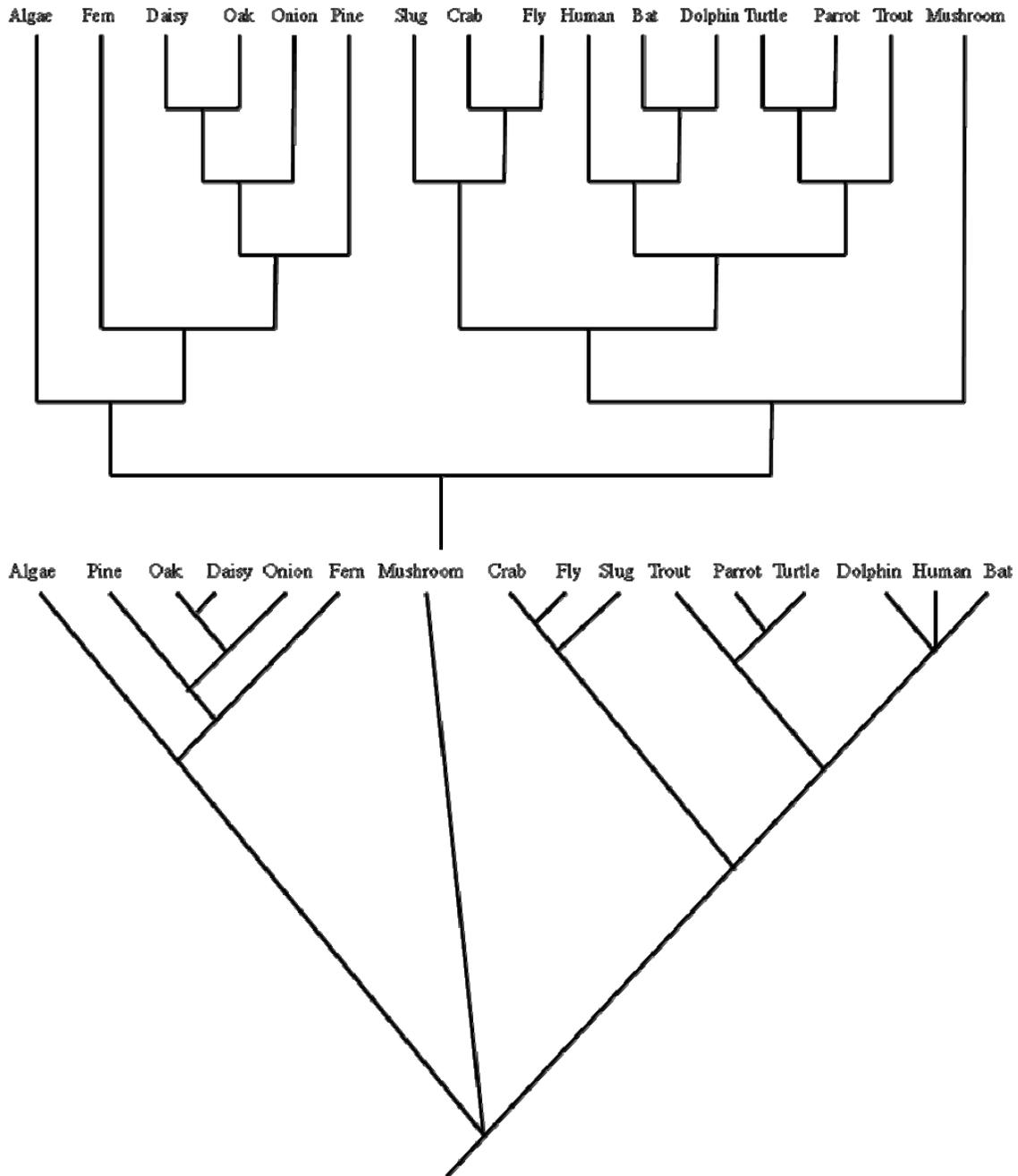
Students using this criterion compared relationships based on proximity of taxa to one another, or the order of taxa at the terminal tips. Although scientific comparisons of the clades show tree *b* and *c* as representing differing relationships, students using this criterion claimed that tree *b* and *c* illustrate the same relationships (see Figure 11). For example, Sally considered trees *b*, *c*, and *d* to represent identical relationships because, “[Tree] *a* shows that G is closer to B than to all the others.” Likewise, Kathryn made the same selection because, “Tree *a* gives a different pattern because taxon B comes before taxon A on this tree, but A comes before B on the other three trees.” These students compared phylogenetic trees based on the superficial ordering of the terminal tips rather than the relationships actually represented.

### *Summary*

Five criteria for comparing phylogenetic representations emerged from the data: physical branching patterns, style of representation, clade comparison, branch length, and patterns in tip proximity. Of these criteria, only clade comparison was consistent with scientific thinking. However, most students using this criterion to explain their responses did not use the criterion consistently or inaccurately identified the clades being compared. The remaining four alternative criteria were influenced by the approach students used to interpret individual phylogenetic trees. For example, students such as Darren, who interpreted trees based on the assumption of a main branch, tended to compare trees based on branching patterns or perceived branch lengths. Likewise, three of the students who interpreted individual phylogenetic trees based on the proximity of terminal tips compared relationships across representations based on patterns in tip proximity.

### *Generating Representations*

Generating a phylogenetic tree involves isolating, interpreting, and using data as evidence of evolutionary relationships. There are many different styles of representation an expert could generate if asked to draw a visual representation illustrating the relationships among the following 16 organisms: bat, onion, dolphin, parrot, oak tree, fern, pine tree, slug, daisy, human, trout, algae, mushroom, turtle, crab, and fly (e.g., Figure 13). However, scientifically accurate representations share the following features: relationships are grouped based on evolutionary histories and common ancestry, all organisms are considered to be related and are connected within a single representation, taxa are placed at the terminal tips assuming there are hypothetical ancestors at the nodes, and consensus nodes are used when relationships are unknown.



*Figure 13.* Two examples of scientifically accurate phylogenetic trees representing the relationships among 16 selected organisms. The second of these trees is an example of how a scientist can use consensus nodes when exact relationships are uncertain.

I asked students to consider the same 16 organisms, ranging from plants and fungi to animals, and draw a visual representation that illustrated their understanding of how these organisms are related to one another. No students interpreted the scenario using

accurate scientific understanding at the beginning of the course. Students either could not complete this task or generated one of eight types of representations (see Table 10).

Although some images shared characteristics with multiple types of student-generated representations, I classified each image by the primary type of representation generated.

Table 10

*Types of representations generated by students at the beginning of the course*

Type of Representation	Number of Students	Percentage
Folk Taxonomy Classification	7	26%
Single Progressive Tree	6	22%
Separate Trees Segregating Organisms	3	11%
Flow Chart	3	11%
Single Tree with Taxa along Branches	2	7%
Phylogenetic Diagram	2	7%
Written Lists of Organisms	1	4%
Drew a Picture of the Organisms	1	4%
No Representation Attempted	2	7%

*Folk Taxonomy Classification*

Several students (26%) generated dichotomous keys using brackets or rectangular diagrams, to represent relationships among the organisms given. The evidence students used to support these representations was largely based on taxonomic categories, ecological characteristics, and behavioral attributes. For example, Jamie created a representation that segregated organisms based on physical characteristics such as the presence of roots, habitat, and wings. While she did not place the actual organisms on her representation, in her representation, the bat and parrot would be grouped together (see Figure 14).

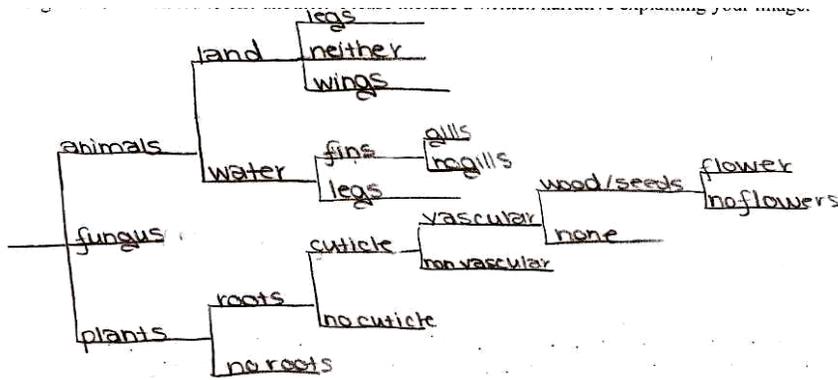
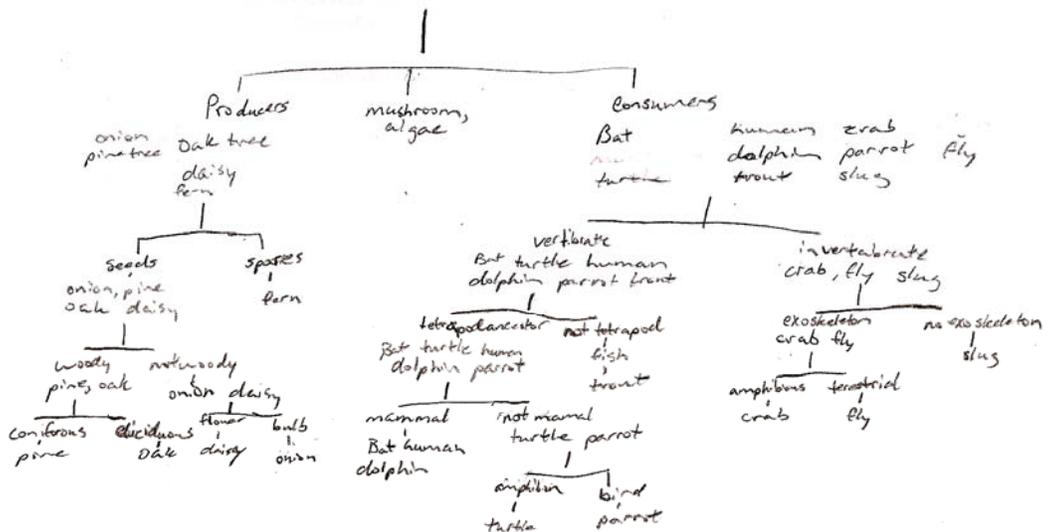


Figure 14. Jamie's dichotomous key.

Jeremy also developed a dichotomous key in order to represent relationships among the organisms (see Figure 15). He stated that his representation was appropriate for this scenario because his representation was, "A dichotomous key that lists similarities that the organisms currently have or in the case of the tetrapod dolphin, there is evidence of (pelvic girdle, fossil record)." However, using folk taxonomy to group organisms is not consistent with the scientific classifications of these organisms. According to phylogenetics, oak trees are more closely related to daisies than pine trees.



A dichotomous key that lists similarities that ~~the~~ organisms currently have or in the case of the tetrapod dolphin there is evidence of. (pelvic girdle, fossil record.)

Figure 15. Jeremy's dichotomous key that organized species based on ecological role (e.g., producers or consumers) and taxonomic characteristics.

Likewise, Chad generated multiple dichotomous keys representing how he considered the organisms were related to one another (Figure 16). In this example, Chad used folk taxonomy to organize the organisms rather than consider evolutionary histories. When asked about what his images represented he stated, “It’s a dichotomous key which doesn’t really show what has happened in the past so this is not a good representation of evolution . . . Dichotomous keys are organized by traits. Like they are based on flower color and on a tree you wouldn’t see flower color.”

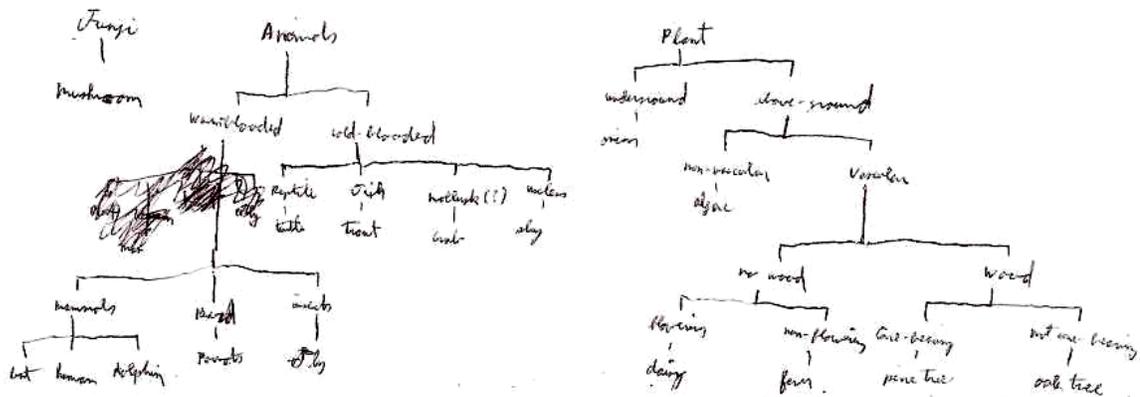


Figure 16. Chad generated three representations to illustrate relationships among the organisms by using a folk taxonomy style of categorization.

These bracket representations do not represent evolutionary events or patterns of shared ancestry among organisms. Rather these representations categorize organisms based on ecological elements, physical similarities, and taxonomical groups as they exist in their current form and offer no implication of a time scale.

### Single Progressive Tree

The second most common type of representation generated by 22% of students was a ladderized diagonal tree (e.g., Figure 17). Only one student, Miranda, provided any type of justification for her image. She simply stated, “Animals evolved after plants and fungi.”

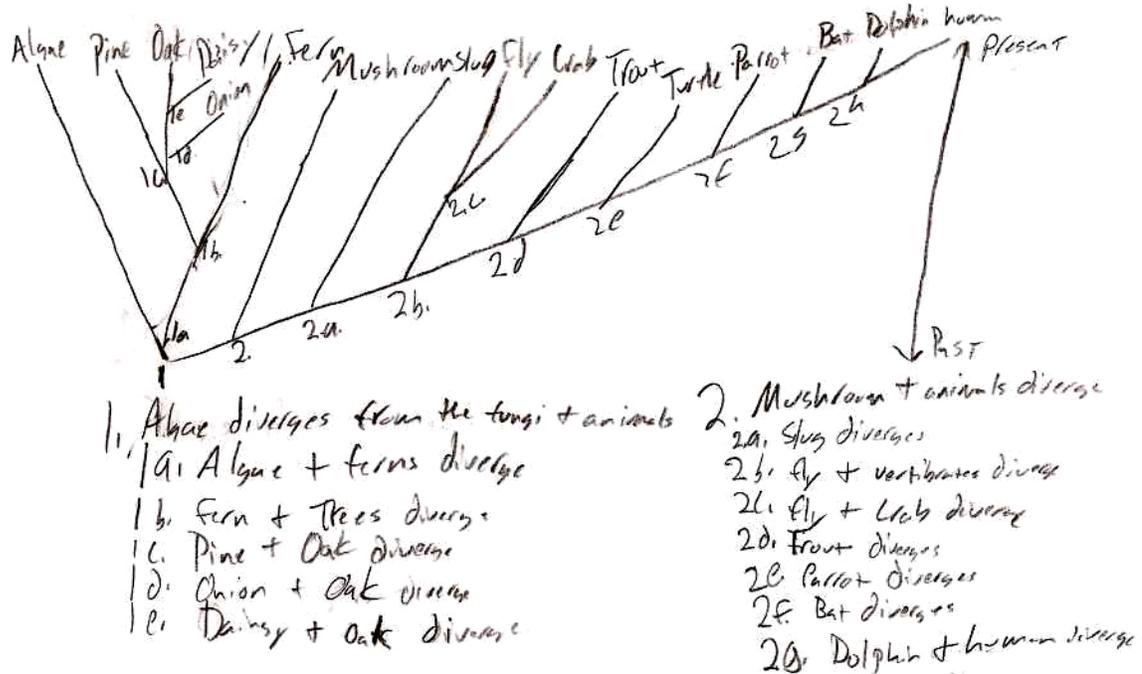


Figure 17. Tim's ladderized representation with organisms diverging in order of implied progression.

When these representations are viewed in the context of students' previous interpretations of phylogenies, it suggests that these students transferred notions of a main branch and progressive evolution. For example, Aimee considered the crocodile the most advanced organism (in Figure 8) because it was located on what she considered to be a main branch. In the representation she generated, Aimee left off a majority of the organisms and placed humans at the position she had previously indicated as representing the most advanced or evolved organism (Figure 18). This placement implies that she considered humans the most evolutionarily advanced organism.

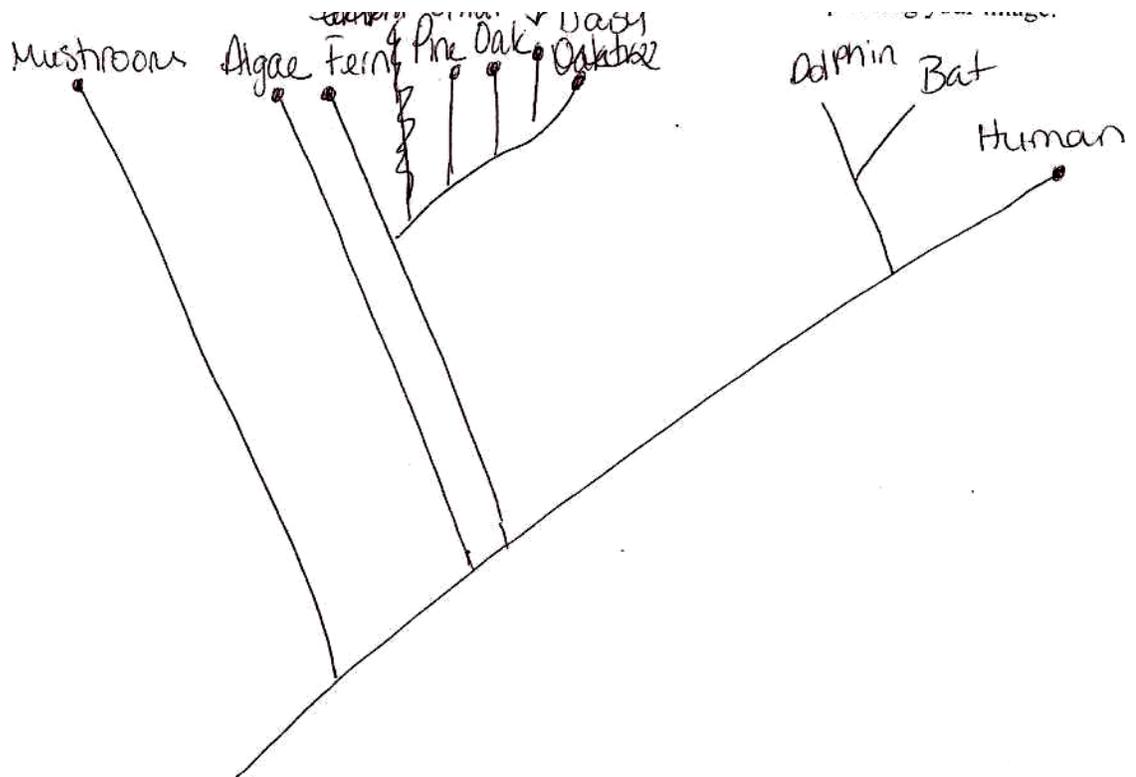
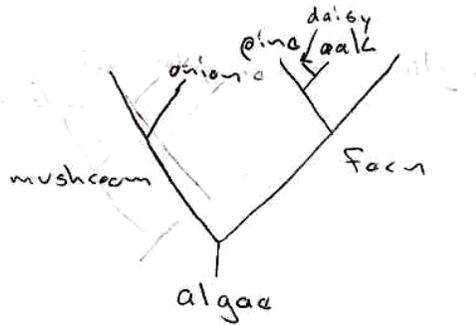


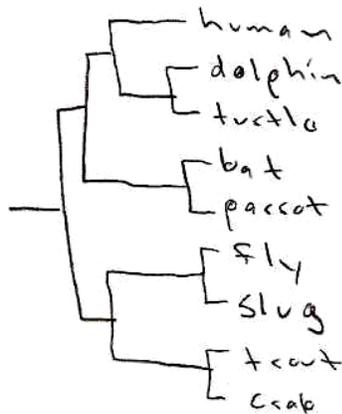
Figure 18. Aimee generated a progressive tree placing humans at the point she considered most advanced.

*Separate Trees Segregating Organisms*

By generating multiple representations to illustrate relationships among organisms, these students (11%) implied that different groups of organisms (e.g., plants and animals) are not evolutionarily related to one another. For example, Mitch organized the organisms into two main groups (Figure 19).



algae is the oldest life form in this group & the rest developed from the algae



I categorized them by the physical characteristics & relatedness

Figure 19. Mitch generated two separate trees segregating plants and fungi from animals.

Mitch explained in his first representation, “Algae is the oldest form of life in this group and the rest developed from algae.” In his second representation, Mitch stated, “I categorized them by the physical characteristics and relationships.” These two individual trees signify Mitch’s idea that these two groups of organisms are not related to one another, as confirmed during later explanations of these representations. These representations also highlight how Mitch interpreted individual phylogenies in relation to a main branch, as described earlier. In his first representation, he placed the mushroom and fern taxa along the branches rather than at the terminal tips, suggesting the other taxa

branched off from these organisms. Additionally, considering an onion as edible, he grouped that organism with mushrooms rather than considering evolutionary histories and grouping onions with flowering plants, as would have been scientifically accurate.

*Flow Chart*

A few students (11%) generated flow charts to represent how organisms were related to one another. In these representations, students placed taxa at the nodes (e.g., Figure 20). In phylogenetic trees, nodes represent a hypothetical common ancestor. By placing taxa at the nodes, the flow chart style of representations illustrates an alternative evolutionary idea that species evolve into the other species drawn after that point.

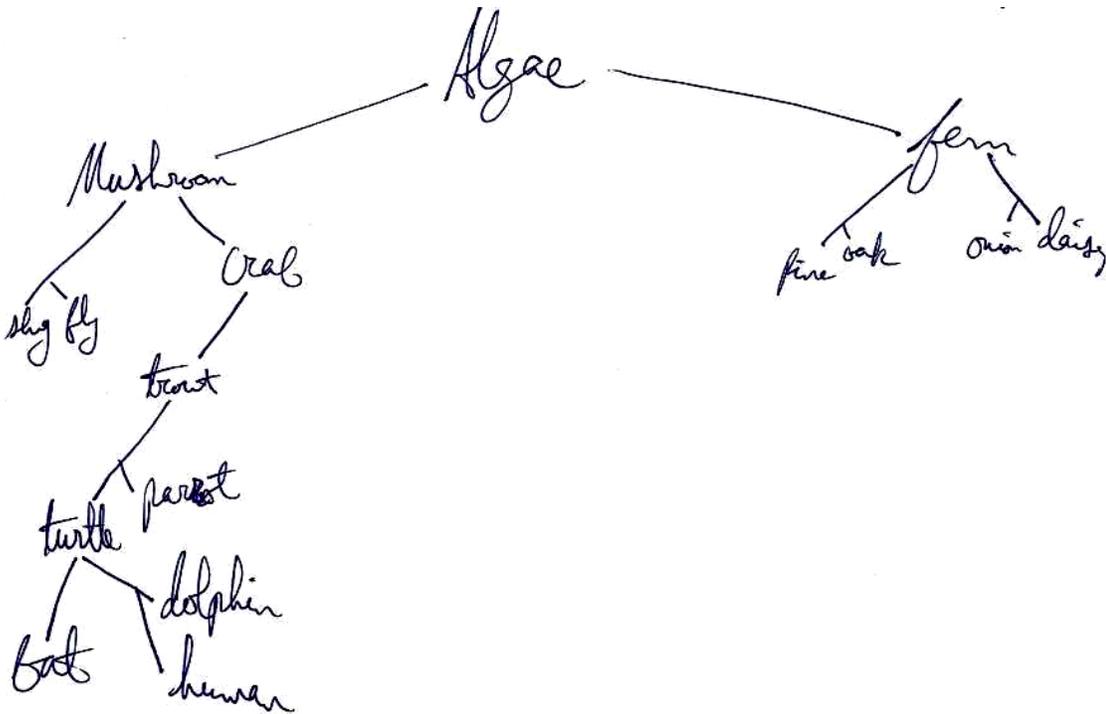


Figure 20. Randy generated a flow chart to illustrate how the organisms were related to one another.

Lauren generated a flow chart (see Figure 21) and justified how her representation illustrated the evolutionary history of the organisms. “It started with basic algae then animals evolved on one side and plants evolved on the other.”

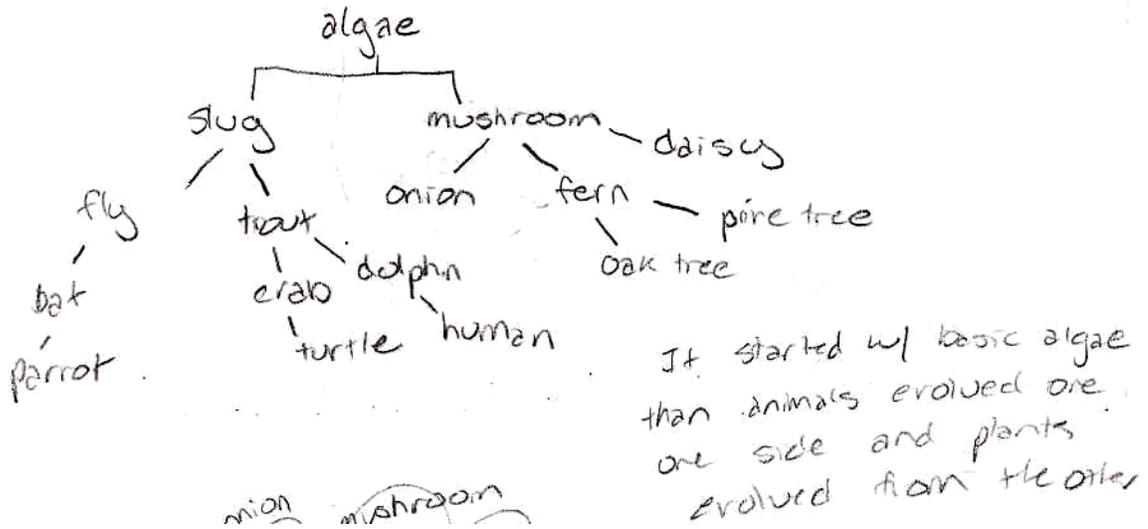


Figure 21. Lauren generated a flow chart to illustrate how the organisms were related to one another.

*Single Diagonal Tree with Taxa along Branches*

Two students drew diagonal trees and placed taxa along the branches of the representations. These representations emphasize the inaccurate notion of a main branch and organisms evolving off of other branches. For example, in Peter’s representation, it appears as though the fly evolved out of the slug branch (Figure 22). He justified his representations by stating, “The image just shows how different species have evolved over time in a tree of evolution.” This representation is consistent with Peter’s alternative interpretations of phylogenetic trees in which he used a main branch approach to determine relationships. He considered organisms to be more closely related to one another if they branched off of one another.

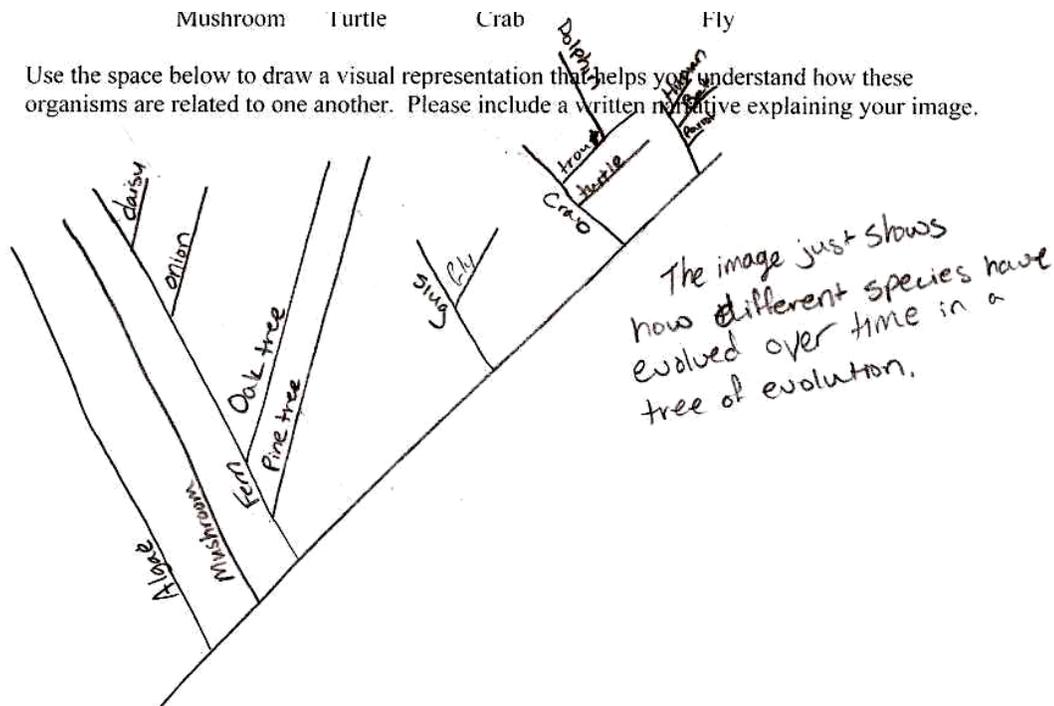


Figure 22. Peter indicated taxa along the branches of a diagonal tree.

### Phylogenetic Diagram

Only two students, Bob and Darren, generated phylogenetic diagrams at the beginning of the course. Both of these students had prior experiences reading phylogenetic trees in earlier biology courses. These diagrams were the most scientifically accurate representations generated by students. However, these representations were inaccurate in content and misrepresented some of the phylogenetic relationships among the organisms. For example, in Bob's representation (Figure 23), he illustrated pine trees as most closely related to daisies, and onions as equally related to oak trees, daisies, and pine trees. However, the pine tree should have been represented as equally related to the flowering plant monophyletic group of oak trees, daisies, and onions. Aside from the content errors, the physical characteristics of the representations were consistent with scientifically accepted phylogenetic trees.

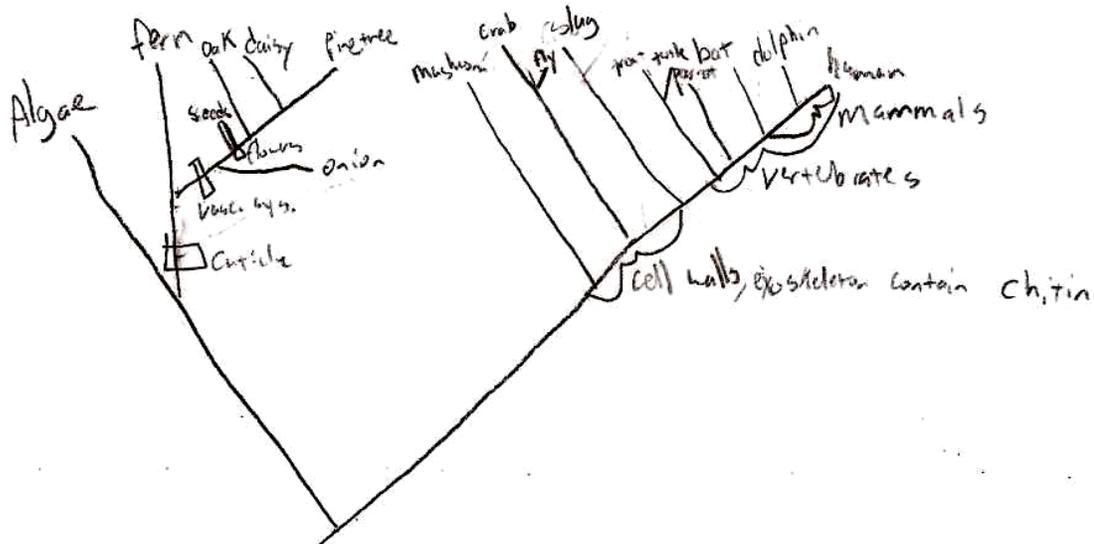


Figure 23. Bob drew a diagonal representation illustrating character states, secondary branching structures, and common ancestry. However, the relationships represented are not scientifically accurate.

### Written Lists of Organisms

Krystal was the only student who generated written lists of organisms to represent relationships at the beginning of the semester. She listed the animals with relation to taxonomic groups, e.g., mammals, vertebrates, and invertebrates (Figure 24). Krystal's list of organisms was similar to the folk taxonomy style of representation. However, she illustrated only one level of relationship among the organisms with her list and did not develop a visual representation to show specifically how the animals related to one another.

Animal mammal - bat, dolphin, human  
 vertebrate - bird - parrot  
                   fish - trout  
                   reptile - turtle  
 invertebrate - outer shell = crab  
                   - no outer shell = slug  
                   - wings = fly

Figure 24. Krystal generated a written list of animals.

*Picture of the Organisms*

Aaron interpreted the task literally and drew pictures of all the organisms in the environment they would be found (Figure 25). He explained the relationships in his image:

The trees are in a forest. The oak tree has a hole in it for the bat to live in. The guano fertilizes the ground where a mushroom grows. The slug lives off of the mushroom. West of the forest, a farmer with a pet parrot tends his onion patch. East of it is a stream with an algae which the turtle eats. The trout eats flies and lives in the stream. The stream leads to the ocean where there are crabs and dolphins.

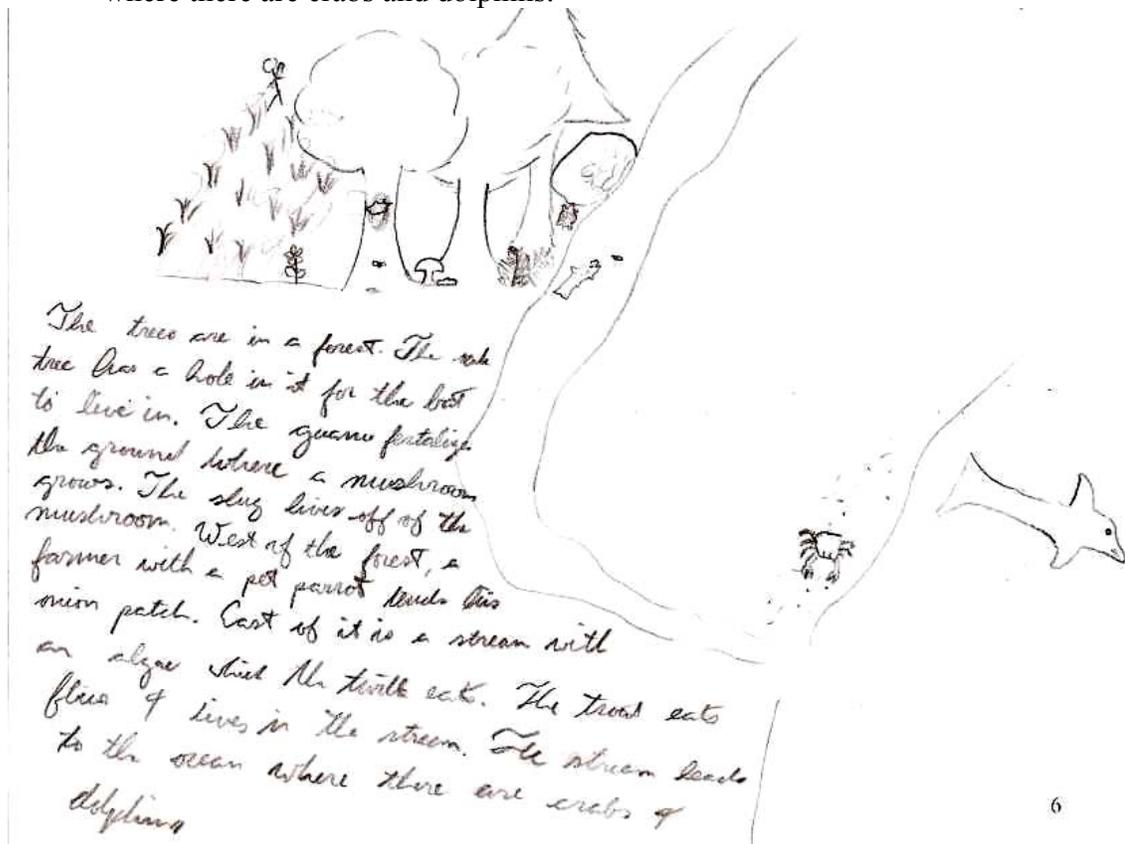


Figure 25. Aaron illustrated relationships among organisms by drawing images of each species and describing the ecological interactions connecting each organism.

Aaron used the term *related* to reference ecological relationships rather than evolutionary relationships. This interpretation of relationships was consistent with his interpretations

of phylogenies based on the ecology of the organisms rather than the topology of a phylogenetic representation.

### *No Representation Attempted*

At the beginning of the plant systematics course, two students, Abe and Roger, could not generate a representation to explain a phylogenetic scenario. Abe commented, “I honestly can’t even give this a try. But my best guess is that there is a hierarchical chain that could put these into an evolutionary timeline. I just don’t know what that is.”

### *Summary*

At the beginning of the course, no students generated a phylogenetic tree that was scientifically accurate. Rather, students generated one of eight alternative representations or were not able to generate any type of representation to illustrate a phylogenetic scenario. Often, the types of representations students generated were consistent with the strategies students used to interpret and compare phylogenetic trees. For example, students who generated a single progressive tree interpreted relationships represented in phylogenetic trees in context to a main branch. The two students who did generate phylogenetic trees were able to do so because they had previous instruction with tree thinking. In the next section of this chapter, I describe how interpretations of phylogenetic trees and the types of representations generated by students changed by the end of the course.

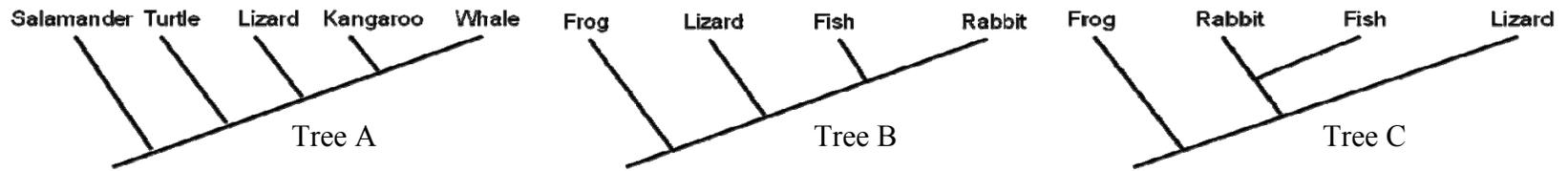
### Students’ Ideas at the End of the Course

I used the same four categories of phylogenetic understanding identified during the pretest analysis to answer my second research question and examine the ways students showed improvement in their phylogenetic conceptual understandings upon

completion of the plant systematics course. In the next sections, I discuss the themes that emerged from the data regarding 1) Interpretation of phylogenies; 2) Placement of time on simple, diagonal phylogenetic representations; 3) Comparison of phylogenetic representations; and 4) Types of representations generated to illustrate a phylogenetic scenario.

### *Interpretation of Phylogenies*

Students completed three posttest questions in which they explained how they interpreted relationships represented on individual phylogenetic trees. While the questions were identical in form to the three posed on the pretest, I replaced the organisms on each of the trees (see Figure 26). Students showed improvement on selecting scientific responses for each tree interpretation question upon completion of the course. Table 11 details the responses students provided to the multiple choice portion of these questions on the posttest.



*Figure 26.* Representations used in the three tree interpretation questions were replaced for the posttest. Each new representation illustrated the same pattern of relationships as previously indicated. Tree A replaced the former tree used for tree interpretation question one and illustrates the salamander as equally related to the turtle and whale. Tree B replaced the former representation for tree interpretation question two and illustrated the lizard more closely related to the rabbit than the frog. Tree C replaced the former representation for tree interpretation question three and also illustrates the lizard more closely related to the rabbit than the frog.

Table 11

*Student responses to the multiple choice portion of posttest questions involving interpretation of relationships represented on a phylogenetic tree*

Tree Interpretation Question	Response	Number of Students	Percentage
Question 1 (see Figure 26 Tree A)	A: <i>Salamander</i> is more closely related to <i>Turtle</i> than <i>Whale</i>	3	11%
	B: <i>Salamander</i> is more closely related to <i>Whale</i> than <i>Turtle</i>	3	11%
	* C: <i>Salamander</i> is equally related to <i>Turtle</i> & <i>Whale</i>	21	78%
	D: <i>Salamander</i> is related to <i>Whale</i> , but not to <i>Turtle</i>	0	0%
Question 2 (see Figure 26, Tree B)	A: <i>Lizard</i> is more closely related to <i>Frog</i> than <i>Rabbit</i>	3	11%
	* B: <i>Lizard</i> is more closely related to <i>Rabbit</i> than <i>Frog</i>	22	82%
	C: <i>Lizard</i> is equally related to <i>Frog</i> & <i>Rabbit</i>	2	7%
	D: <i>Lizard</i> is related to <i>Frog</i> , but not to <i>Rabbit</i>	0	0%
Question 3 (see Figure 26, Tree C)	A: <i>Lizard</i> is more closely related to <i>Frog</i> than <i>Rabbit</i>	0	0%
	* B: <i>Lizard</i> is more closely related to <i>Rabbit</i> than <i>Frog</i>	21	78%
	C: <i>Lizard</i> is equally related to <i>Frog</i> & <i>Rabbit</i>	6	22%
	D: <i>Lizard</i> is related to <i>Frog</i> , but not to <i>Rabbit</i>	0	0%

Note. \*Denotes a scientifically accurate selection

At the end of the course, students used eight approaches to interpret phylogenetic trees (see Table 12). Five of these approaches were consistent with interpretations made at the beginning of the course: common ancestry, main branch, proximity of terminal tips, nodal emphasis, and unidirectional reading. Three of the approaches students used were novel approaches not used at the beginning of the course: monophyletic groupings, rotate branches, and implied apomorphies. Many students (44%) used more than one approach to make sense of relationships represented on individual phylogenetic trees. Below, I describe each of the new interpretation approaches students used at the end of the course. Additionally, I explain connections between improvements in students' responses to the tree interpretation questions and interpretation approaches used.

Table 12

*Student approaches in interpreting phylogenetic representations upon completion of the course*

Approach	Number of Students*	Percentage
Common Ancestry <sup>‡</sup> °	21	78%
Monophyletic Groupings°	8	30%
Rotate Branches	8	30%
Implied Apomorphies	5	19%
Main Branch <sup>‡</sup>	2	7%
Proximity of Terminal Tips <sup>‡</sup>	1	4%
Nodal Emphasis <sup>‡</sup>	1	4%
Unidirectional Reading <sup>‡</sup>	1	4%

*Note.* \*Total equals more than 27 students because some students used more than one approach when interpreting phylogenetic representations.

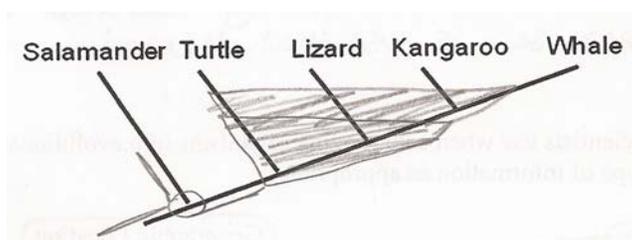
<sup>‡</sup> These approaches are the same interpretation approaches as used at the beginning of the course.

°Common ancestry and Monophyletic groupings represent scientifically accurate interpretations.

### *Monophyletic Groupings*

Upon completing the plant systematics course, nearly one third (30%) of students used monophyletic patterns to interpret relationships represented in phylogenetic trees in the same manner as scientists. These students identified a point of common ancestry and

all of the associated lineages as one closely related set of organisms. For example, Kathryn explained why she selected her response that the salamander was equally related to the turtle and whale, “I chose *c* because if all organisms are considered in one monophyletic group, then they are equally related. The branches can be rotated at the common node so whale is physically closer to salamander, but the relationship is the same.” Likewise, she used this same reasoning to explain her response to the second and third tree interpretation questions. “I chose *b* because a lizard and a rabbit are in a monophyletic group that doesn’t include frogs, but if extended, frogs can be taken out of the group properly. But rabbits cannot because it would then be paraphyletic.” Aimee also read phylogenetic trees using patterns in monophyletic groups by the end of the course. She stated, “The salamander is sharing a common ancestor with the *Turtle-Lizard-Kangaroo-Whale* clade and is equally related to each” (see Figure 27). By relying on clades to explain the relationships represented within phylogenetic trees, Kathryn, Aimee, and the rest of the students using this approach were able to interpret phylogenetic relationships consistently with scientific accuracy.



*Figure 27.* Aimee explained her response to the first tree interpretation question by illustrating how the monophyletic group, turtle, lizard, kangaroo, and whale, was represented on the phylogenetic tree.

### *Rotate Branches*

In phylogenetic tree representations, it is understood among scientists that the branches can swivel around a node without altering the relationships illustrated. In class,

students were taught to consider phylogenetic trees similar to a mobile. Nearly one third (30%) of students used this reasoning as their approach toward interpreting phylogenetic relationships upon completion of this course. For example, Abe supported his interpretations of relationships represented in phylogenetic trees because, “You can turn the tree at the node and thus switching the appearance, but not the relationships.” However, while this approach facilitates students selecting the appropriate response, these interpretations are lacking scientific content to justify the evolutionary meaning behind the relationships represented. Furthermore, this approach can cause additional confusion regarding the branching structure of phylogenetic representations that were not apparent previously, such as students developing the idea that branch rotation allows all taxa represented to be equally related to one another. Emily selected the appropriate response regarding salamanders’ relationships to turtles and rabbits based on the notion that branches, “can be switched, so they are all equally related.” However, in her explanation, Emily did not flip branches correctly in the drawing she provided to supplement her explanations (Figure 28). Instead, Emily altered the monophyletic groups. Whereas the original tree illustrated whales and kangaroos as sister species in one monophyletic group with lizards, Emily’s rotated tree illustrates lizards and turtles as sister species in a monophyletic group with kangaroos.

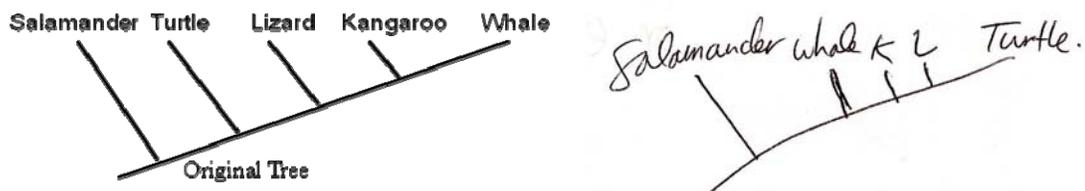


Figure 28. Emily inaccurately illustrated branches rotated around a node.

Roger was also confused by the idea that branches could rotate around nodes. Roger interpreted these rotations to mean that phylogenetic trees could be manipulated to represent equal relationships among all of the organisms shown, the response he selected for each of the three tree interpretation questions. He stated, “Tree reading should not be ‘tips’ (taxa). Instead trees should be read at nodes. When reading the tree at the nodes, you can manipulate the tree to show turtle/whale switched to whale/turtle.” According to Roger’s explanation, each branch rotation altered the relationships among the organisms. His understanding was that any given tree can be altered to represent different sets of sister relationships. Therefore, he thought that all organisms included on a phylogenetic tree are equally related to one another.

#### *Implied Apomorphies*

Although no character states were represented on the trees used for the tree interpretation questions, several students (19%) based their interpretation approach on the implication of apomorphies present within the phylogeny. Krystal correctly responded that the second tree interpretation question represented the lizard as more closely related to a rabbit than a frog (Figure 26, Tree B). She explained that this was because, “There is a significant apomorphy keeping the lizard from being similar to the frog.” While phylogenies are built using evidence from shared derived character states, most students using this approach confused the term *apomorphy* with the term *synapomorphy*. Scientists define apomorphies as derived character states that segregate species from one another while synapomorphies are derived character states that are shared by a group of organisms. For example, Jared explained that the lizard and rabbit were more closely related than the lizard and frog because, “There was an apomorphy that the lizard and

rabbit shared.” In this statement, he should have used to the term synapomorphy because he was using the implied character state to group lizards and rabbits.

### *Improvements*

I compared students’ overall responses (n=27) to the three tree interpretation questions. Upon completion of the plant systematics course, 18 students (67%) consistently used scientific approaches to interpret relationships represented in phylogenetic trees. This marks a 60 point improvement from the beginning of the course when only two students (7%) consistently used common ancestry to interpret phylogenetic representations. At the end of the course, 15 of the students relied on points of common ancestry or the more sophisticated idea of monophyletic groupings to justify their responses.

More specifically, of the 21 students who accurately interpreted the salamander as equally related to the turtle and the whale in the first question, 16 used scientifically acceptable explanations regarding their selection. These students used common ancestry and implied apomorphies as evidence for their selection. For example, Kathryn and Amiee relied upon their ideas about monophyletic groupings to interpret the relationships illustrated in the tree. The remaining five students relied upon their understanding of how branches are capable of swiveling around nodes without altering depicted relationships. While this explanation is technically accurate, it is not a content-oriented justification for explaining the scientific basis represented by the tree. Regardless, these responses and explanations show improvement over the answers given at the beginning of the course, when only three students used a scientific approach to interpret this phylogenetic tree.

At the beginning of the course, only seven students selected the accurate response to the second tree interpretation question, and only four provided a scientific rationale based on common ancestry to support their responses. However, upon completion of the plant systematics course, 22 of the 27 students selected the appropriate response, indicating the lizard as more closely related to rabbit than the frog. For example, Sally stated, “the lizard and rabbit are in the same clade and they share a common ancestor.” All but one of these students used a scientific explanation such as common ancestry, monophyletic groupings, or implied ancestry, to support their answers. Chad selected the accurate answer by using an alternative reasoning approach. He explained that, “You always say something is more related to the thing that is higher up in the tree than the thing that is lower.” Chad’s interpretation was based on a unidirectional reading approach.

Although the majority of the students (23 or 85%) answered the third tree interpretation question correctly at the beginning of the course, only five students, or 22% of the 23, used a scientific approach to justify their response. However, at the end of the course, fewer students (21 or 78%) selected the correct response to this question. All of these students (100%) at the end of the course relied upon scientific ideas of common ancestry, monophyletic groupings, or implied apomorphies to explain how they approached their interpretation that the lizard was represented as more closely related to the rabbit than the frog. Thus, by the end of the course, while accurate responses on the multiple choice portion of each question were not directly related to correct reasoning, students showed improvement toward using scientific approaches to interpret phylogenetic trees.

### *Summary*

At the end of the plant systematics course, students used interpretation approaches that were aligned with scientific thinking more often than alternative approaches. The four most common approaches used by students to interpret phylogenetic trees, common ancestry, monophyletic groupings, rotate branches, and implied apomorphies, were grounded in scientific understanding. These approaches showed that students improved their understandings of the context of the relationships represented within phylogenetic trees, even though not all students used these approaches to interpret the trees accurately. At the end of the course, only 19% of students relied upon non-scientifically accurate approaches to interpret phylogenetic trees. This is an improvement from the beginning of course when only 19% of the students used an interpretation approach grounded in scientific thinking.

I identified trends emerging from the data related to shifts in the approaches students used when interpreting phylogenetic trees at the beginning of the course to those used at the end of course. For example, students (e.g., Roger and Emily) who interpreted phylogenetic trees based on the proximity of organisms along the terminal tips, or those who used knowledge about the organisms unrelated to the representation (e.g., Aaron and Emily) at the beginning of the course tended to shift their approach to rotation-based interpretations by the end of the course. This trend illustrated a shift from students using superficial location of organisms along the tips of the representation or ignoring the representation when forming conclusions about relationships among the organisms, to acknowledging scientific meaning in representation and recognizing the mobile nature of trees. Another trend was that students who used a nodal emphasis approach when

interpreting trees at the beginning of the course (e.g., Jamie, Brandt, and Tim) shifted their approach to focus on implied apomorphies and common ancestry. These students still used the nodes to interpret relationships illustrated on the tree. By the end of the course, however, these students recognized the scientific meaning of common ancestry and divergence events represented by these points of intersection.

*Placement of Time*

Upon completion of the plant systematics course, students showed improvements in their understanding of the progression of time represented on phylogenetic trees. Students transposed the directionality of time in only one of two ways: vertically from root to terminal tips or diagonally from root to terminal tips. As indicated by Table 13, 85% of students illustrated the scientifically accurate progression of time, vertically from the root of the phylogenetic tree to the terminal tips. This indicates a 22 point improvement in students’ skills in correctly identifying how time is represented on a phylogenetic tree. Only 15% students drew an alternative direction of time, illustrating time progressing diagonally upwards on the phylogenetic representation.

Table 13

*Student perceptions of time on a diagonal phylogenetic representation upon completion of the plant systematics course*

Direction of Time	Number of Students	Percentage of Students
Vertical (↑)	23	85%
Diagonal (↗)	4	15%
Total Students	27	100%

The four students who inaccurately indicated the progression of time on the phylogenetic tree also struggled with tree interpretation, comparison, and generation. For example, Brenda used a main line approach to interpret trees and generated a diagonal

representation based on folk taxonomy classification. Jared, Miranda, and Krystal also used alternative ideas about common ancestry to interpret and compare phylogenetic trees. Jared and Miranda generated progressive diagonal representations consistent with their ideas about time directionality.

### *Comparing Representations*

At the end of the course, I asked students the same questions about comparing relationships shown on phylogenetic representations as on the pretest. Students compared similar styles and different styles of phylogenetic trees. They used the same five criteria to support comparisons of representations: physical branching patterns, style of representation, clade comparison, branch length similarities/differences, and/or patterns in tip proximity (see Table 14). However, upon completion of the course, the majority of students based their comparisons on the clades represented in the trees rather than physical branching patterns.

Table 14

*Reasoning types used to compare phylogenetic representations at the end of the course*

Comparison Criteria	Number of Students*	Percentage
Physical Branching Patterns	2	7%
Style of Representation	2	7%
Clade Comparison <sup>o</sup>	21	78%
Branch Length Similarities/Differences	1	4%
Patterns in Tip Proximity	2	7%

*Note.* \*Totals equal more than 27 students because one student used more than one criterion when comparing phylogenetic representations.

<sup>o</sup>Clade Comparison represents a scientifically accurate comparison criterion.

At the end of the course, the clade comparison criterion was still the only criterion consistent with scientific thinking. However, unlike at the beginning of the course, at the end of the course most students used this criterion in the same manner as scientists.

Thus, over two thirds of the students (70%) were able to accurately compare phylogenetic representations with scientifically appropriate reasoning. The remaining 30% of the students either used the clade comparison inaccurately or used one or more of the alternative reasoning criteria to compare phylogenetic representations. For example, Miranda and Maggie used the clade comparison criterion to compare trees, but each selected an inaccurate response. Maggie justified her response, “In tree *d*, A is included in the clade with B, C, D, and E, but it is not in the other trees.” Actually, taxon A is included in this same clade in all four trees (see Figure 11). Brenda and Randy compared physical branching patterns across the phylogenetic trees. Brenda concluded that all of the trees represented different relationships than the others. “I think they all vary in some way when looking at the common ancestors. I don’t see three that have the same relationships with one that is completely different.” Randy selected tree *a* as the representation that illustrated different relationships than the others because “It is the only tree in which A is derived from B.” Lauren also selected tree *a* as different, but she based her answer on patterns in tip proximity, “B is closer related to G than A which is wrong.” Roger was the only student to use more than one criterion to compare phylogenetic representations at the end of the course. He used the style of representation and branch length criteria in response to the tree comparison questions. He was also unable to generate a representation that illustrated his understanding of a phylogenetic scenario.

### *Generated Representations*

I asked students to consider 14 of the organisms previously given to them on the pretest (bat, onion, dolphin, parrot, oak tree, fern, pine tree, daisy, human, trout, algae,

mushroom, turtle, and fly) and draw a visual representation illustrating their understanding of how these organisms relate to one another. I removed two organisms, slug and crab, from pretest version of this problem to decrease the amount of animal taxa incorporated in the phylogeny and the time students were spending on this problem. Student-generated representations ranged from phylogenetic diagrams to no representation, with four additional alternative types of representations in between (see Table 15). There were no new types of student-generated representations. In the next sections, I describe and selected examples of each representation type students generated.

Table 15

*Types of representations generated by students at the end of the course*

Type of Representation	Number of Students	Percentage
Phylogenetic Diagram	10	37%
Single Progressive Tree	6	22%
Folk Taxonomy Classification	5	19%
Separate Trees Segregating Organisms	3	11%
Written Lists of Organisms	2	7%
No Representation	1	4%

*Phylogenetic Diagram*

By the end of the course, 37% of students generated phylogenetic diagrams to represent their ideas about how the 14 species were related. These representations were the most scientifically accurate representations generated by students. Each of these diagrams represented key features expected in a phylogenetic tree and correct or nearly correct relationships among the taxa. For example, Tim generated a scientifically accurate, species-poor phylogenetic tree (Figure 29).

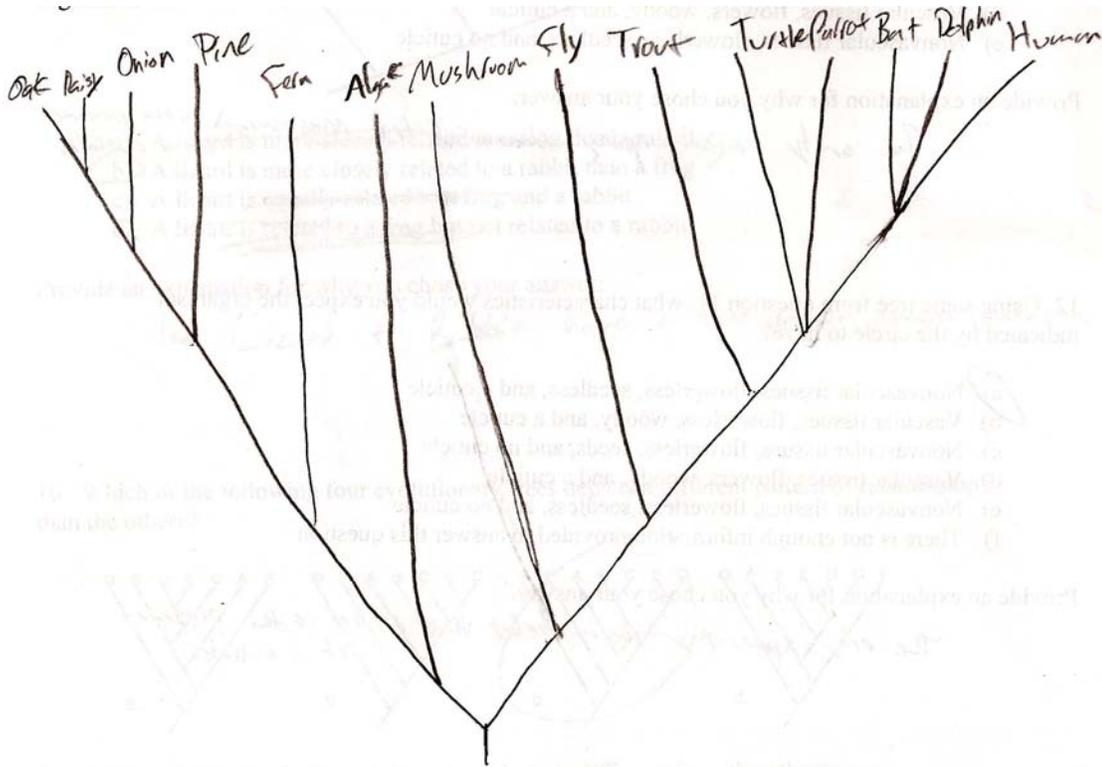


Figure 29. Tim generated a scientifically accurate, species-poor phylogenetic representation at the end of the plant systematics course.

In this tree, he used consensus nodes to represent relationships when he was uncertain of the exact relationships among the animals. While this representation is ladderized in appearance, Tim no longer implied a progressive nature of evolution with taxa diverging in order as he implied with the representation he generated at the beginning of the course. This representation does not suggest plants evolved prior to animals, but rather they are included in different monophyletic groups.

Aimee also generated a phylogenetic diagram at the end of the course (Figure 30). She also used consensus nodes to represent relationships of which she was uncertain. The only inaccurate relationship represented on this tree is fungi as more closely related to plants than animals. However, due to the nature of the plant systematics course, I did not expect students to have advanced content understanding of fungi and animal

relationships. Rather, the purpose of including non-plant organisms was to see how students would represent historic relationships. In Amiee's tree, she represented this historic relationship by having plants and animals diverge at the most basal node.

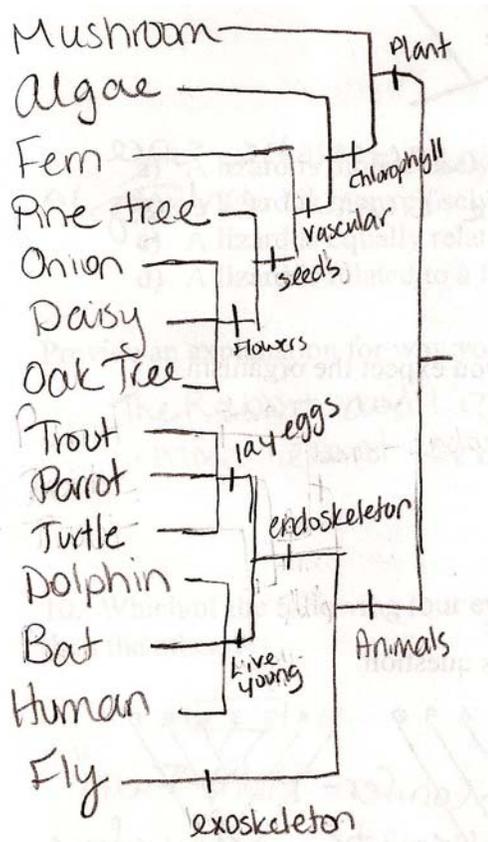


Figure 30. Aimee generated a phylogenetic diagram using apomorphies to define monophyletic groups of taxa.

### Single Progressive Tree

The second most common type of representation generated by 22% of students at the end of the course was a single progressive, ladderized tree (Figure 31). These trees, like at the beginning of the course, implied that evolution was progressive, beginning with either algae or mushrooms and advancing toward humans. Chad drew a progressive tree and explained that when he generated his representation, “I just went from least complex to most complex.”

is really go.

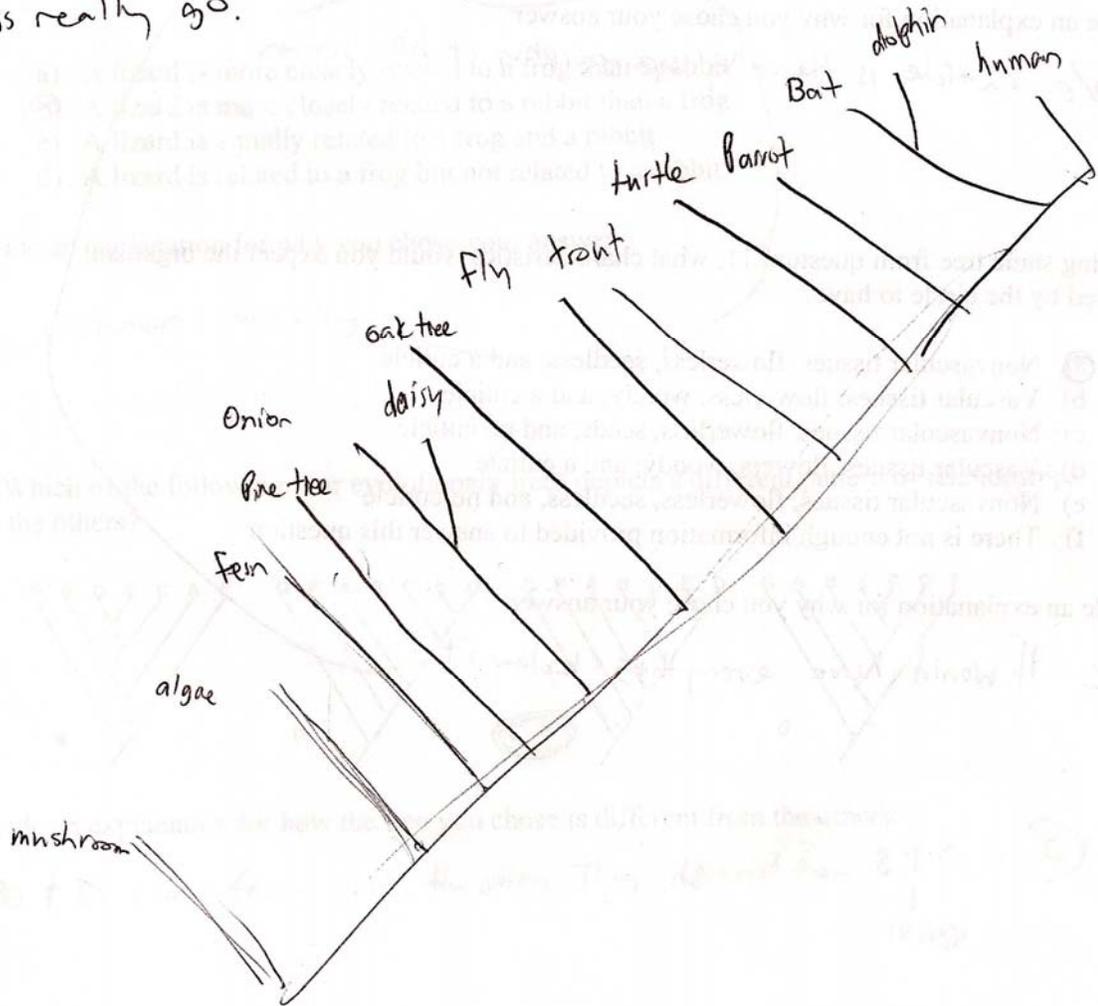


Figure 31. Jared generated a ladder tree progressing from mushrooms to humans.

Mitch also generated a single progressive tree (Figure 32). However, his representation is not a ladderized diagonal tree, but rather a rectangular progression of organisms from left to right. Mitch organized his representation based on the progressive age of the taxa, “Algae and fern are the oldest organisms while the dolphins and humans are the newest.”

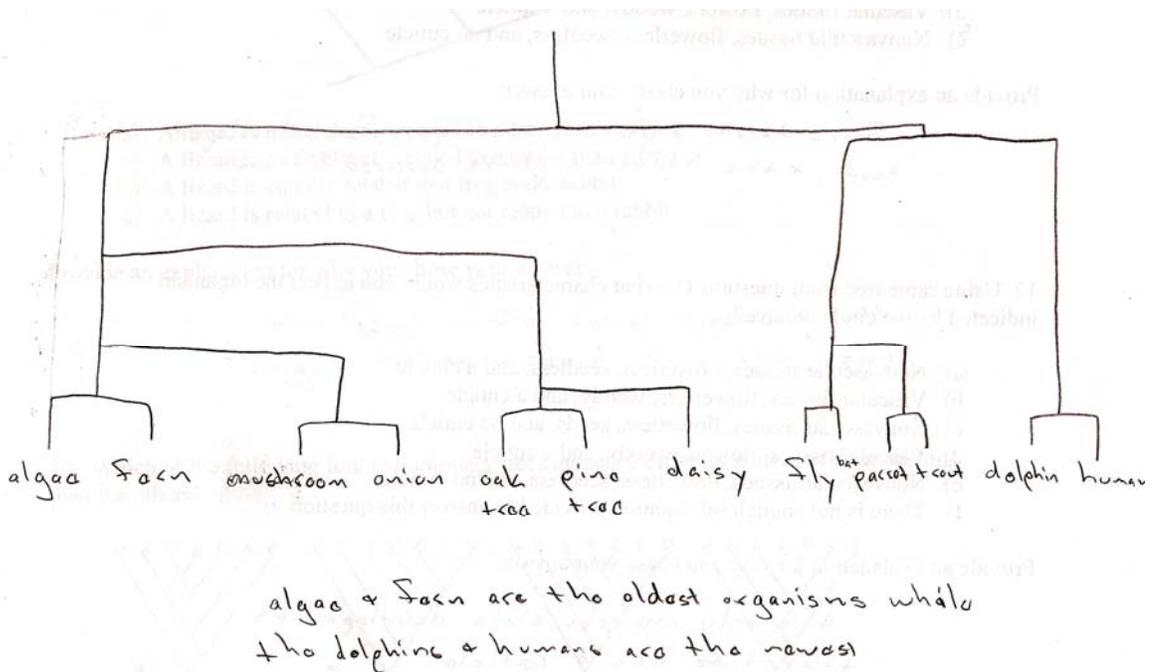


Figure 32. Mitch generated a progressive rectangular tree based on his perception of the age of the taxa.

### *Folk Taxonomy Classification*

At the end of the course, 19% of students generated dichotomous keys to represent relationships among the given organisms. Jeremy generated a key very similar to the one he generated at the beginning of the course (see Figure 15 and Figure 33). He used evidence of ecological roles (e.g., autotrophic, heterotrophic) and taxonomic classifications rather than phylogenetic evidence to illustrate the relationships among taxa.

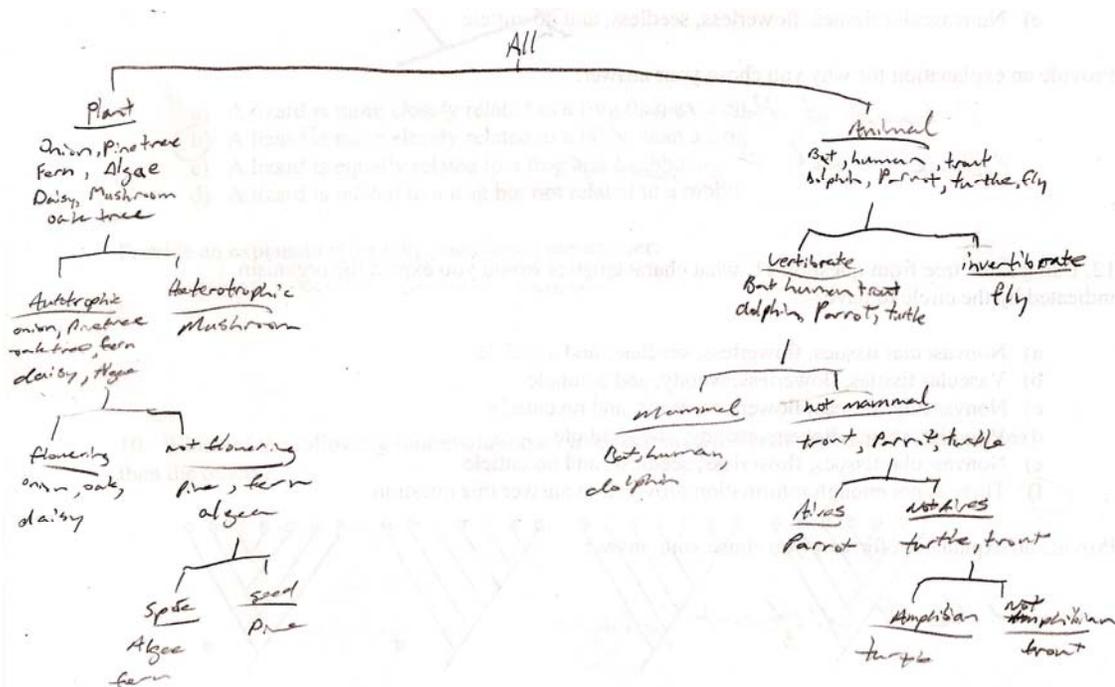


Figure 33. Jeremy generated a dichotomous key that organized species based on ecological roles (e.g., autotrophic, heterotrophic) and taxonomic classifications rather than phylogenetic evidence.

Kristen also generated a key-based representation similar to her representation at the beginning of the course. She stated that the relationships were, “based on how they travel: stationery, swims, flies.” Likewise, Brenda stated, “I tried to group the plants together, food, animals, flying animals, and walking animals together.” These representations were not generated within the context of evolution, even though evolutionary relationships were stressed throughout the course.

#### *Separate Trees Segregating Organisms*

Only three students generated multiple trees to sort the 14 taxa at the end of the course. At the start of the course, all three of these students, Karen, Sally, and Jamie generated a single representation to illustrate relationships among the taxa. At the beginning of the course, Jamie created a key using folk taxonomy to generate a representation. At the end of the course, she generated two trees segregating organisms

into two primary groups: animals and plants (including fungi) (Figure 34). By drawing two separate trees, she implied that each group is unrelated to the other.

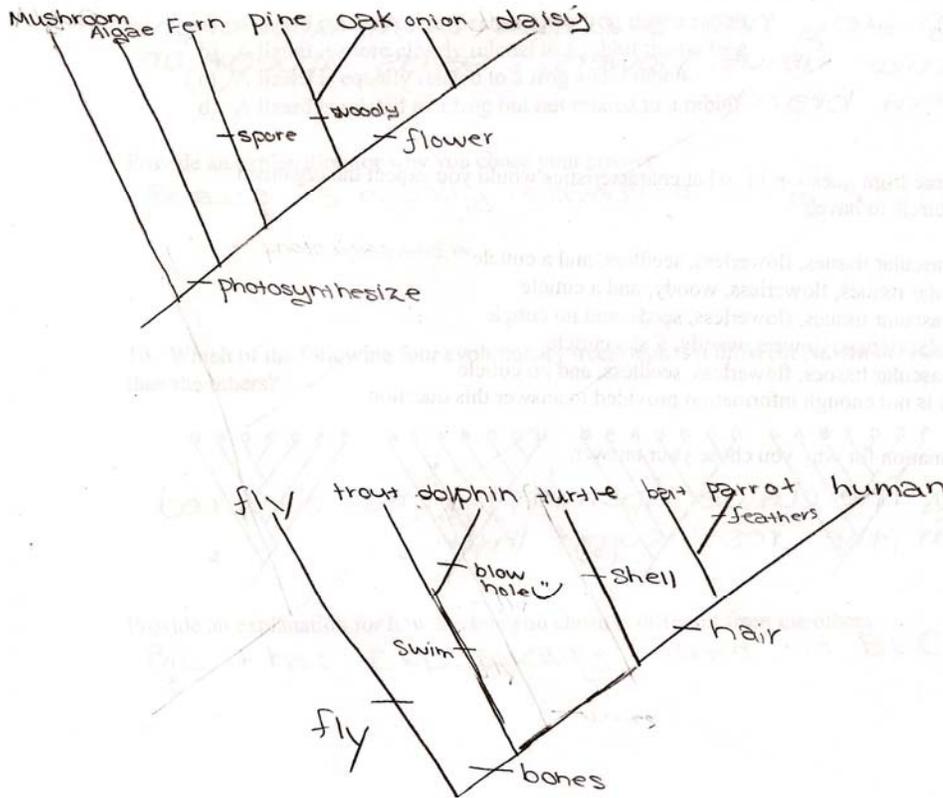


Figure 34. Jamie generated two separate trees segregating plants and fungi from animals.

### Written Lists of Organisms

Abe and Krystal were the only students who generated written lists of organisms to represent relationships among the taxa at the end of the course. Krystal composed three lists: plants, almost plants, and animals. This approach was a cross between generating multiple representations and no representation (Figure 35). She explained why she wrote lists. “Though this is less than technical, putting all these in a tree would have been confusing because I would not know which came first evolutionarily (mushroom vs. fern) and so forth. Thus, because dates are not known, a list is

appropriate.” She acknowledged that a tree could be used to represent relationships, but did not consider that to be the most appropriate representation. Instead, she illustrated only one level of relationship among the organisms with her lists, the same way she represented these organisms at the beginning of the course.

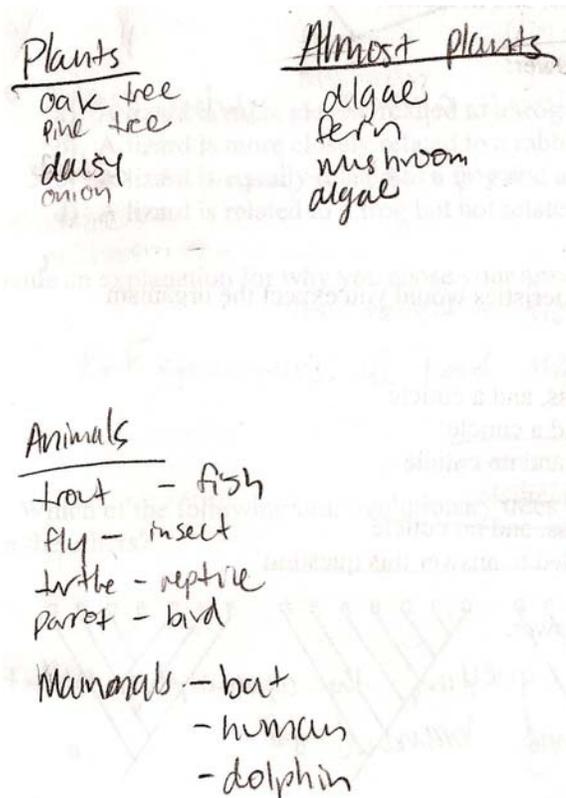


Figure 35. Krystal generated three separate lists -- plants, almost plants, and animals -- to group how she thought the given taxa were related to one another.

### No Representation

Only one student, Roger, did not attempt to generate a representation explaining the relationships among the organisms provided. While he did not actually build a tree at the end of the course, he highlighted a phylogenetic tree provided on the posttest and stated, “I would use this image to show the different classifications of these organisms.”

This statement shows an awareness of the appropriate representation but he was lacking the skills to generate a phylogenetic tree.

### *Summary*

At the end of the course, students generated fewer types of representations to illustrate a phylogenetic scenario. No students generated alternative flow charts, pictorial images, or placed taxa along the branches of a representation by the end of the semester. Instead, more students (37%) generated scientifically appropriate phylogenetic representations than at the beginning of the course. Students (33%) also generated alternative images that had superficial resemblance to phylogenetic trees, but were not organized or justified with scientific reasoning. One student, Roger, did not generate any form of representation. Roger also relied upon alternative interpretation approaches and comparison criteria at the end of the semester.

Over the course of the semester, three trends emerged from the data related to shifts in types of representations students generated when illustrating a phylogenetic scenario. First, and least common, four students (15%) generated fewer scientifically appropriate representations than they had previously. For example, Karen generated a single diagram at the beginning of the course but elected to generate multiple trees at the end of the course. Also, Maggie, drew a single progressive tree at the beginning of the course and used folk taxonomy to represent how organisms were related at the end of the course. These students accurately interpreted phylogenetic trees but inaccurately compared phylogenetic trees at the end of the course.

The second trend was that many students (30%) generated the same types of representations as they had at the beginning of the course. For example, Kristen and

Jeremy continued to generate folk taxonomy-based representations. Also, Bob and Darren consistently generated phylogenetic diagrams to represent the relationships among the organisms.

The third and most common trend was that over half of the students (55%) generated more scientifically appropriate representations than had at the beginning of the course. For example, Jamie, Sally, Kathryn, and Emily transitioned from generating folk taxonomy-based representations to multiple, single, or phylogenetic trees. Likewise, Aaron shifted from drawing a pictorial image of the organisms to generating a phylogenetic tree. Tim, Aimee, Chip, and Brant were also able to generate phylogenetic trees at the end of the course in place of the single progressive trees they had generated at the beginning of the course. In each of these cases, students also had become better scientific tree readers over the course of the semester.

Overall, the majority of students (70%) were able to accurately interpret and compare phylogenetic representations with scientifically appropriate reasoning. In other words, a majority of the class gained scientific proficiency in tree reading by the end of the course. However, only 37% of students were able to generate a phylogenetic tree to represent how organisms were related to one another when given a phylogenetic scenario. A minority of the students gained scientific proficiency in tree building.

#### Student Perceptions of Improvement from Instructional Interventions

The third research question I investigated was: “How do students perceive improvements in their tree thinking related to three instructional interventions?” I organized this section around each of three instructional interventions for improving tree thinking implemented in the plant systematics course: 1) A pipe cleaner activity designed

to improve students' tree reading abilities (see Appendix I). 2) A Pseudocot fossil activity designed for students to make predictions from a tree and build a cladogram (see Appendix J). 3) The Whippo activity (modified from BioQUEST Curriculum Consortium, 2006) in which students compared trees built from different data sets in search of supporting evidence for a given hypothesis (see Appendix K). I selected these three instructional interventions because they were included in the course to address tree thinking challenges identified in the pilot study. In the next sections, I present student perceptions of how each of these instructional interventions affected their tree thinking abilities.

#### *Student Perceptions of Improvement in Tree Thinking Skills*

Students completed three instructional interventions in which they were engaged in explicit tree reading and tree building activities. Upon completion of each activity, students were asked to reflect upon their understanding of phylogenetic trees. For example, students were asked: What in class activities have been most helpful in your efforts to interpret, use, and build phylogenetic trees? How have these activities helped improve your tree thinking? The reflection questions were administered via online weekly reflections, in-class assignments, and during interviews with the key informants. In the following sections, I describe each activity, the specific goals for the intervention, and students' perceptions of how each activity improved their tree thinking.

#### *Pipe Cleaner Phylogeny*

I designed a pipe cleaner model (Figure 36) to allow students to interact with a phylogenetic manipulative and think deeper about evolutionary relationships represented in phylogenetic trees. In this instructional intervention, I removed the taxa from the

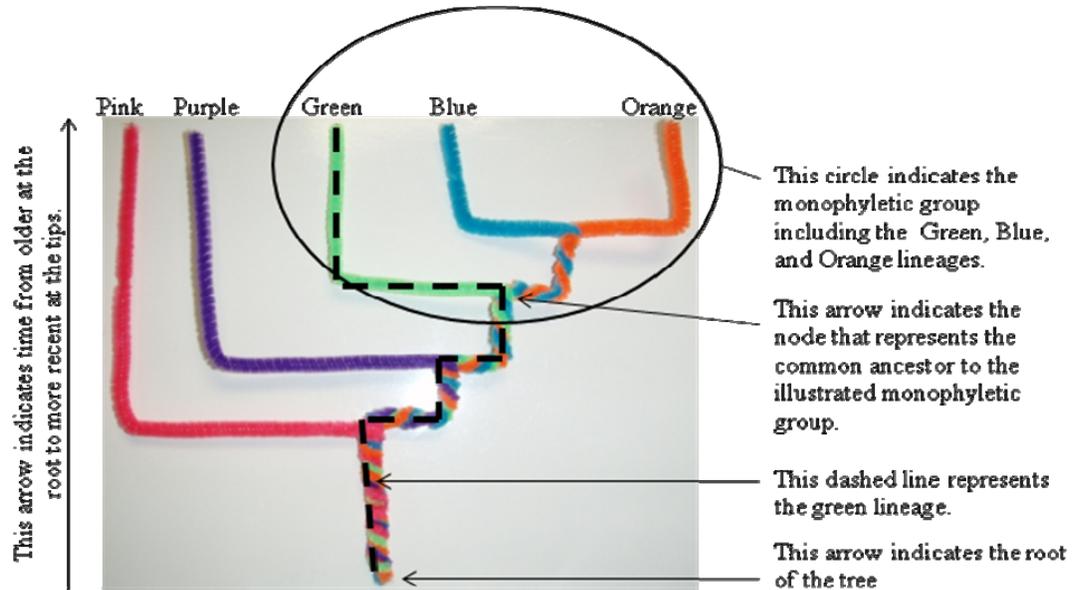
terminal tips on the tree to force students to draw conclusions about relationships based on the branching patterns in the tree rather than their prior ideas about the organisms. I designed this instructional intervention to help students identify informative portions of a phylogenetic tree, highlight lineages by using color rather than a black and white diagram, and provide a three-dimensional manipulative to help students visualize how branches can bend and rotate around nodes. The goal for this activity was to address explicitly and overcome the known misconceptions with phylogenetic tree reading. More specifically, the major objectives of this activity were:

- Students will be able to recognize similarities and differences in patterns of relationships across trees with different topographies, formats or orientations.
- Students will understand that flipping branches around a node does not affect the relationships depicted by the representation.
- Students will be able to trace an entire organism's lineage from tip to root of the tree.
- Students will become familiar with the key features of a phylogenetic tree and gain an understanding of what they represent.
- Students will be able to recognize bends/intersections on a phylogenetic tree contain information about evolutionary relationships.
- Students will learn how to use a manipulative in response to phylogenetic tree thinking problems.

The instructor introduced the activity and pipe cleaner model to the students.

Then, students were paired up and given pipe cleaner models to solve a series of prompts provided on a work sheet. As students worked in their pairs, the instructor assessed understanding and provided additional prompts for students to consider using their pipe cleaner trees, such as "How would you represent time on the tree?" and "Does the way time is represented change as you alter your models?" After students completed their

worksheets, the instructor asked students to discuss their responses to each prompt as a class.



*Figure 36.* This is an example of a pipe cleaner model with one full lineage (from root to tip) indicated by a dashed line. This depicts the smallest inclusive monophyletic group and most recent node for this lineage.

With the pipe cleaner tree manipulative, students could physically bend and rotate the pipe cleaners into new shapes, directions, and different topologies without altering the relationships. As Maggie worked with her model, she commented, “The pipe cleaners allow us to see how manipulating the tree by twisting and straightening does nothing to the tree's meaning, just its appearance.” Likewise, Karen identified the node as being more informative than the style of the branches. She stated, “The lines can be curved, waved, or straight. The node or connection between the lines is what depicts real information.”

In phylogenetic tree representations, it is understood among scientists that the branches can swivel around a node without altering the monophyletic groupings (or the

relationships illustrated). Due to the design of this manipulative, the only way to change the relationships illustrated on these models is to untwist the pipe cleaners and alter the lineage paths. Students stated that as they began manipulating the pipe cleaner trees by swiveling the branches, they began relying upon the nodes to determine relationships rather than the tips. After participating in the pipe cleaner activity, Brandt perceived it as helping him understand how branches could rotate along nodes. When asked how he would help someone else understand tree reading, he responded “That when studying trees, one should focus on nodes.” He elaborated on how the branches represented points where species diverged and the pipe cleaner model could help him show how “trees can be displayed in different formats while still showing the same information.” In another example, Jared perceived the pipe cleaner tree as helpful for shifting his thinking from tips to nodes. “It is very helpful in showing that you need to look at nodes. The shape of the tree can change dramatically, and the tips can change, but where branches come off the main trunk is what matters.” Kathryn also described the usefulness she perceived in these pipe cleaner models, claiming the model improved her understanding of how branches can rotate without changing the relationships represented:

I found this model to be very helpful for node thinking. I had trouble imagining the ‘rotation’ of the branches in my head, and this provided a physical rotation that I could see. It also helps to show how certain species are related by the location of the nodes, and how all of the species came from the common ancestor at the root of the tree.

Sally provided a statement that addressed the benefits of having a 3D pipe cleaner model. She indicated that this model provided a novel context for phylogenetic trees that was more effective than traditional printed phylogenetic trees in helping instruct how branches could rotate. “This is something you cannot do with a drawing on paper.”

Furthermore, by using multiple colors for the pipe cleaner tree model, this activity emphasized individual lineages from tip to root. Maggie stated, “The colored pipe cleaners allow you to follow each lineage back to its common ancestry and it lets you see where they are more closely related to one another.” The colored pipe cleaners were perceived as beneficial in highlighting points of common ancestry. Bob stated how the colors assisted his ability to visualize common ancestry, “The pipe cleaner was beneficial in visualizing points at which common ancestors existed. Because each species had its own color, points at which species shared common ancestry were easily identified because of the presence of that color twisted together [*sic*].”

During a weekly reflection prompt in week eight<sup>2</sup>, nearly all students (93% or 25 students) discussed how they thought this model helped improve their tree reading. Additionally, 44% (11 of 25 students) of these students referenced this activity as being the most beneficial instructional activity in the course for improving their tree reading. Students’ statements focused on how they perceived this instructional intervention as helping them overcome four main challenges: 1) visualizing how branches can rotate around nodes; 2) reading tree using the nodes rather than just the tips; and 3) mapping a species lineage from tip to root of a tree; and 4) identifying informative bends and structures in a tree from uninformative features.

---

<sup>2</sup> In week eight reflection question five, students were asked to select up to two instructional interventions that they perceived as being most helpful in improving their tree thinking in the course. Therefore, percentages of students that found each activity most helpful may add up to over 100%. Additionally, students were not limited to the three instructional activities described in this section. Rather, they were allowed to select any instructional activities presented in class that they perceived as helpful.

### *Pseudocot Fossil Activity*

I designed hypothetical flowering plants, Pseudocots (Figure 37), to facilitate student development of tree building skills, making predictions from phylogenies, and ancestral state reconstruction. My specific goals for this instructional intervention were:

- Students will be aware of limitations in predicting ancestral character states from a phylogenetic tree.
- Students will be able to identify informative character states used to develop phylogenies.
- Students will be able to generate a phylogenetic representation illustrating accurate evolutionary relationships among hypothetical flowering plants.
- Students will be able to transfer empirical data from fossil records into a phylogenetic tree.

The Pseudocot fossil activity was completed in class. Students were allowed to work in groups of two or three. The instructor provided the students with a phylogenetic tree. From this tree, students predicted ancestral states, compared their prediction to a fossil record, and developed a phylogenetic tree using ages and morphological data of 15 Pseudocot species. In order to create a tree, the students were instructed to fill out a data matrix with morphological character states and group organisms by looking for derived character states. Upon completion of the activity, all of the students entered into a class discussion about the activity and the instructor reviewed how scientists would approach this problem as a comparison for the students to reflect upon how they approached the scenario.

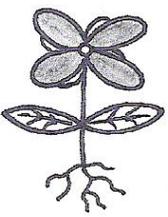
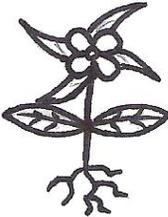
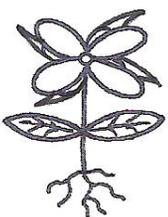
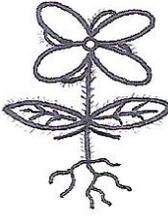
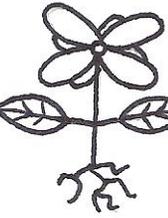
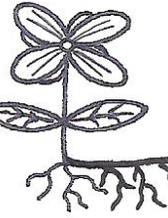
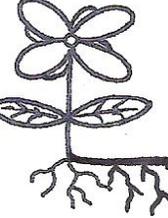
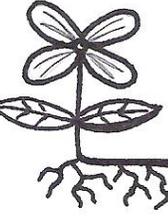
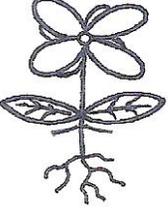
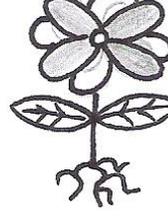
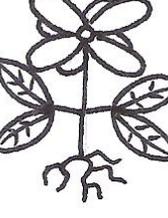
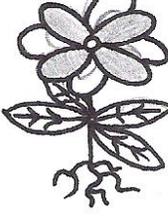
 <p>Species 1 5 MYA</p>	 <p>Species 2 1 MYA</p>	 <p>Species 3 16 MYA</p>	 <p>Species 4 4 MYA</p>	 <p>Species 5 7 MYA</p>
 <p>Species 6 17 MYA</p>	 <p>Species 7 25 MYA</p>	 <p>Species 8 6 MYA</p>	 <p>Species 9 14 MYA</p>	 <p>Species 10 2 MYA</p>
 <p>Species 11 18 MYA</p>	 <p>Species 12 13 MYA</p>	 <p>Species 13 9 MYA</p>	 <p>Species 14 11 MYA</p>	 <p>Species 15 20 MYA</p>

Figure 37. Pseudocot fossil record. (MYA – Million Years Ago)

Student perceptions of how this activity helped improve their tree thinking varied greatly across the students. However, the consistent trends in students' statements focused on how this instructional intervention provided a structured way to generate phylogenetic trees and helped them understand how to interpret phylogenetic trees. For example, Mitch stated that this activity helped improve his tree building ability. "This activity helped me in drawing an actual tree based on just the characteristics of a taxon and in understanding the relationships based the characteristics shared." The Pseudocot fossil activity allowed students to practice tree reading by having them make predictions and consider how the taxa were related. Bob stated that this activity improved his comfort with tree reading. "The fossil exercise involved a lot of critical thinking, allowing me to become more comfortable with interpreting trees." Furthermore, this activity improved students understanding of why phylogenetics is important for biologists. For example, Emily stated, "Backwards thinking helped me understand how trees are made and their importance, because we can know our evolutionary history and similarities/differences between organisms."

Another trend that emerged from the data focused on the importance of the review portion at the end of this activity. This review discussion was considered critical for some students in helping them make sense of tree building with these Pseudocots. For example, Sally stated,

I liked the fossil activity, but not while I was doing it. I was having trouble combining physical characteristics with the time factor. Too many variables for my mind to assimilate. But later when we discussed it, things made more sense and now I think I understand things more clearly.

Likewise, Brenda also stated how she thought the class discussion after the activity was essential to her learning:

When first handed to me, I felt very overwhelmed, but after going over [the fossil activity] in class, it gave me a better understanding of how to reconstruct a tree from a fossil record and to assign apomorphies and synapomorphies.

Student responses suggested that modifications to this activity would have increased the effectiveness of this instructional intervention. For example, Karen stated that this activity improved her understanding of the types of data that were informative for developing phylogenies and how multiple hypotheses can be developed from the same data set.

When we constructed phylogenetic trees from an ancestral species I was able to better understand how scientists create these trees. In the past I thought it was all based on genetics. Little did I know, genetic information is expensive and only more recently available. This assignment also helped me view how mistakes can be made and independently derived apomorphies can be overlooked. Sometimes it seems that two things are closely related, but really they derived from completely different lineages.

However, she thought that the activity would have helped her tree building improve more if the students could:

Share the trees with those around us in class. That way we could see how different our tree is compared to someone else's. Our trees would be different even though we are using the same supply of information. I can't imagine how different the trees turn out when scientists are using a variety of resources to create a phylogenetic tree.

By sharing trees with others in class, she thought the activity would have helped her compare different approaches students used and see how others reconciled instances of conflicting data.

During the week eight reflection prompt, over half of the class (52% or 14 students) perceived this instructional intervention as the most helpful activity in improving their tree thinking. However, while this activity was designed as an

instructional intervention to improve tree building, students' statements focused on how they perceived this instructional intervention as helping them improve in four main areas, three of which related to tree reading: 1) interpreting phylogenetic trees; 2) identifying and using informative data; and 3) recognizing the importance of phylogenies. And only one of their reasons had to do with generating phylogenetic trees. The Pseudocot fossil activity was administered during the same week of instruction as the Whippo activity.

### *Whippo Activity*

I modified an instructional intervention from the Whippo problem space developed by the BioQUEST Curriculum Consortium (2006) (Appendix K). This problem involved using data to resolve conflicting hypotheses about the hippo phylogeny. The specific goals of this intervention were:

- Students will be able to read multiple styles of representations
- Students will recognize clades in multiple phylogenetic trees and compare those patterns in order to accept or reject a hypothesis

In this instructional intervention, students were presented with a current scientific debate: Are hippos more closely related to whales or artiodactyls (even-toed ungulates)? The students read a related article (Gatesy & O'Leary, 2001) as a homework assignment and discussed the problem as a class. Then students were divided into groups of three and considered a proposed hypothesis (see Figure 38) in relation to phylogenies generated from multiple data sources (e.g., skeletal/dental, cytochrome b, and 16SrDNA). Students compare each data source to the hypothesis and selected which nodes, if any, were supported. After students reached their conclusions, the instructor led a class discussion about how scientists search for support for hypothesized phylogenies and reviewed the correct answers to the Whippo activity.

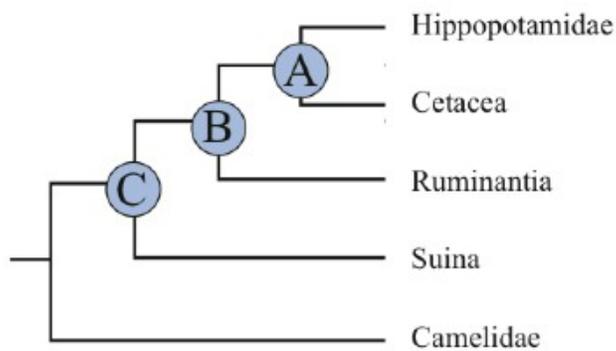


Figure 38. Proposed Whippo hypothesis.

In the week eight reflection prompt, about 44% of the class (12 students) perceived this activity as being helpful in improving their tree thinking in the plant systematics course. These students found this activity improved their understandings of monophyletic groupings and comparing clades across trees. For example, both Maggie and Cameron perceived that their skill in comparing trees was improved by this activity. Maggie stated, “The Whippo activity helped me really clarify monophyletic groupings better.” Likewise, Cameron stated that this activity helped him with tree reading and identifying sister groups:

The [activity] helped me out because I can look at a tree and determine sister groups and other things better. Also, the Whippo activity was helpful because like problem four on this assignment about if clade A doesn't have to be true if you are looking at clade B.

Other students commented on how they perceived this activity as improving concepts that were not the main goal of the activity. For example, Emily stated,

Whippo was helpful in the sense when I understood the concept of exclusion, and when there is a common ancestor to two groups, it is to these two groups that this ancestor is an ancestor to, and it is important to know that any mix/allowance of another branch or species is not allowed.

Mitch perceived this activity as most influential in improving his understanding that the orientation of phylogenetic trees did not influence relationships represented. He stated that his overall tree reading improved because,

This activity helped me understand the relationships between taxa in a horizontal tree and comparing that to a vertical tree and also helped me understand the relationships between the nodes in the tree better.

As with the Pseudocot fossil activity, students perceived the follow-up discussion of the activity as helpful for understanding the learning objectives for the Whippo activity. Before the class discussion, students perceived the Whippo activity as the most confusing activity, and many were confused and/or used alternative criteria for comparing phylogenetic trees. However, after the class discussion and review of correct answers, students perceived this activity as helpful in improving their tree thinking. For example, Sally stated,

Recently in class we looked at the Whippo activity in more detail. This helped a lot. I think what helped the most was discovering the misconceptions that others had and clearing them up because I had many of the same problems. The tree representing A, B and C as configured in a way that made things a little confusing, but maybe that's a good thing because we then had to go over it and now I understand things better.

Likewise, Cameron stated, "I didn't understand it fully until Dr. Pires explained it."

The Whippo activity provided additional value in improving students' understandings when viewed in connection with the other instructional interventions. For example, Aimee discussed how she perceived the Pseudocot fossil activity and Whippo activity as complementary to one another. She commented that without both activities, she would not have achieved the intended learning outcomes for each individual activity.

The Whippo activity definitely helped me understand how certain data can support phylogenetic tree information once we went over it in class. Then, once I understood that activity I finally understood the fossil activity that

we did earlier in the class with the flower cartoons. Using an actual, labeled, timeline to help place the unknown, extinct flowers with the known ones made it logical in my mind.

Students' statements about the Whippo activity focused on how they perceived this instructional intervention as helping them improve understanding in four main areas: 1) Recognize clades represented in a phylogenetic tree; 2) Compare patterns in clades across phylogenetic trees; 3) Transfer meaning across styles of phylogenetic representations; and 4) Understand what constitutes support for a hypothesized phylogeny.

### *Summary*

During the plant systematics course, students were exposed to three instructional interventions explicitly targeting known challenges students' face with tree thinking. Most students identified each of these interventions as helpful in improving their tree thinking skills. Their perceptions of how these activities improved their tree thinking varied according to each task. Not all students' perceptions of improvement were aligned with the instructor's learning objectives. For example, the instructor's goals for the Whippo activity were to recognize clades in multiple phylogenetic trees and compare those patterns to accept or reject a hypothesis. However, Mitch perceived this activity as improving his skill in reading one tree positioned in different orientations, vertical or horizontal. Regardless, according to the students, these three instructional interventions did improve their tree thinking. Collectively, these interventions were perceived as helping students: provide a context for phylogenetic representation, define the informative parts of the representation and introduce the symbolic meaning of each part, visualize how branches can move within the 3D representation, map individual lineages

within a representation, transfer evidence of phylogenies into a phylogenetic tree, and compare patterns of relationships across representations.

### Essential Tree Thinking Skills

Being able to correctly interpret phylogenetic trees is a critical skill in developing tree thinking. Student performance in this study suggests that there are two sets of core skills necessary for developing representational competence in tree thinking. To be a highly competent tree thinker, students must develop core skills essential to both tree reading and tree building. I analyzed the full informative data set (see Table 5) from the entire semester to address my final research questions: “What are the core skills essential for students to develop competence in tree thinking?” I identified essential core skills by investigating students’ tree thinking progression over the course of the semester. Then, I searched for patterns of skills that students developed and used over the course of the semester as well as the tree thinking skills used by the expert instructor. After identifying tree thinking skills used, I condensed the skills into two sets: tree reading and tree building. After identifying core skills, I conducted member checks with two key informants to ensure my interpretations were consistent with how students reflected upon their own learning of tree thinking.

Three major patterns emerged from the data: 1) Sixteen core skills were essential for students to develop tree thinking competence; 2) Tree reading skills developed before tree building skills; and 3) Students’ became better tree readers than tree builders by the end of the plant systematics course. In the next sections, I describe and provide evidence for each core skill set.

### *Tree Reading Core Skills*

Emergent trends from the data revealed shifts in the rationales students used when interpreting and comparing phylogenetic trees over the course of the semester. For example, students who interpreted phylogenetic trees based on the proximity of organisms along the terminal tips or on knowledge about ecology tended to shift their rationale to rotation-based interpretations by the end of the course. This trend illustrates a shift from students using superficial location of taxa along the tips of the representation or ignoring the representation when forming conclusions about relationships among the taxa, to acknowledging scientific meaning in the representation and recognizing the mobile nature of trees. Another trend showed that students who began the course using a nodal emphasis rationale when interpreting trees shifted their rationale to focus on implied apomorphies and common ancestry by the end of the course. While these students still used the nodes to interpret relationships illustrated on the tree, they learned to recognize the symbolism of these intersections to represent common ancestry and divergence events. By probing students' understandings throughout the course and observing students' tree reading abilities, I identified the following core skills that were essential for students to develop as they became tree readers. In order to accurately read phylogenetic trees, a student must be able to:

- Recognize key features/parts of a simple phylogenetic tree (e.g., branches, nodes, and time);
- Understand the symbolic meaning of each part and the representation as a whole;
- Understand the meaning of patterns represented (e.g., monophyletic and paraphyletic groups);
- Apply understandings and interpret relationships represented on a simple phylogenetic tree in terms of evolutionary relationships represented;
- Transfer this understanding to different styles and more complex representations;

- Make comparisons of similarities and differences in patterns across representations;
- Select a representation that is appropriate to support a specific phylogenetic scenario;
- Use a phylogenetic tree as evidence to support claims, draw inferences, and make predictions about phylogenies.

Next, I describe evidence of these skills through examples of students using tree reading skills and instances where students had not yet developed specific skills. For example, at the beginning of the course, Emily and Aaron did not know the parts or meanings of informative features on a phylogenetic representation. They learned phylogenetic terminology during the first month of the plant systematics course. Thus, at the start of the course, each of these students ignored the represented relationships and provided responses to tree reading questions based on their knowledge of the ecology of each organism presented on the tree. For example, Aaron selected two organisms as most closely related because they “both are reptiles,” although this was not consistent with the relationships represented by the phylogenetic tree.

At the beginning of the course, nearly half of the students (44%) recognized key features of phylogenetic trees but were unfamiliar with the symbolic meaning of each feature or the meaning of patterns represented. Miranda was able to define key features of a phylogenetic representation. However, she was not able to apply her understandings of these features when interpreting a phylogenetic tree. For example, she stated, “In tree 1, A and B are closer related to F. In tree 2, A and B are further related to F,” (see Figure 39). However, in a scientific interpretation of the two trees given, Species A and B are equally related to Species F.

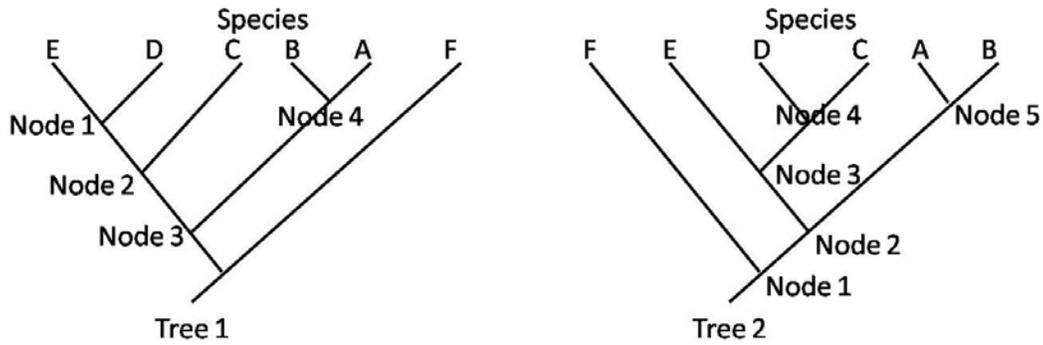


Figure 39. Explain how these two attached trees are the same or different.

Likewise, Kristen was able to recite appropriate terminology associated with phylogenetic trees and even offer definitions such as, “Monophyletic groups include a common ancestor and all their descendants.” However she did not understand what these terms/definitions symbolized on a phylogenetic tree. I coded students as understanding the meaning or symbolism of tree features when they were able to provide more than a definition but rather use that symbolism to interpret a tree accurately using the feature. Even after one month into the course, 41% students could explain the scientific basis behind clades, common ancestry, branch rotations, etc. but were unable to use these ideas when interpreting a tree. For example, at this point in the semester, Kristen interpreted trees using a main branch approach, relying upon how she perceived organisms as branching off from one another rather than how they fit within a monophyletic group. However, she was unable to build a tree. At this point in the semester, Randy, Karen, and Mitch were among the students who used references to a main line, such as Randy’s statement “when a branch separates from the main line,” when explaining their responses to tree reading problems.

Prior to tree-thinking instruction, Brandt’s responses to tree reading questions suggested that he counted the number of nodes to determine relationships between the

terminal tips of a tree regardless of presence or absence of taxa. For example, in answer to question one (see Table 6), he stated that a seal is more closely related to a horse than to a whale because “the divergence on the lineage that led to the horse is only one up from the seal.” Aaron understood branches represented lineages and these could rotate around nodes. However, his understanding was flawed and he thought that these rotations altered relationships as well as the physical tree orientation. These students were able to recognize and define informative features of phylogenetic trees. However these students did not understand the meaning of patterns represented within the tree.

Jeremy relied on common ancestry to read an individual tree. He could verbally describe relationships on a given tree in addition to recognizing and defining informative features of the tree. However, when he tried to compare patterns across phylogenetic representations, he focused on differences in patterns of branching or the style of representation. If the tree appeared to have more bends in the branches then he considered that representing different patterns of relationships regardless of the actual relationships represented among the taxa. He was not able to make comparisons of patterns across trees or transfer their understandings to different styles of representations.

Chip used scientific reasoning to read and compare phylogenetic trees accurately over the course of the entire semester. For example, he interpreted relationships based on common ancestry and compared phylogenetic representations accurately based on patterns of clades regardless of the style of the representation. Chip was also able to select appropriate representations to support a given phylogenetic scenario and use trees to make predictions and support claims. For example, during the interview, Chip selected a phylogenetic tree as being most appropriate to show relationships among species over

examples of historic representations and flow charts. He stated the tree was “easy to read” and was good “to show relatedness between different taxa.” He was critical of the other models and thought they “would be very difficult to show time” and the flow chart was problematic because it showed taxa evolving into other taxa. Chip also used phylogenetic trees to make predictions about ancestral states and how new species could be integrated into an existing phylogeny.

In order for students to read phylogenetic trees accurately, they must develop eight core skills. Students must first be able to identify, understand and apply meanings to interpret trees. Once this foundation is in place, students must develop more advanced skills such as using a phylogenetic tree to support claims and draw predictions to become an expert tree reader.

#### *Tree Building Core Skills*

A second critical component to developing tree thinking involves being able to accurately build phylogenetic trees. Emergent trends from the data revealed shifts in the styles and types of representations students generated when interpreting phylogenetic scenarios over the course of the semester. The types of representations students generated were consistent with the approaches they used to interpret and compare phylogenetic trees. For example, students who generated a single progressive tree, interpreted relationships represented in phylogenetic trees using a main branch approach. By probing the steps students took to generate representations and their interpretations of their representations throughout the course, and by observing students tree building activities, I identified the following core skills that were essential for students to develop as they became tree builders. These skills do not represent a linear developmental trajectory, however they do build upon the foundational tree reading skills discussed earlier. In order to accurately generate phylogenetic trees, a student must be able to:

- Interpret phylogenetic trees and recognize how patterns of relationships are represented;
- Prioritize informative evidence from non-informative evidence as it relates to interpreting phylogenies;
- Transform raw data into evidence of shared evolutionary histories and derived character states;
- Use that evidence to construct a visual representation, symbolic of evolutionary relationships;
- Use evidence to create a parsimonious representation;
- Create consensus nodes/polytomies to illustrate discrepancies in the data;
- Organize hierarchical branching structures as necessary to represent the supported phylogenies;
- Use words to describe the relationships represented in their phylogenetic tree and justify their representation.

Next, I describe evidence of these skills through examples of students using tree building skills and instances where students had not yet developed specific skills. For example, Roger was unable to generate any type of visual representation at any point during the course. And, at the beginning of the course, Aaron drew a literal image of the given organisms and described the ecological relationships they shared. Neither student had past experience with phylogenetic trees. Over the course of the semester, students enrolled in the plant systematics course were guided through numerous tree building activities, during and outside of class time. However, by the end of the semester, Roger was still unable to generate a visual representation. At this point, he misinterpreted patterns of relationships represented on phylogenetic trees and did not understand how to transform raw data into a visual representation symbolizing how taxa shared evolutionary histories. These students had not developed core tree reading skills and were unaware how to infer phylogenies from a given set of taxa.

At the beginning of the course, Brandt constructed a phylogenetic tree depicting the relationships among multiple flora and fauna, he generated a single representation that was comb-like and divided organism by taxonomic type (see Figure 40). Furthermore, the empty terminal tips suggested the presence of main branches. He provided no rationale for his representation. Additionally there were three organisms left off of the diagram completely: dolphin, oak tree, and fly. At this point in the semester, Brandt had also not developed all of the identified tree reading skills. During my initial interview with Brandt, he admitted that the tree building questions were difficult for him at the beginning of the course because he had “no idea how to go about doing that.” He reviewed his initial tree from the pretest and told me that he should have based the relationships on apomorphies and modified the branches so that all of the organisms were derived from a single lineage. When I asked him to construct a new tree, Brandt initially drew a single line along a blank page to begin his phylogenetic tree. This action suggests the idea of a “main branch.” When probed why he took this action, Brandt responded, “It’s like a reference. I can’t remember the term, maybe it’s an out group.” He went on to add branches based on how he thought the taxa might be related and commented that, “this looks like a ladder, I don’t like it.” So while he recognized that his representation was comb-like in nature, he did not take measures to correct this issue.

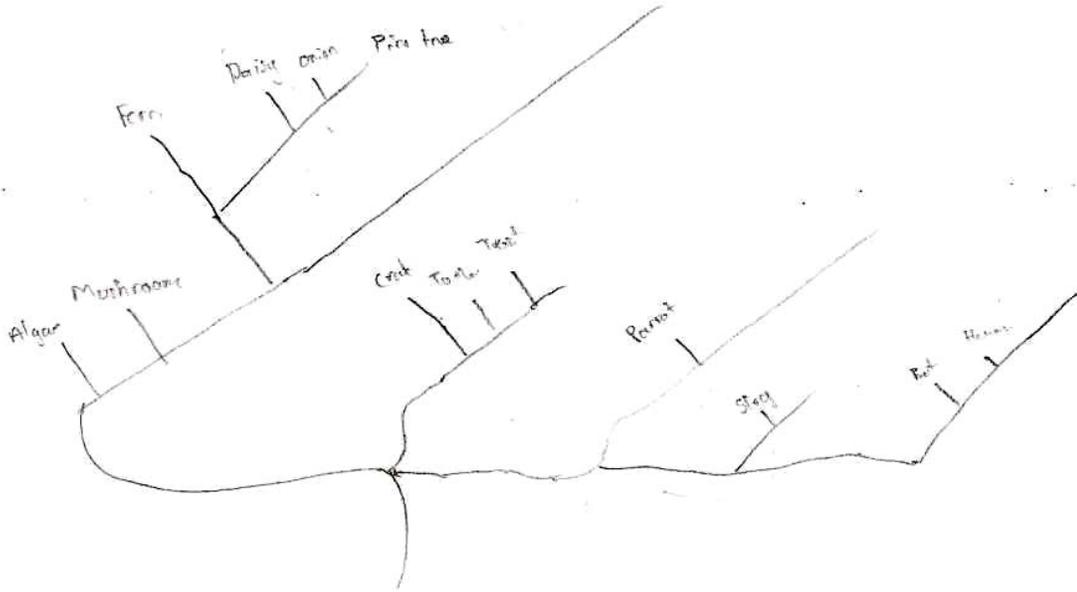


Figure 40. Brandt's representation at the beginning of the course.

Tree building remained problematic for Brandt even after Dr. Pires had the class participate in a tree building activity using hypothetical flowering plants and a data matrix. Initially, Brandt tried to incorporate all data available when generating a comb-like tree diagram similar to his representation on the pretest. However after multiple tree building opportunities, Brandt did show initial evidence of purposeful selection to isolate appropriate phylogenetic data. "I don't like the characteristics on this data matrix. I'm not sure if things like location or being edible make for good data when constructing phylogeny. I don't think me being able to eat tells me much of its evolution, but maybe I'm wrong." His data selection process was refined after completing the Pseudocot fossil activity. By the end of the course, Brandt consistently used only informative data to help understand evolutionary relationships among organisms. When asked how he would help someone else understand tree building, he offered a vague response that did not explain how one could transition from data to a data matrix to a phylogenetic tree representation.

This led me to believe he did not fully understand the processes involved with tree building.

At the end of the second interview, we discussed the differences between tree reading and tree building. Brandt offered his insights:

I think tree building requires you to have a better understanding of it. Reading, it is just given to you, but with building it takes a bit more knowledge of it. [the skills used for reading and building] should be [the same] but at the same time you have to take all of this data and make sense of it and sort it and then throw it onto a piece of paper but when you read a tree all you have to do is look at what is already organized. For students to understand it more I think you should have them draw trees even though it is tougher.

As Brandt described, tree building is cognitively a more difficult task that requires a core skill set that builds upon tree reading skills.

Sally and Jamie recognized key features of phylogenetic trees, however they did not view nodes as symbolizing hypothetical common ancestors, a point of shared evolutionary history. These students generated several independent trees to represent a single phylogenetic scenario at the end of the course. They explained that these trees represented two groups of organisms unrelated to the other or having such a historic relationship they should not be connected on the same tree. Rather than separating the organisms into different representations, scientists would have included all of the given taxa onto a single “tree of life.” This indicated that these students were not able to transform data into evidence of shared evolutionary histories.

Bob generated a representation at the beginning of the course that was consistent with building a phylogenetic tree. He also had previous experience with reading trees. By the end of the course, Aimee and Chip had developed each of the core tree reading and building skills sets. Aimee used her understanding of phylogenetics to generate a

rectangular phylogenetic tree that represented accurate relationships among the plant taxa (see Figure 30). Furthermore, both students were able to describe their trees and redraw them in various styles and orientations while maintaining the integrity and hierarchy of the relationships represented. For example, during Chip's second interview, he developed a diagonal tree of 15 extant Pseudocot species, three extinct species, and an out group. He was later able to alter his diagram accurately to accommodate a new species and redrew the phylogeny as a rectangular diagram with several of the branches rotated around the nodes. Additionally, he was able to describe his scientific thought process while he was developing the representation and making alterations to accommodate the evidence provided.

A set of eight core skills is required for student to become expert tree builders. These skills range from recognizing and interpreting patterns in phylogenetic trees and progress toward being able to turn informative data into evidence of phylogenies via a hierarchical branching visual representation.

### *Summary*

Systematists are acknowledged as expert tree thinkers who can both read and build phylogenetic trees accurately. I identified specific critical skills necessary for tree reading and tree building in the plant systematics course investigated. These skills do not reflect a developmental trajectory within each aspect of tree thinking. However, tree reading and tree building represent tasks of varying levels of difficulty; tree building is more conceptually difficult. I found that tree reading skills were foundational to tree building skills. For example, at the beginning of the course Roger read trees based on superficial interpretations and he could not develop a representation at the beginning of

the course. By the end of course Roger used his understanding of branch rotation to read trees inaccurately, but was still unable to generate a representation without constant guidance. Students who had not developed tree reading skills were not able to build phylogenetic representations accurately, and students who were able to generate advanced phylogenetic representations were able to read trees.

### Summary of Interpretations

#### *Sub-Research Question 1: Students' Incoming Ideas*

Students entered the plant systematics course with multiple alternative understandings about phylogenetic trees. I identified seven approaches to interpreting phylogenetic trees emerged from the data at the beginning of the plant systematics course: main branch, proximity of terminal tips, common ancestry, knowledge of organisms, nodal emphasis, unidirectional reading, and physical measurements. Common ancestry was the only scientifically accurate approach. Many students also inaccurately placed an implied time scale on phylogenetic representations. These students perceived time as progressing in one of three alternative directions. I also identified five criteria students used to compare phylogenetic representations at the beginning of the course: physical branching patterns, style of representations, clade comparison, branch length similarities/differences, and patterns in tip proximity. Clade comparison was the only scientifically accurate approach. No students generated an accurate phylogenetic representation to illustrate a given phylogenetic scenario at the beginning of the course. Students either could not complete the task or generated one of eight types of representations: folk taxonomy classification, single progressive tree, separate trees segregating organisms, flow chart, single tree with taxa along branches,

inaccurate phylogenetic diagram, written lists of organisms, or drew a picture of the organisms. Student generated representations were often consistent with the approaches and criteria used for tree reading.

*Sub-Research Question 2: Improvements in Students' Tree Thinking*

By the end of the semester the majority of students (67%) consistently used scientific approaches to read trees. These students recognized the scientific meaning of common ancestry and monophyletic groupings. There was also a substantial improvement in how students placed an implied time scale on a phylogenetic tree – 85% of students could place time on representations accurately. Students also improved tree comparison skills. By the end of the semester, over two thirds (70%) of students used the clade comparison criterion when comparing phylogenetic representations. Three trends emerged related to shifts in the types of student generated representations: 1) 15% of students generated less accurate representations; 2) 30% of students generated similar styles of representations; and 3) 55% of students generated more appropriate representations (37% of all the students generated scientific representations). Overall, students tree thinking improved by the end of the semester. Specifically, students showed more improvement in tree reading than tree building

*Sub-Research Question 3: Students' Perceptions of Instructional Interventions*

During the plant systematics course, student participated in three instructional interventions targeting tree thinking challenges. Students perceived all three instructional interventions as helpful in improving their tree thinking. These interventions provided a context for phylogenetic representations, helped students identify and define the key features of phylogenetic representations, explained the symbolism of each feature,

facilitated students' visualization of how branches can rotate around nodes and lineage mapping, allowed practice with transferring evidence of phylogenies into a phylogenetic tree, and offered a change to compare patterns of relationships across representations.

#### *Sub-Research Question 4: Core Skills for Tree Thinking*

I identified 16 core skills divided into two sets essential for students to develop tree thinking. I organized these skills into two core skill sets, one for tree reading and one for tree building.

##### *Tree Reading Skills*

- Recognize key features/parts of a simple phylogenetic tree (e.g., branches, nodes, and time);
- Understand the symbolic meaning of each part and the representation as a whole;
- Understand the meaning of patterns represented (e.g., monophyletic and paraphyletic groups);
- Apply understandings and interpret relationships represented on a simple phylogenetic tree in terms of evolutionary relationships represented;
- Transfer this understanding to different styles and more complex representations;
- Make comparisons of similarities and differences in patterns across representations;
- Select a representation that is appropriate to support a specific phylogenetic scenario;
- Use a phylogenetic tree as evidence to support claims, draw inferences, and make predictions about phylogenies.

##### *Tree Building Skills*

- Interpret phylogenetic trees and recognize how patterns of relationships are represented;
- Prioritize informative evidence from non-informative evidence as it relates to interpreting phylogenies;
- Transform raw data into evidence of shared evolutionary histories and derived character states;
- Use that evidence to construct a visual representation, symbolic of evolutionary relationships;
- Use evidence to create a parsimonious representation;

- Create consensus nodes/polytomies to illustrate discrepancies in the data;
- Organize hierarchical branching structures as necessary to represent the supported phylogenies;
- Use words to describe the relationships represented in their phylogenetic tree and justify their representation.

Tree building is a cognitively more complex task than tree reading and builds upon tree reading skills. To be a highly competent tree thinker, students must develop both sets of skills.

## CHAPTER FIVE: DISCUSSION AND IMPLICATIONS

The purpose of this study was to understand how undergraduate college biology majors use phylogenetic representations in a plant systematics course and developed tree thinking. I accomplished this by investigating students' incoming ideas about phylogenetic trees at the beginning of a course on plant systematics, describing how students' ideas developed over the course of the semester, determining what instructional interventions students perceived as most influential in improving their tree thinking, and identifying core skill sets for tree reading and tree building. This chapter includes: a) a comparison of the findings in relation to the literature discussed in chapter two, and a discussion of how this study contributes to the bodies of literature on student learning with representations in biology; b) a proposed framework of seven levels of representational competence associated with tree thinking that emerged from the data; c) implications for tree thinking instruction; d) recommendations for future science education research; and e) conclusions.

### Contributions to the Literature

Current tree thinking research takes a holistic approach and investigates tree thinking as a culmination of tree reading and tree building. This study utilized a more in-depth and expanded approach to studying tree thinking. My analysis broke down tree thinking into two main categories: tree reading and tree building. Furthermore, I expanded tree reading into different aspects: interpretation and comparison. This view of tree thinking allowed me to diagnose student problems within specific areas of tree thinking and identify essential skills. Thus, this study presents a more in-depth analysis

of student tree thinking than previously reported in the literature. In the following sections, I compare trends in my findings to the reported literature.

### *Students' Tree Thinking Approaches*

Based on the interpretations of the first research question, this study reported that students relied more upon foundational misunderstandings than previously described in the literature. Researchers are aware that students often rely upon superficial features of biological representations when making meaning of a representation (e.g., Patrick et al., 2005). For example, Baum et al. (2005) investigated how students failed to see patterns of evolutionary relatedness because of the topology of phylogenetic trees. They proposed that students misunderstood these trees because they relied upon tip proximity and “read across the tips,” assuming the organisms that appeared closest to each other physically were most closely related. Others (Gregory, 2008; Meir et al., 2007; Omland et al., 2008; Perry, Meir, Herron, Maruca, & Stal, 2008) suggested that students were simply reading trees across the tips from left to right.

The type of approaches students use can cause them to generate a variety of responses when interpreting and using phylogenetic trees. Current quantitative assessment instruments (e.g., Baum et al., 2005) fail to uncover the underlying reasoning patterns students use to answer tree thinking questions. In this study, I found that student errors often prevail due to deeper conceptual misunderstandings about the relationships depicted on the tree representation. Thus, while a student may appear to “read across the tips,” they may hold a deeper biological-based misconception, or he/she may base ideas upon perceived ecological connections. For example, while a student may appear to identify evolutionary relationship by considering species proximity on a phylogenetic

tree, in actuality, the student may hold a deeper biological-based misconception or base his/her ideas upon perceived ecological connections. Such an approach can be masked by misconception defined error categories such as “reading the tips.” I found that proximity did interfere with some students’ reasoning, but this was not the only, or primary, challenge associated with tree thinking. Four of the alternative tree thinking approaches I identified were consistent with misconceptions reported by Gregory (2008) and Baum et al. (2005): main branch, proximity of terminal tips, nodal emphasis, and unidirectional reading. Students using these approaches were using the representation to draw conclusions about the relationships shown. However, these students also demonstrated a lack of understanding of the symbolic meaning behind the parts of the phylogenetic trees and superficially interpreted the representations. Thus, my study confirmed and extended some of the claims existing in the current literature.

My study contributes to the literature by identifying four new alternative student approaches to tree thinking not previously reported: knowledge of organisms, physical measurements, rotate branches, and implied apomorphies. These approaches are not completely consistent with systematic ways of interpreting phylogenetic trees. For example, the *knowledge of organisms* approach went beyond misreading the topology of phylogenetic trees. My findings indicated that when students using this approach were presented with a question about a phylogenetic tree, not all students thought the tree contained the information to answer the question. Instead, these students relied upon their prior knowledge of the ecology or morphology of the organisms represented on the tree to draw conclusions. These students did not recognize the type of information in the tree or its usefulness in understanding how taxa were related to one another. Students

using the *physical measurements* approach lacked an understanding of the symbolic meaning of branch arrangements. These students focused on measuring distance of taxa from the root of the tree or from the most recent node rather than proximity of tips to one another. With the *rotate branch* approach, I found that students understood the symbolic meaning of the key features of the representation. However, these students inaccurately applied rotation principles which interfered with their tree reading. The students who used the *implied apomorphies* (derived character states that distinguish clades) approach interpreted phylogenetic trees accurately and understood the symbolic meaning behind the key features of the representation. However, these students drew their conclusions based on information not included on the representation, but rather using apomorphies and synapomorphies they projected onto the representation. While this approach is not technically inaccurate, it does demonstrate how students can rely on information not presented within a representation when drawing conclusions from phylogenetic trees. My study contributes to the literature by expanding the known student misconceptions with tree reading. Having an inclusive collection of student approaches to tree reading allows teachers to provide more informed instruction. By understanding how students make sense of phylogenetic trees, instructors can be better prepared to counter alternative approaches and present scientific interpretations explicitly.

Previous studies (e.g., Gregory, 2008; Meir et al., 2007, Omland et al., 2008; Perry et al., 2008) reported students struggled with transferring the concept of time onto trees. My investigation confirmed that students struggle with placing time on the representation, particularly at the beginning of the course. Additionally, I found that the manner in which individuals identified time on phylogenetic representations impacted

their interpretations of the representation. When students engaged in the pipe cleaner activity and traced lineages from a tip of a tree to the root, they were able to accurately transfer the direction of time onto multiple types of phylogenetic representations. And, by the end of the course, 85% of the students correctly indicated the orientation of time on a phylogenetic tree. Thus, these students showed improvement in identifying an essential feature of the tree accurately and overcame a potential challenge with tree reading. My study goes beyond identifying problems and studies students' perceptions of how instructional interventions helped improve their tree thinking.

The Whippo activity (BioQUEST) assumed that students used clade comparisons when comparing phylogenetic representations. However, one study (Novick & Catley, 2008) found that students struggle with the notion that altering the format or orientation of the tree does not alter the relationships. My investigation found that only a small percentage of students (19%) at the beginning of the course used the clade comparison criterion to compare phylogenetic trees. Most students relied upon alternative criteria when comparing representations. It is imperative that students are able to recognize patterns when comparing phylogenetic trees. If a student cannot recognize patterns within the tree, then they will not be able to accurately test hypotheses presented; as was the scenario for students in this course. My conclusion adds to the literature because investigations of how students compare phylogenetic representations have not been previously reported.

Identifying how students build trees is another area that must be addressed in order to fully understand how students develop tree thinking. Gendron (2000) published a lesson to facilitate students' tree building. In this lesson, Gendron assumed that

students could read phylogenetic trees and would generate appropriate styles of representations. This is an example of a published activity that lacks a grounding in the research on the core skills necessary for student to learn tree thinking, such as beginning with tree reading. O'Hara (1998) documented that students do not always generate appropriate phylogenetic trees. I investigated the styles of representations students generated in an upper level plant systematics course and found students generated eight alternative styles of representations. Thus, students failed to generate representations in the same manner as scientists. Evolutionary biologists recognize the roles of descent from common ancestry and evolutionary adaptation in establishing patterns of similarity and differences among groups of organisms when developing phylogenies. But students struggle with understanding and developing phylogenies. By identifying the ways that students approach tree building, I was able to diagnose student challenges with tree building.

Cavallo (1996) and Tabachneck et al. (1994) proposed the idea of an essential connection between representations and tree reading approaches used. In this study, I also found a connection between students' tree reading approaches and the types of trees they built. Student ideas about evolution impacted the way students visualized evolutionary relationships among organisms. For example, I found that if students viewed evolution as progressive, they tended to interpret trees in a directional manner and generated ladderized or flow chart representations. However, I did not investigate students' tree thinking in terms of predicting their problem solving ability or their understanding of advanced evolution and systematics concepts. Investigations of tree building are largely missing from the current literature. By using an expanded view of

tree thinking, my study contributes to the literature on how students' ideas about evolution are reflected in their representations and how they approach tree building tasks different from scientists. This is important to report because it provides evidence that students' tree thinking and tree building are interconnected and not two completely separate ways of viewing evolutionary relationships.

### *Tree Thinking Challenges and Instructional Interventions*

Research has shown multiple areas in which interpreting phylogenetic trees is difficult for students (e.g., Baum et al., 2005; Gregory, 2008; Halverson et al., 2008; Meir et al., 2007; Omland et al., 2008). I was able to identify additional challenges in tree thinking development through my expanded analysis of tree reading and tree building approaches. After comparing my findings with those reported in the current literature, I identified 13 major challenges students encounter when developing tree thinking skills:

- Overcoming prior ideas about organisms and using the representation to draw conclusions (Gregory, 2008; Halverson et al., 2008);
- Visualizing how branches can rotate (see Chapter 4);
- Reading from the tips rather than nodes (Baum et al., 2005; Gregory, 2008; Perry et al., 2008);
- Mapping a species lineage from tip to root of a tree (see Chapter 4);
- Comparing patterns of relationships among trees (Halverson et al., 2008; Novick & Catley, 2008);
- Lumping organisms based on single characteristics rather than looking holistically at the organisms (Gendron, 2000);
- Ignoring critical data and/or using uninformative evidence to construct phylogenetic trees (Halverson et al., 2008; Van Fraassen, 2008);
- Difficulties transferring empirical data into a visual representation illustrating evolutionary relationships (Gendron, 2000; see Chapter 4);
- Creating consensus nodes to address discrepancies (see Chapter 4);
- Altering the format or orientation of the tree alters the relationships depicted (Catley, Novick, & Shade, 2009; Halverson et al., 2008; Novick & Catley, 2008);

- Generating accurate, branching, hierarchical representations (Halverson et al., 2008, see Chapter 4);
- Using trees to reconstructing ancestral states (Perry et al., 2008);
- Comparing representations to identify the most supported tree (BioQUEST Curriculum Consortium, 2006).

Some instructional resources (e.g., University of California Museum of Paleontology, 2009) have attempted to address some of the listed tree thinking challenges by explaining how scientists interpret and use data as evidence to build phylogenetic trees. However, these resources do not provide opportunities for students to practice tree thinking nor do they provide scaffolds to facilitate tree building skills. Thus, while tree thinking challenges are sometimes acknowledged, they are not always explicitly addressed in ways that help students overcome the challenges and, in turn, improve tree thinking skills. Few studies focus on instructional strategies to help students overcome challenges (Gendron, 2000; Meir et al., 2005; Perry et al., 2008). There are numerous published lessons that propose activities using phylogenetic trees or are aimed at helping students develop tree thinking (over 50 published in the *American Biology Teacher* alone). However, none of these activities is grounded in research on how students overcome identified challenges or on how students learn core tree thinking skills. Additionally, published instructional activities (e.g., Gendron, 2000; Meir et al., 2005) assume students are aware that trees contain information on evolutionary histories and can interpret and build these representations. I have found that this is not the case. My study used research-based activities to help students overcome the major challenges associated with tree thinking, something novel to tree thinking instruction. Furthermore, my study investigated students' perceptions of how the research-based instructional interventions improved their tree thinking. This is the first study to investigate the impact

of instructional inventions by asking students how they perceived tree thinking activities to improve their learning. I found that the research-based instructional interventions helped students overcome challenges with tree thinking at the same time they facilitated students' development of core tree thinking skills.

The three instructional interventions described in this study were designed based on the findings of my pilot study and a review of the literature. Students perceived the pipe cleaner phylogeny activity as the most effective instructional intervention. This activity is unique -- no published activities approach tree reading using a manipulative. Upon completion of the pipe cleaner activity, the majority of students showed improvements in tree reading skills that were aligned with the activity's learning objectives. The other two activities, Pseudocot fossils and Whippo, were designed to improve tree building. Students reported these activities alone were confusing, and that accompanying discussions were required to be effective instructional interventions. Students needed more guidance for tree building tasks than for tree reading tasks.

Upon completion of my study, I revised the instructional interventions and designed a set of two tree thinking activities. One activity, pipe cleaner phylogeny, was modified to explicitly facilitate students' development of tree reading. I made several alterations to improve the effectiveness of this lesson and to explicitly target tree reading skills. Specifically, I included two new prompts: to trace a single lineage and to consider the orientation of time of different orientations of the tree. I also placed more explicit of an emphasis on identifying monophyletic groups. The other activity, interpreting Pseudocot phylogeny, was designed to facilitate advancing students' tree reading skills and development of their tree building skills explicitly. For example, this lesson

addresses challenges associated with transitioning data into a representation by providing a five step scaffold for students to building a phylogenetic tree. This scaffold includes having students complete a data matrix, reorganize the matrix to highlight patterns in the data, create a Venn Diagram of the taxa included in the matrix, draw branches representing monophyletic groups connecting each group until a hierarchical tree is generated, and comparing representations to ensure a parsimonious tree (or the best fit tree). The full lesson plans for this revised set of instructional interventions is available in Appendix L.

### Representational Competence Frameworks

Representations play a key role in mathematics, geography, and science (Cuoco, 2001; Gilbert, 2005b). This is especially true in evolutionary biology, particularly phylogenetics. Phylogenetic representations provide a natural and meaningful way to order data with an enormous amount of evolutionary information. For students to develop expertise in phylogenetics, they must cultivate representational competence by developing tree reading and tree building skills (see Chapter 4). Frameworks for representational competence or fluency have been described in chemistry education (Kozma & Russell, 2005) and mathematics education (Meyer, 2001). Both of these frameworks assume that there are different levels at which individuals interact with representations based on content specific skills associated with each level. I investigated the transferability of a chemistry education representational competence framework for use with phylogenetic trees. In Chapter 4, I identified two core skill sets for tree thinking encompassing tree reading and tree building. While the seven core skills outlined by Kozma and Russell (2005) were related to the skills I identified for tree thinking, these

skills were not all inclusive and tended to be content specific for chemistry education. I identified content specific skills necessary for students to read phylogenetic trees accurately (such as understanding the symbolic meaning of key features and transferring understandings across multiple styles of representations). I also identified a secondary skill set necessary to generate phylogenetic trees, a cognitively more difficult tree thinking task (such as using informative evidence to construct a visual representation and organizing hierarchical branching structures to represent a supported phylogeny). This second set of skills built upon students' tree reading skills. All of these skills influenced the approaches and criteria students used to make sense of phylogenetic representations as well as the styles of representations they generated.

Kozma and Russell (2005) organized the core skills for chemistry education into a representational competence framework (see Table 16).

Table 16

*Representational competence levels in chemistry education (Kozma & Russell, 2005)*

---

Level 1: Representation as Depiction
Level 2: Early Symbolic Skills
Level 3: Syntactic use of Formal Representations
Level 4: Semantic use of Formal Representations
Level 5: Reflective use of Representations

---

In this framework, Level 1 competence is achieved, “when asked to represent a physical phenomenon, the person generates representations of the phenomenon based only on its physical features. That is, the representation is an isomorphic, iconic depiction of the phenomenon at a point in time” (Kozma & Russell, 2005, p. 132). This level of competency focuses on a person's ability to generate representations, not just their ability to make sense of a representation. This initial level may be appropriate for chemistry

education, because many chemical phenomena are readily observable. However, biological evolution is a dynamic process that occurs over long periods of time and cannot be observed at a single point in time. Additionally, the Kozma and Russell (2005) framework does not account for students who fail to use representations to answer questions, as I reported in this study. For example, I found that students' prior knowledge about taxa interfered with the process of gaining representational competence. When students were familiar with the organisms on the phylogenetic tree, they used their knowledge of physical and ecological similarities rather than the information represented in the structure of the phylogenetic tree. When images or names of taxa were present, 15% of participants harbored misconceptions about the taxa that prevented them from reasoning using the representation at the beginning of the course. Third, the Kozma and Russell framework does not account for students failing to generate representations.

I interpreted students as interacting with phylogenetic trees at different levels of competence throughout the plant systematics course. I propose a tentative framework of seven levels of representational competence (Levels 0-6) that emerged from the empirically based skills I identified. I based these levels on patterns in core skill development and accuracy of students' tree thinking over the course of the semester. I observed students skills over time and I developed individual profiles of students' progression during the course and compared the profiles to identify trends. This proposed framework includes two additional levels not developed by Kozma and Russell (2005). Six of the levels were associated with student tree thinking development and one level of competence was associated with expert tree thinking as demonstrated by the instructor (see Table 17). An initial level of representational competence, Level 0,

accounts for students who do not use representations at all, an aspect missing from the Kozma and Russell framework.

Table 17

*Levels of representational competence associated with tree thinking*

---

Level 0: No Representational Competence
Level 1: Superficial Interactions with Representations
Level 2: Reliance upon a Main Branch
Level 3: Overemphasis on Nodal Symbolism
Level 4: Disconnection of Representation to Scientific Content
Level 5: Advanced Representational Competence
Level 6: Expert Representational Competence

---

Barnea and Yehudit (2000) and Kozma and Russell (2005) suggested that students' representational competence can change with the difficulty of the task. I found that tree reading and tree building represent tasks of varying levels of difficulty; tree building is more conceptually difficult. Because of the difference in difficulty levels presented by tree reading and tree building tasks, I divided the proposed representational competence framework into two separate sets, one for tree reading and one for tree building. First, I present and describe each of the levels of this proposed representational competence framework. Second, I present the number of students I identified at each level of competence at the beginning and end of the semester.

*A Representational Competence Framework for Tree Thinking*

*Level 0: No Representational Competence*

*Tree reading.* Prior knowledge about the morphology and ecology of the organisms represented on a phylogenetic tree interfered with students' abilities to recognize information presented in the representation. Thus, students at this level did not use the representation to make sense of the phylogenetic scenario depicted. Additionally,

these students viewed all phylogenetic representations as unique and could not make comparisons of similarities across the trees.

*Tree building.* At this level, students did not consider or were not able to generate a visual representation as a possible solution to a phylogenetic scenario. At most, these students generated written lists organizing taxa or a pictorial image that represented a literal translation of a phylogenetic scenario. The pictorial images represented how students understood organisms to exist in the natural world, often related to prior knowledge of ecology connected to each organism.

#### *Level 1: Superficial Interactions with Representations*

*Tree reading.* Students at this level based interpretations of phylogenetic trees on superficial features of the representation (such as uninformative bends, proximity of the organisms placed along the tips, etc.) without connections to the underlying meanings about the phylogenetic relationships illustrated. When comparing phylogenetic trees, students looked at the same superficial features and patterns to determine the similarity and differences shown among representations. So, students try to use the representation but they do not understand any of the symbolism.

*Tree building.* Students at this level recognized that scientists use representations to organize how taxa are related to one another. However, they generated representations based on folk taxonomy, or classification on morphological and/or ecological characteristics rather than evolutionary histories. These students generated dichotomous key visual representations.

### *Level 2: Reliance upon a Main Branch*

*Tree reading.* Students operating at this level generally interpret phylogenetic trees based on the idea of a main branch, with taxa branching off from a main branch and later branching off from one another. These students compare representations by looking at differences and similarities in branch length stemming from the main branch or last point of divergence. In these instances, branches, or lineages, are viewed as straight and cannot be bent.

*Tree building.* Students rely upon Lamarckian views of evolution (purposeful, progressive evolution with multiple origins of taxa) and generate flow chart representations with taxa evolving into other taxa. More advanced students at this level generate ladderized representations that more resemble phylogenetic tree representation, but still symbolize progressive evolutionary histories.

### *Level 3: Overemphasis on Nodal Symbolism*

*Tree reading.* Students at this level understand the symbolic elements associated with parts of phylogenetic trees; however, they overly emphasize nodes when interpreting and comparing phylogenetic representations. These students tend to count nodes between taxa and place importance on the location of the nodes to make sense of the phylogenetic scenario represented. In these instances, more nodes are viewed inaccurately as representing more differences between organisms. Other students at this level understood that branches could rotate around nodes, but associated rotations with inaccurate interpretations of altered relationships represented. This could be due to students misinterpreting what is included within a monophyletic group (a common ancestor and all of the associated lineages).

*Tree building.* Students separate organisms into different representations and indicated that some groups of taxa are not related to others rather than including all taxa onto a single “tree of life.” One reason for this separation is because some students do not agree that all living organisms shared a single common ancestor.

*Level 4: Disconnection of Representation to Scientific Content*

*Tree reading.* Phylogenetic trees are viewed as 2D illustrations of 3D representations and branches are able to rotate around nodes without altering the relationships represented. However, students at this level based comparisons among phylogenetic representations on the physical branching patterns. Similarities and differences are restricted to perceptions of how trees can be rotated and different styles of phylogenetic representations are often excluded from consideration.

These students were able to recognize and define informative features of phylogenetic trees and verbally describe relationships on a given tree. However, these students were not able to make comparisons of patterns across trees or transfer their understandings to different styles of representations.

*Tree building.* Generated representations begin to have hierarchical branching structures. However, these representations are flawed in that they illustrate multiple inaccurate relationships. Students were identified at Level 4 tree building competence when the relationships among the plant taxa were flawed in their generated representation.

*Level 5: Advanced Representational Competence*

*Tree reading.* Students are able to scientifically interpret the relationships illustrated within the topology of a basic phylogenetic tree based on represented common

ancestry, monophyletic patterns, and implied apomorphies separating taxa. These students consistently compared phylogenetic representations accurately based on patterns of clades regardless of the style of the representation. However, these students do not regularly use phylogenetic trees for advanced tree reading tasks such as communicating proposed hypotheses and problem solving.

*Tree building.* Students at this level of competence with tree building generate scientifically accurate phylogenetic representations with hierarchical branching structures and can justify/explain what their representations illustrate in terms of evolutionary content.

#### *Level 6: Expert Representational Competence*

*Tree reading.* This level is reserved for describing experts in the field of systematics and is not appropriate for beginning students. These scientists can quickly interpret simple and complex representations on the underlying phylogenetic meanings that trees represent, regardless of style of representation. They regularly interact with phylogenetic trees and use them to assist with advanced tree reading tasks.

*Tree building.* At this level, multiple representations are used and generated consistently to solve phylogenetic problems, explain evolutionary phenomena, and make predictions. Additionally, these scientists can identify and explain why one representation is more appropriate than another when comparing or generating phylogenetic representation. Acceptance of hypotheses is positively influenced when multiple representations support similar interpretations (e.g., high bootstrapping values).

*Representational Competence for Tree Thinking in a Plant Systematics Course*

Using this framework with my study, the majority of students demonstrated Level 2 or lower representational competence in overall tree thinking at the beginning of the course. By the end of the course, 85% of students could read trees using scientifically accurate approaches (Level 5 tree reading competence), while only 7% of students developed the same level of competence in tree building (see Table 18). Of the 7% of students at Level 5 tree building competence, all of these students were also at Level 5 tree reading competence by the end of the course.

Table 18

*Levels of representational competence exhibited by participants\**

	Representational Competence Level	Start of the Course	End of the Course
Tree Reading	0	15%	0%
	1	48%	4%
	2	44%	11%
	3	11%	4%
	4	0%	30%
	5	7%	85%
Tree Building	0	15%	11%
	1	22%	19%
	2	41%	22%
	3	15%	11%
	4	7%	30%
	5	0%	7%

\* When a student held multiple levels of competence, credit was given to each competence level represented. Therefore, percentages add up to over 100%. Due to the nature of the course and the tasks administered, I was not able to gather evidence for Level 6 competency.

The framework proposed by Kozma and Russell (2005) was based on assumed skills and progressions. The present study adds to the literature by proposing a tentative empirically based framework for representational competence for tree thinking in biology education. This framework may allow biology instructors to gain insight into

developmental shifts in tree thinking. This framework represents the next stage in thinking about phylogenetic trees and the levels must be tested before using the framework as an instructional guideline.

My proposed framework is hierarchical in nature, progressing from Level 0 to Level 6 competence, although not every level needs to be achieved – students can skip levels when improving competence. Using this framework within the context of the course I investigated, not all of the students began at Level 0. However, these students had varying exposure to phylogenetic trees in their prior course work. Still, although the level of competence students held varied by task, every students' competence level remained constant or improved over the course of the semester.

#### Implications for Teaching

In systematic biology, phylogenetic trees act as a communication tool to map and evaluate evolutionary relationships among species (Cooper, 2002). However, tree thinking is generally inconsistent with everyday thinking about biological groups and their relationships and students often struggle with making sense of these representations (Cobern et al., 1999). With the growing inclusion of phylogenetic trees in biology instruction, it is imperative that curriculum design reflects students' needs for learning how to interpret and use these representations as well as helps them overcome known tree thinking challenges. The biology curriculum must be redesigned to recognize and target content misconceptions in addition to representation-based challenges that students face when learning tree thinking.

By not providing an evolutionary framework for students to place phylogenetic representations, tree thinking instruction will be ineffective and can lead to unintended

learning outcomes (such as progressive or Lamarckian views of evolution). Rather, instructors must design instructional interventions toward explicitly developing evolutionary reasoning in addition to developing tree thinking skills early on in systematics courses. Such ideas include common ancestry and the notion of a single tree of life. In addition to identifying and targeting misconceptions about evolution and tree thinking, students must be given opportunities to explore systematics problems in ways that utilize evolutionary trees. Explicit direction on how to utilize tree thinking is necessary to help students develop high levels of representational competence.

Based on the findings of this investigation, it is important that when teaching tree thinking, tree reading skills are developed first. It is imperative that key features (such as nodes and branches) and symbolic meanings are made explicit to students and they are given opportunities to practice tree reading with multiple styles of representations. By using and talking through multiple styles of phylogenetic trees during course lectures, instructors can help students see how experts interpret and compare multiple styles of representations. My findings support that teaching pattern recognition across phylogenetic representations needs to be further explored and explicitly addressed in tree thinking instruction. This approach is consistent with instructional guidelines provided by Gilbert (2005b): a) begin by using the simplest form of a representation to explain features and meanings, b) once students have a basic understanding of how interpret a given representation, layer on complexity to teach how to use and make sense of the representation in a more advanced manner. In this case, interpreting one diagonal tree with limited branches is a simple way to teach tree thinking. After students master this initial diagram, altering the style or topology of the tree will add complexity to the tree

thinking task. Students should also be provided with 3D manipulatives to help them visualize the mobile structure of phylogenetic trees. I found the pipe cleaner model to be a low cost manipulative that was well received by the students and effective for improving tree thinking skills. Furthermore, the nature of this model allows students to explore tree reading starting from simple (basic phylogenetic tree) to complex aspects (by being able to form different styles of representation and alter topology).

Developing tree reading skills is only one aspect of becoming a tree thinker. Once tree reading fundamentals are in place, students can begin developing tree building skills, a second, more difficult component of tree thinking. Students need scaffolds to help them understand how to transform informative data into a phylogenetic tree. By providing concrete steps for students to follow, they become more adept tree builders. I provide a five step scaffold built into the interpreting Pseudocot phylogeny activity (see Appendix L) to facilitate students' skill development in creating phylogenetic trees. These five steps were designed to assist students with the process of creating a data matrix from informative data sources, translating this into evidence of phylogenetic relationships, and creating a scientifically appropriate branching representation.

As a result of this study, I designed and modified two instructional interventions designed to explicitly overcome common challenges students encounter with tree reading and tree building. These activities need to be evaluated for effectiveness. Furthermore, there is a need to design instructional guidelines and new research-based curricular materials for enhancing tree thinking in secondary and postsecondary biology courses. The secondary curriculum module should include an introductory module on tree-thinking, while the postsecondary curricular materials should be organized as multiple

lessons that can be implemented as one cohesive, multi-period unit or as individual skill building activities. The curriculum should also integrate effective thinking and evolution assessments to facilitate the transfer of research instructional practice.

### Implications for Policy

This study's call for curricular reform leads to two policy implications. First, funding needs to be prioritized to finance curriculum design. The National Science Foundation (NSF) should prioritize funding research leading to tree thinking curriculum reform such as the efforts of the Tree Reasoning in Evolutionary Education working group funded by NSF through the National Evolutionary Synthesis Center. Furthermore, funding should be dedicated to support professional development workshops to help instructors include explicit tree thinking instruction in their curriculum. Second, national and state biology standards need to be rewritten to include tree thinking at the secondary level. Unless the standards are revised to include tree thinking skills, instruction is not going to be explicitly included in course curriculum, regardless of funding.

### Future Research Directions

The lack of literature and research-based instruction in this area leads to the need for future research on to the role that representations play in learning biology. By better understanding our students, we will be able to design an informed curriculum that enhances meaningful learning in biology. Based on the findings and discussion of this study, I propose the following directions for future research on student learning with phylogenetic tree representations.

### *Student Learning at Additional Grade Levels*

This research has explored upper-level science students learning with tree thinking. Other research (e.g., Baum & Offner, 2008; Meir et al., 2007; Perry et al., 2008) investigated tree thinking with introductory biology majors and non-majors. However, this area of research needs to be expanded to incorporate a larger range of students: from graduate biology students to secondary students.

#### *Advanced Tree Thinking Skills*

While this study and current literature have explored how students learn tree thinking, we need to investigate how students develop more advanced tree thinking skills, such as interpreting consensus nodes and accommodating new data into a phylogeny. It is essential that we understand the core skills necessary for advanced tree thinking development to facilitate students developing expertise in phylogenetics.

#### *Testing the Proposed Framework*

I have proposed a framework for representational competence in tree thinking based on the findings of my study. However, it is necessary to further test this proposed representational competence framework for applicability to tree thinking in other contexts, such as in introductory and graduate level courses. Further investigations of student learning should also be conducted that encompass additional biological representations, such as data matrices and Venn diagrams.

#### *Synthesizing Tree Thinking Research and Evaluating Instructional Activities*

We need to continue synthesizing research on how students make sense of phylogenetic trees and review published lessons involving tree thinking. By synthesizing the current research on students understanding of tree thinking we can develop a comprehensive list of challenges and skills associated with developing tree thinking.

This list should be used to critique current tree thinking lessons. More specifically, we need to develop an evaluation rubric to critique the strengths and weaknesses of currently published tree thinking lessons.

### Conclusions

Reforms in science education emphasize the importance of achieving scientific literacy (National Research Council, 1996). One component of science literacy is the ability to use common representations of phenomena, such as phylogenetic trees. However, it is clear that most students do not interpret trees in the same manner as evolutionary biologists. In this study, I used a qualitative approach to learn how 27 upper-level undergraduate students used phylogenetic trees and developed tree thinking throughout a plant systematics course. By diagnosing challenges students face with tree thinking, identifying core skills necessary to overcome these challenges, designing effective instructional interventions, and developing a framework for representational competence, this study adds to our understanding of critical elements necessary for improving student learning with phylogenetic trees. Evidence from this study suggests that students require explicit instruction to develop tree reading and, later, tree building. Representations are critical for communicating abstract science concepts (Gilbert, 2005a). Ignoring how students use and develop scientific representations will prevent them from developing expertise in their field. Rather we need to focus on helping students learn how to interact and communicate through with scientific representations. Research-based instructional interventions facilitate improvements in students' representational competence with phylogenetic trees and will begin to maximize the potential of evolution education and improve science literacy.

## REFERENCES

- Alexander, P. A., Schallert, D., & Hare, V. (1991). Coming to terms: How researchers in learning and literacy talk about knowledge. *Review of Educational Research, 61*, 315-343.
- Anderson, K. C., & Leinhardt, G. (2002). Maps as representations: Expert novice comparison of projection understanding. *Cognition and Instruction, 20*, 283-321.
- Bailer-Jones, D. M. (1999). Tracing the development of models in the philosophy of science. In L. Magnani, N. J. Nersessian & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 23-40). New York: Kluwer Academic Publishers.
- Barnea, N. (2000). Teaching and learning about chemistry and modelling with a computer managed modelling system. In J. K. Gilbert & C. Boulter (Eds.), *Developing models in science education* (pp. 307-324). Dordrecht: Kluwer.
- Barnea, N., & Yehudit, J. D. (2000). Computerized molecular modeling - The new technology for enhancing model perception among chemistry educators and learners. *Chemistry Education: Research and practice in Europe, 1*, 109-120.
- Baum, D. A., & Offner, S. (2008). Phylogenies and tree-thinking. *American Biology Teacher, 70*, 222-229.
- Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree-thinking challenge. *Science, 310*, 979-980.
- Beck, I. L., & McKeown, M. G. (2001). Inviting students into the pursuit of meaning. *Educational Psychology Review, 13*, 225-241.

- Bereiter, C., & Scardamalia, M. (1993). Chapter four: Expertise as process. In *Surpassing ourselves: An inquiry into the nature and implications of expertise* (pp. 77-120). Chicago: Open Court.
- BioQUEST Curriculum Consortium. (2006, October 15). BEDROCK: Whippo problem space. Retrieved October 15, 2006, from [http://www.bioquest.org/bedrock/problem\\_spaces/whippo/](http://www.bioquest.org/bedrock/problem_spaces/whippo/)
- Boster, J. S., & Johnson, J. C. (1989). Form or function: A comparison of expert and novice judgments of similarity among fish. *American Anthropologist*, *91*, 866-889.
- Botzer, G., & Reiner, M. (2005). Imagery in physics: From physicists' practice to naive students' learning. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 147-168). Dordrecht, The Netherlands: Springer.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). Washington D.C.: National Academy Press.
- Briggs, M., & Bodner, G. (2005). A model of molecular visualization. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 61-72). Dordrecht, The Netherlands: Springer.
- Briggs, M. W. (2007). Models and modeling. In M. Orgill & G. M. Bodner (Eds.), *Theoretical frameworks for research in chemistry/science education* (pp. 69-83). Upper Saddle River, NJ: Prentice Hall.
- Brumby, M. (1979). Problems in learning the concept of natural selection. *Journal of Biological Education*, *13*, 119-122.

- Caravita, S. (2001). A re-framed conceptual change theory? *Learning and Instruction, 11*, 421-429.
- Catley, K. M., Novick, L. R., & Shade, C. (2009, April). *Reinforcing macroevolutionary misconceptions: Students' interpretations of textbook diagrams*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Garden Grove, CA.
- Cavallo, A. (1996). Meaningful learning, reasoning ability, and students' understanding and problem solving of topics in genetics. *Journal of Research in Science Teaching, 33*(6), 625-656.
- Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.
- Chi, M. T. H., & Roscoe, R. D. (2002). The process and challenges of conceptual change  
In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 3-27). Dordrecht: Kluwer.
- 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.
- Christopherson, J. T. (1997, October). *The growing need for visual literacy at the university*. Paper presented at the Visionquest: Journeys Towards Visual Literacy - 28th Annual Conference of the International Visual Literacy Association, Cheyenne, WY

- Clement, J., Zietsman, A., & Monaghan, J. (2005). Imagery in science learning in students and experts. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 169-184). Dordrecht, The Netherlands: Springer.
- Cobern, W. W., Gibson, A. T., & Underwood, S. A. (1999). Conceptualizations of nature: An interpretive study of 16 ninth graders' everyday thinking. *Journal of Research in Science Teaching*, *36*, 541-564.
- Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, *90*, 1073-1091.
- Cooper, R. A. (2002). Scientific knowledge of the past is possible: Confronting myths about evolution and scientific methods. *American Biology Teacher*, *64*, 427-432.
- Crisp, M. D., & Cook, L. G. (2005). Do early branching lineages signify ancestral traits? *TRENDS in Ecology and Evolution*, *20*, 122-128.
- Cuoco, A. A. (Ed.). (2001). *The roles of representation in school mathematics (2001 Yearbook of the National Council of Teachers in Mathematics)*. Reston, VA: National Council of Teachers in Mathematics.
- Denzin, N. K., & Lincoln, Y. S. (2000). Introduction: The discipline and practice of qualitative research In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed.). London: Sage.
- Denzin, N. K., & Lincoln, Y. S. (Eds.). (2005). *Handbook of qualitative research* (3rd ed.). Thousand Oaks, CA: Sage.
- Donovan, S. S. S. (2004). A brief introduction to tree thinking. Retrieved January, 2007, from <http://www.lrdc.pitt.edu/donovan/intro.html>

- Dori, Y. J., & Belcher, J. (2005). Learning electromagnetism with visualization and active learning. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 187-216). Dordrecht, The Netherlands: Springer.
- Driver, R., Squires, A., Rushworth, P., & Woods-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas* London, England: Routledge.
- Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*, 671-688.
- Ferguson, R. L. (2007). Constructivism and social constructivism. In M. Orgill & G. M. Bodner (Eds.), *Theoretical frameworks for research in chemistry/science education* (pp. 27-48). Upper Saddle River, NJ: Prentice Hall.
- Ferk, V., Vrtacnik, M., Blejec, A., & Gril, A. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education, 25*, 1227-1245.
- Friedlander, A., & Tabach, M. (2001). Promoting multiple representations in algebra. In A. A. Cuoco (Ed.), *The roles of representation in school mathematics (2001 Yearbook of the National Council of Teachers in Mathematics)* (pp. 173-185). Reston, VA: National Council of Teachers in Mathematics.
- Fullan, M., & Steigelbauer, S. (1991). *The new meaning of educational change* (2nd ed.). New York: Teachers College Press.
- Gabel, D. (1999). Improving teaching and learning through chemical education research: A look into the future. *Journal of Chemical Education, 76*, 548-554.
- Gardner, H. (1983). *Frames of mind*. New York: Basic Books.

- Gatesy, J., & O'Leary, M. A. (2001). Deciphering whale origins with molecules and fossils. *TRENDS in Ecology and Evolution*, *16*, 562-570.
- Gendron, R. P. (2000). The classification & evolution of caminalcules. *American Biology Teacher*, *62*, 570-576.
- Gilbert, J. K. (2005a). Visualization: A metacognitive skill in science and science education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 9-27). Dordrecht, The Netherlands: Springer.
- Gilbert, J. K. (Ed.). (2005b). *Visualizations in science education* (Vol. 1). Dordrecht, The Netherlands: Springer.
- Gilbert, J. K., Boulter, C. J., & Rutherford, M. (2000). Explanations with models in science education. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing models in science education* (pp. 193-208). Dordrecht, The Netherlands: Kluwer.
- Gilbert, J. K., & Reiner, M. (2000). Thought experiments in science education. *International Journal of Science Education*, *22*, 265-283.
- Gilbert, J. K., & Treagust, D. (Eds.). (2009). *Multiple representations in chemical education* (Vol. 4). Dordrecht, The Netherlands: Springer.
- Gregory, T. R. (2008). Understanding Evolutionary Trees. *Evolution: Education and Outreach*, *1*, 121-137.
- Guba, E. G., & Lincoln, Y. S. (1989). *Fourth generation evaluation*. Thousand Oaks, CA: Sage.
- Haber, R. N. (1970). How do we remember what we see? *Scientific American*, *222*, 104-112.

- Hackling, M. W., & Lawrence, J. A. (1988). Expert and novice solutions of genetic pedigree problems. *Journal of Research in Science Teaching*, 25, 531-546.
- Halverson, K. L., Pires, J. C., & Abell, S. K. (2008, March). *Undergraduates' abilities to use representations in biology: Interpreting phylogenetic tree thinking*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Baltimore, MD.
- Hildebrand, A. C. (1986, March). *Cognitive representations of basic biological entities*. Paper presented at the annual meeting of the American Education Research Association, San Francisco, CA.
- Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator*, 4, 1-29.
- Howell, F. C. (1970). *Early man*. New York: Time Life Books.
- Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to a changing demand. *Journal of Chemical Education*, 70, 701-705.
- Kindfield, A. C. H. (1994). Biology diagrams: Tools to think with. *Journal of the Learning Sciences*, 3, 1-36.
- Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomenon. *Journal of Research in Science Teaching*, 34, 949-968.
- Kozma, R. B., & Russell, J. (2005). Modelling students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 121-145). Dordrecht, The Netherlands: Springer.

- Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind*. Chicago: University of Chicago Press.
- Lamon, S. J. (2001). Presenting and representing: From fractions to rational numbers. In A. A. Cuoco (Ed.), *The roles of representation in school mathematics (2001 Yearbook of the National Council of Teachers in Mathematics)* (pp. 146-165). Reston, VA: National Council of Teachers in Mathematics.
- Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Expert and novice performance in solving physics problems. *Science*, *208*, 1335-1342.
- Lawson, A. E., Alkhoury, S., Benford, R., Clark, B. R., & Falconer, K. A. (2000). What kinds of science concepts exist? Concept construction and intellectual development in biology. *Journal of Research in Science Teaching*, *37*, 996-1018.
- Lewis, J., Leach, J., & Wood-Robinson, C. (2000). All in the genes? – Young people's understanding of the nature of genes. *Journal of Biological Education*, *34*, 74-79.
- Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Thousand Oaks, CA: Sage.
- Lord, T. R., & Marino, S. (1993). How university students view the theory of evolution. *Journal of College Science Teaching*, *22*, 353-357.
- Luisi, P. L., & Thomas, R. M. (1990). The pictographic molecular paradigm: Pictorial communication in the chemical and biological sciences. *Naturwissenschaften*, *77*, 67-74.
- Mabee, P. M. (2006). Integrating evolution and development: The need for bioinformatics in in evo-devo. *BioScience*, *56*, 301-309.
- Mach, E. (1976). On thought experiments. In J. McCormack (Ed.), *Knowledge and error* (pp. 134-147). Dordrecht: Reidel.

- Mammino, L. (2008). Teaching chemistry with and without external representations in professional environments with limited resources. In J. K. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 155-185). Dordrecht, The Netherlands: Springer.
- Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education*, 83, 33-54.
- Matuk, C. (2007). Images of evolution. *Journal of Biocommunication*, 33(3), E54-E61.
- Meir, E., Perry, J., Herron, J., Maruca, S., Stal, D., & Kingsolver, J. (2005, August). *How effective are individual-based simulations in EvoBeaker at overcoming misconceptions in evolution?* Paper presented at the ESA Annual Meeting, Montreal, Canada
- Meir, E., Perry, J., Herron, J. C., & Kingsolver, J. (2007). College student's misconceptions about evolutionary trees. *American Biology Teacher*, 69, 71-76.
- Meyer, M. R. (2001). Representation in realistic mathematics education. In A. A. Cuoco (Ed.), *The roles of representation in school mathematics (2001 Yearbook)* (pp. 238-250). Reston, VA: National Council of Teachers in Mathematics.
- 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.
- National Research Council. (1996). *National science education standards*. Washington D.C.: National Academy Press.
- Niedderer, H., & Goldberg, F. (1994, March). *An individual student's learning process in electric circuits* Paper presented at the NARST Annual Meeting, Anaheim, CA.

- Novick, L. R., & Catley, K. M. (2008, March). *Assessing students' understanding of cladograms*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Baltimore, MD.
- O'Hara, R. J. (1998). Population thinking and tree thinking in systematics. *Zoologica Scripta*, 26, 323-329.
- Omland, K. E., Cook, L. G., & Crisp, M. D. (2008). Tree thinking for all biology: The problem with reading phylogenies as ladders of progress. *BioEssays*, 30, 854-867.
- Palmer, S. E. (1978). Fundamental aspects of cognitive representation. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 259-303). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Patrick, M. D., Carter, G., & Wiebe, E. N. (2005). Visual representations of DNA replication: Middle grades students' perceptions and interpretations. *Journal of Science Education and Technology*, 14, 353-365.
- Patton, M. Q. (2002). *Qualitative research & evaluation methods*. Thousand Oaks, CA: Sage.
- Pearsall, N., Skipper, J., & Mintzes, J. (1997). Knowledge restructuring in the life sciences: A longitudinal study of conceptual change in biology. *Science Education*, 81, 193-215.
- Perry, J., Meir, E., Herron, J. C., Maruca, S., & Stal, D. (2008). Evaluating two approaches to helping college students understand evolutionary trees through diagramming tasks. *CBE-Life Sciences Education*, 7, 193-201.

- Peterson, M. P. (1994). Cognitive issues in cartographic visualization. In A. M. MacEachren & D. R. F. Taylor (Eds.), *Visualization in Modern Cartography* (pp. 27-43). Oxford: Pergamon.
- Pires, J. C., & Sytsma, K. J. (2002). A phylogenetic evaluation of a biosystematic framework: *Brodiaea* and related petaloid monocots (Themidaceae). *American Journal of Botany*, 89, 1342-1359.
- Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 211-227.
- Reiner, M., & Gilbert, J. K. (2008). When an image turns into knowledge: The role of visualization in thought experimentation. In J. K. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education*. Dordrecht, The Netherlands: Springer.
- Reiss, M. J., & Tunnicliffe, S. D. (2001). Students' understandings of their internal structure as revealed by drawings. In H. Behrendt, H. Dahncke, R. Duit, W. Graber, M. Komorek, A. Kross & P. Reiska (Eds.), *Research in science education - Past, present, and future* (pp. 101-106). Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Reynolds, S. J., Johnson, J. K., Pilburn, M. D., Leedy, D. E., Coyan, J. A., & Busch, M. M. (2005). Models visualization in undergraduate geology courses. In J. K. Gilbert (Ed.), *Visualization in science education*. Dordrecht, The Netherlands: Springer.

- Rogers, Y. (2008). Using external visualizations to extend and integrate learning in mobile and classroom settings. In J. K. Gilbert, M. Reiner & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 89-102). Dordrecht, The Netherlands: Springer.
- Roth, W.-M., Bowen, G. M., & McGinn, M. K. (1999). Differences in graph-related practices between high school biology textbooks and scientific ecology journals. *Journal of Research in Science Teaching, 36*, 977-1019.
- Russell, J., & Kozma, R. (2005). Assessing the learning from multi-media packages in chemical education. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 299-332). Dordrecht, The Netherlands: Springer.
- Rutherford, J. F., & Ahlgren, A. (1990). *Science for all Americans*. New York: Oxford University Press.
- Sandvik, H. (2008). Tree thinking cannot be taken for granted: Challenges for teaching phylogenetics. *Theory Bioscience, 127*, 45-51.
- Simon, H. A., Larkin, J. H., McDermott, J., & Simon, D. P. (1989). Expert and novice performance in solving physics problems. In H. A. Simon (Ed.), *Models of thought* (Vol. 2, pp. 243-256). New Haven, CT: Yale University Press.
- Simpson, M. G. (2006). *Plant Systematics*. Burlington, MA: Elsevier Academic Press.
- Staub, N. L., Pauw, P. G., & Pauw, D. (2006). Seeing the forest through the trees: Helping students appreciate life's diversity by building the tree of life. *The American Biology Teacher, 68*, 149-151.
- Tabachneck, H. J. M., Leonardo, A., & Simon, H. A. (1994, August). *How does an expert use a graph? A model of visual and verbal inferencing in economics*. Paper

presented at the 16th Annual Conference of the Cognitive Science Society,  
Atlanta, GA.

Takayama, K. (2005). Teaching visualizing the science of genomics. In J. K. Gilbert (Ed.), *Visualization in science education* (pp. 217-251). Dordrecht, The Netherlands: Springer.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, *10*, 159-169.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353-1368.

Trouche, L. (2005). Instrumental genesis, individuals and social aspects. In D. Guin, K. Ruthven & L. Trouche (Eds.), *The didactical challenge of symbolic calculators: Turning a computational device into a mathematical instrument* (pp. 197-230). New York: Springer.

Tufte, E. R. (2001). *The visual display of quantitative information* (2nd ed.). Cheshire, CT: Graphics Press.

Tyson, L., Venville, G., Harrison, A., & Treagust, D. (1997). A multidimensional framework for interpreting conceptual change events in the classroom. *Science Education*, *81*, 387-404.

University of California Museum of Paleontology. (2009). Understanding Evolution.

Retrieved August 22, 2008, from

[http://evolution.berkeley.edu/evolibrary/article/0\\_0\\_0/evo\\_03](http://evolution.berkeley.edu/evolibrary/article/0_0_0/evo_03)

- Van Fraassen, B. C. (2008). *Scientific representation: Paradoxes of perspective*. Oxford: Oxford University Press.
- Vosniadou, S. (2003). Exploring the relationships between conceptual change and intentional learning. In G. M. Sinatra & P. R. Printrich (Eds.), *Intentional conceptual change* (pp. 377-406). Mahwah, NJ: Lawrence Erlbaum Associates.
- Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 177-210). New York: Macmillan.
- Williams, J. M., & Tolmie, A. (2000). Conceptual change in biology: Group interaction and the understanding of inheritance. *British Journal of Developmental Psychology*, 18, 625-649.
- Woleck, K. R. (2001). Listen to their pictures: An investigation of children's mathematical drawings. In A. A. Cuoco (Ed.), *The roles of representation in school mathematics (2001 Yearbook)* (pp. 215-227). Reston, VA: National Council of Teachers in Mathematics.
- Wu, H.-K., & Shah, P. (2004). Exploring visiospatial thinking in chemistry learning. *Science Education*, 88, 465-492.
- Zazkis, R., & Liljedahl, P. (2004). Understanding primes: The role of representations. *Journal for Research in Mathematics Education*, 35, 164-186.
- Zbiek, R. M., Heid, M. K., Blume, G. W., & Dick, T. P. (2007). Research on technology in mathematics education: A perspective of constructs. In F. K. Lester (Ed.), *Second handbook of research on mathematics teaching and learning* (Vol. 2, pp. 1169-1207). Charlotte, NC: Information Age Publishing.

## APPENDICES

## APPENDIX A. PILOT STUDY

RUNNING HEAD: INTERPRETING PHYLOGENETIC TREE THINKING

Undergraduates' Abilities to use Representations in Biology: Interpreting Phylogenetic  
Tree Thinking

Kristy L. Halverson (klhf25@mizzou.edu)

J. Chris Pires

Sandra K. Abell

University of Missouri

Paper presented at the 2008 annual meeting of the National Association for Research in  
Science Teaching. Baltimore, MD

Halverson, K. L., Pires, J. C., & Abell, S. K. (2008, March). *Undergraduates' abilities to  
use representations in biology: Interpreting phylogenetic tree thinking*. Paper  
presented at the annual meeting of the National Association for Research in  
Science Teaching, Baltimore, MD.

\*\*This manuscript has been submitted for publication. Do not cite without permission.

## Abstract

College students struggle with abstract reasoning and problem solving skills, especially in biological sciences (where visual representations have not been well studied). In order to be efficient problem solvers in systematics and evolutionary biology, students must develop expertise in phylogenetic tree thinking. Ideally, having scientifically accurate content knowledge should help students chunk visual information represented by phylogenetic trees, allowing them to make sense of new species and develop the skills necessary to build hypothetical, testable trees. In this study, we used pre/post tests and interviews of college biology students to learn how students interpreted and used phylogenetic trees. Using observations and document analysis as supporting data, we identified multiple misconceptions within students' content knowledge of systematics. By relying upon these misconceptions, students developed alternative types of reasoning that prevented them from interpreting and using phylogenetic trees. Importantly, we identified types of reasoning that go beyond merely misreading phylogenetic trees. The types of reasoning we identified were: inconsistent, reliance on expert knowledge, ecological, morphological, branch-influenced, tree shape-influenced, node-influence, quasi-scientific, and phylogenetic. We also found that students' tree-reading expertise differed from their tree-building abilities. These findings have implications for identifying students' misconceptions and developing instructional methods to help college biology students become more effective problem solvers.

## Introduction

Reforms in science education emphasize the importance of achieving scientific literacy (National Research Council, 1996), where students gain an understanding of and

abilities to do science. College science courses are all too often taught as a litany of facts, leading many students to focus on memorization rather than gain conceptual understanding and inquiry abilities. For example, systematics courses are common biology courses traditionally taught as collections of facts rather than focusing on phylogenetic reasoning and methodologies that practicing systematists use to determine how characteristics and species relate to one another in an evolutionary sense. However, systematics and similar organismal diversity courses can involve teaching and learning that engages students in developing conceptual foundations and provides opportunities to develop skills needed to achieve expertise within their discipline. The purpose of this study was to understand students' ideas about systematics and how they made sense of representations presented in an undergraduate systematics course in an effort to facilitated student learning.

#### Theoretical Framework and Literature Review

The expert-novice conceptual framework allows investigators of student learning to place knowledge and skill improvement along a gradient of expertise. This gradient incorporates multiple intermediary levels between novice learners and students who have mastered expertise within the discipline. We define experts as people who have “acquired extensive knowledge that affects what they notice and how they organize, represent, and interpret information in their environment. This, in turn, affects their abilities to remember, reason, and solve problems” (Bransford, Brown, & Cocking, 2000, p. 31). Novice learners are often incapable of seeing patterns in information and instead focus on memorizing facts (Bransford et al., 2000). Thus, instruction that focuses on memorizing facts is not sufficient for helping students solve problems, especially when

complex or abstract biological concepts are required (Fullan & Steigelbauer, 1991). For learners to develop expertise in a science discipline, they must, (a) have a deep foundation of usable knowledge, (b) understand facts in the context of a conceptual framework, and (c) be able to organize that knowledge in ways that facilitate retrieval and application (Bransford et al., 2000). In addition to revisiting the conditions that lead toward developing expertise, Bransford et al. (2000) assembled a list of six characteristics that experts share:

1. Experts notice features and meaningful patterns of information that are not noticed by novices.
2. Experts have acquired a great deal of content knowledge that is organized in ways that reflect a deep understanding of their subject matter.
3. Experts' knowledge cannot be reduced to sets of isolated facts or propositions but, instead, reflects contexts of applicability; that is, the knowledge is "conditionalized" on a set of circumstances.
4. Experts are able to flexibly retrieve important aspects of their knowledge with little attentional effort.
5. Though experts know their disciplines thoroughly, this does not guarantee that they are able to teach others.
6. Experts have varying levels of flexibility in their approach to new situations. (p. 31)

As learners move toward developing expertise, they develop these identifiable characters. Thus, expert knowledge allows a learner to chunk information into meaningful patterns and to transfer what he/she has learned to think through new problems. deGroot (1965)

found that experts were better able to understand and generate representations of the problems presented as well as better recall more and critical information. Thus, developing expertise within a discipline includes learning to use common representations of phenomena within that discipline (e.g., Punnett squares, Hardy-Wienburg equation). A great deal of research about student understanding of representations has taken place in chemistry and physics, but little has been investigated within biology (Gilbert, 2005). Thus, there is a need to understand the role that representations play with regard to learning in the biological sciences.

Representations can refer either to internal cognitive representations or external representations (e.g., graphs, maps, and phylogenetic trees), that are tools for shared reasoning within a subject matter domain (Palmer, 1978). Understanding the nature and role of external representations in subject matter areas is important when thinking about issues concerning learning, because external representational systems are often the focus of a primary reasoning component within a domain (Anderson & Leinhardt, 2002). External representations have been used to supplement the ability to visualize concepts that only exist in the mind. Unfortunately, the interactive characteristics of representations are constrained by their design, allowing only certain types of tests and alternatives. The plausibility of new conceptions may be tested using representations only when the information tested fits within the design. Because non-expert users tend to treat representations as concrete rather than flexible hypotheses, this limits the amount and type of concepts that can be explored through representations (Caravita, 2001). A large difference between novices and experts lies within their conceptual understanding and the type of strategy used to approach the problem (Hackling & Garnett, 1992;

Heyworth, 1999). Boster and Johnson (1989) investigated how experts and novices approached a common systematics problem dealing with similarities among different taxa. They found that experts vary more in their responses to this problem since they possess more knowledge to judge similarity than novices. In addition, they found that experts tend to look at multiple levels of similarity (both morphological and functionality), versus novice learners who tended to only look at one level of similarity (only morphology) among fish. Novices tended to hold multiple misconceptions and have poor, superficial understandings about tools that could be used to help develop solutions to problems. As expertise developed, problem solving strategies became more refined, and the use and quality of representations involved in the process improved (Heyworth, 1999). Thus, another way to explore the cognitive complexities involved in understanding representations has been to compare the ways experts and novices use representations to solve domain-specific problems (Simon, Larkin, McDermott, & Simon, 1989; Tabachneck, Leonardo, & Simon, 1994). This research has concluded that “experts use representations as a tool to reason about real-life objects and events, whereas novices tend to reason within the representation itself and have more difficulty in moving back and forth between the representation and the real-world objects represented” (Anderson & Leinhardt, 2002, p. 285).

In systematic biology, “evolutionary trees serve not only as tools for biological researchers across disciplines but also as the main framework within which evidence for evolution is evaluated” (Baum, Smith, & Donovan, 2005, p. 979). If students cannot interpret and use phylogenetic trees in a manner that is consistent with identified experts, then they will not be able to develop personal expertise. Evolutionary biology experts

see biology through the perspective of phylogenetics: they think about biological phenomena in terms of how observations fit within the branching structure of genealogical relationships among species (Cooper, 2002; Donovan, 2005; O'Hara, 1998). They recognize the roles of descent from common ancestry and evolutionary adaptation in establishing patterns of similarity and difference among groups of organisms. However, tree thinking is generally inconsistent with everyday thinking about biological groups and their relationships (Cobern, Gibson, & Underwood, 1999). Our intuitive folk taxonomy is based on overall similarity whereas modern phylogenetic classifications define monophyletic groups (clades) that are defined by shared derived characters. For example, birds and crocodiles belong to the same phylogenetic clade; however, these organisms into two separate categories when using folk taxonomy.

Students display three sets of assumptions about the nature of species (Donovan, 2004). The novice assumption considers species as fixed, non-related entities and is most consistent with what we experience in our everyday interactions with organisms. The intermediate assumption is that species make up different steps along a single evolutionary pathway. For example, the popular, flawed cartoon showing the progression of apes into humans implies that a apes evolved into humans rather than both species evolving independently but share a common, ancient ancestor. The expert assumption emphasizes both the historical relationships among species and their non-linear, or branching, divergence from multiple evolutionary events. Tree thinking involves being able to incorporate the expert assumption into one's biological sense making (Cooper, 2002), using a phylogenetic perspective. Phylogenetic trees are widely used in college biology courses to study the relationships among living taxa. Baum, Smith, and Donovan

(2005) reported that trees are commonly misunderstood by students, leading to confusion about the concept of common ancestry. These researchers believe that students misinterpret trees because of flawed reasoning associated species proximity to each other as depicted in a two-dimensional representation. However, physical location and representation attributes do not explain all of students' difficulties with tree thinking. Novice students incorporate foundational misconceptions into tree thinking and these ideas complicate tree interpretations. A recent article (Gregory, 2008) has compiled a collections of ten common misconceptions that interfere with students' abilities to interpret phylogenetic trees.

It is imperative that students are able to process information and recognize patterns when manipulating or building evolutionary trees. If a student cannot recognize patterns within the tree, then they will not be able to accurately interpret the intended meaning nor test the hypothesis presented. Baum et al. (2005), Gendron (2000), Meir, Perry, Herron, Maruca, Stal, and Kingsolver (2005), and Gregory (2008) have argued that understanding phylogenetic trees as representations of evolutionary relatedness is a cognitively complex task that requires instruction given the numerous misconceptions. Thus, it is expected that novices reason only within the tree itself. On the other hand, experts in systematics are identified by their ability to comprehend phylogenetic trees as representations of species relatedness and to use trees as reasoning tools when solving systematics problems. Interpreting visual representations often is more involved with pattern recognition than with conceptual understanding.

## Research Design

### *Research Questions*

The overarching research question guiding this study was: *How do undergraduate biology majors interpret and use tree thinking to make sense of systematics?* Supporting questions for this study included: (a) How do students interpret and build evolutionary trees when entering a plant systematics course? (b) How do students use tree thinking to make sense of systematics problems? (c) How does student reasoning influence problem solving ability?

### *Methods and Analysis*

Participants for this study included 35 students (14 females and 21 males) enrolled in an upper-level plant systematics course organized around tree thinking instruction at a research extensive university. All of the participants were majoring in a life sciences field. However, only one student had taken a previous course in evolution and none have taken botany. In addition, none of the students had been given instruction on how to use and interpret phylogenetic trees prior to the course. We collected data using a two-tiered diagnostic pre/posttest (Treagust, 1988), semi-structured interviews (Patton, 2002), observations, and document/artifact analysis. The questions on these instruments were open-ended to elicit explanatory responses about species identification and tree interpretations. The two-tiered diagnostic test was adapted from Baum et al. (2005), highlighting questions where their students had difficulties with tree thinking interpretations. We designed these so that students had to justify their responses about phylogenetic trees and species relatedness. We administered the pretest on the first day of class. The explanations that students provided allowed us to customize the interview

protocol to probe student ideas. We administered the posttest during the last week of the course, to determine students' understandings at the end of the semester. We selected nine key informants to interview from three tiers of student "expertise" identified from the pretest responses. These nine student volunteers participated in individual 1.5 hour long semi-structured interviews. Each interview included tasks developed from previous work by Baum et al. (2005) and Gendron (2000). We used the questions and activities to elicit students' explanations and use of tree thinking. We asked students multiple questions targeted at similar understandings of the systematics concepts and performed member check during the interviews to improve the credibility of our findings (Lincoln & Guba, 1985). The documents and artifacts collected came from student assignments, quizzes and exams given as requirements of the course.

We utilized all transcripts, field notes, expanded observation notes, and documents in data analysis. The tests and interviews were the primary sources of data. Constant comparative methods ensured that data collection was appropriate and sufficient (Hatch, 2002). Analysis involved examining responses to pre/posttest and interview questions and looking for themes that pervaded the responses across all students. Rather than approaching the data with predetermined themes in mind, the data led us to identify themes and meanings that the students created.

Data analysis began upon completion of the in-class pretest. We open coded the responses to the pretest with respect to how justify their responses (Hatch, 2002). We used students' own words to develop these initial inductive codes. Next we grouped similar codes into categories and looked for patterns in the data that distinguished types of reasoning used. In addition to the inductive analysis, we conducted a cross-case

comparison (Stake, 1995) by analyzing each student's responses across the entire data set. By using this type of comparison, we were able to find commonalities that emerged from student responses that suggested specific reasoning patterns. The interview data analysis began upon completions of the first interview. We transcribed student responses to the interview questions and utilized inductive, open codes to break down the data with respect to depictions of student problem solving processes (Hatch, 2002). By utilizing inductive coding in conjunction with sensitizing concepts derived from the pretest analysis, we were able to assess reasoning patterns associated with phylogenetic trees without as much bias based on previous research findings.

Once the themes were saturated through analyzing the interviews and pre/posttests, we triangulated using the data from course observations and student documents to ensure our research findings represented accurate interpretations of the data drawn from the participants' ideas.

### Findings

The findings of this study are rich descriptions of how college students used systematics knowledge and tree thinking processes to make sense of systematics problems. (Participants' names are pseudonyms to ensure confidentiality of their responses.) Although understanding the scientific principles of phylogenetics and being able to use these principles to solve systematics problems is the key objective in gaining expertise in plant systematics, we found that the majority of college biology students struggled to grasp these principles. We found that students fit into one of three representation-based thinking abilities determined by their content knowledge and understanding of phylogenetic representations along a gradient of novice to expert (see

Table 1). Within each of these abilities, students utilized nine differing types of reasoning when working with phylogenetic tree representations. The types of reasoning used influenced students' abilities to use phylogenetic trees when approaching systematics problems which in turn allowed us to confirm each student's thinking ability. In the following sections we have defined each of the representation-based thinking abilities and types of reasoning we identified.

Table 1. *Identified novice-expert gradient of abilities and reasoning used to interpret and solve systematics problems.*

<i>Expertise Gradient</i>	<i>Representation-Based Thinking Ability</i>	<i>Type of Reasoning Used</i>	<i>Student Emphasizes</i>
Novice	Inability to recognize and/or solve systematics problems	Inconsistent	Uncertainty; lack of confidence; no emphasis on tree thinking
Intermediate 	Use of disconnected knowledge to attempt or partially solve systematics problems	Reliance on expert knowledge	Knowledge gained from an expert, text, or reliable source
		Ecological	Habitat; where an organism lives; what an organism eats
		Morphological	Similarities in physical appearance; differences in physical appearance
		• Categorizing	
		• Elimination	
		Branch-Influenced	Proximity and order of branch location
		Tree Shape-Influenced	Physical nature of tree's appearance
Node-Influenced	Number and location of nodes		
Quasi-scientific	Correct conclusion, but limited/faulty explanation		
Expert	Use of expertise knowledge to solve systematics problems	Phylogenetic	Scientifically acceptable conclusions and explanations

### *Representation Based Thinking Ability*

#### *Inability to Recognize and/or Solve Systematics Problems*

Students who were unable to recognize or solve systematics problems also placed little emphasis on tree thinking during problem solving activities. These students showed high levels of frustration toward systematics problems and generally displayed large amounts of uncertainty in their responses. Comments made during problem solving activities were dominated by statements such as: "I don't know," "I can't remember," "I

might be wrong,” “I would never use one of these [trees].” When Rachel was asked to build a phylogeny of an imaginary group of animals called caminalcules, she responded:

I’m not sure I would know how to start making a model. So like within your time period you have some that really simple feet, and some that have feet that are starting to differentiate. I don’t know if I could do this, honestly without it just being a complete guess based on kind of what they look like.

We also noted that these types of student sometimes would not respond but rather sat quietly or offered long pauses before giving up on attempting an answer. If a response was given, these students were also likely to continuously alter the response.

#### *Use of Disconnected Knowledge to Attempt or Partially Solve Systematics Problems*

We found that the majority of participants harbored multiple misconceptions regarding phylogenetic trees. Students were unable to connect systematics concepts, tree thinking, and evolutionary ideas in a way that would help them make sense of new systematics problems. Instead, a majority of students demonstrated disconnected knowledge; they processed chunks of information to make sense of the situation without looking holistically at the problem. They were not able to interpret the problem accurately, nor were they able to produce a scientifically acceptable hypothesis that could be tested. This disjointed problem solving was similar to assembling a jigsaw puzzle using pieces from three distinctly different puzzles. While each piece is from a puzzle, it is not possible to create a coherent whole image. The students were not able to see the patterns of interconnections as would be expected in an expert’s response.

Melanie, a sophomore secondary education major, had taken four other biology courses, including one focused upon genetics and evolution, prior to the plant systematics

course. The instructor and teaching assistant perceived her to be a top student in the systematics course. When Melanie was asked to interpret four tree visualizations that illustrated identical relationships (see Figure 1), she said that all four trees could be interpreted to offer the same content. However, she indicated that she would need help through the course to understand how. She could not transfer her knowledge about trees or recognize patterns well enough to interpret the trees on her own with confidence. She stated that the depiction of each tree influenced the content,

I guess the visual representation of each one changes because your eye follows what's happening on the page. Image four is hard to look at anyway just because it's kind of confusing like a maze. And image three is more chunks so you can see the different chunks more. Images one and two are just flip-flopped but in kind of different ways so you can think about the visual representation differently if you want to.

Melanie was most comfortable discussing and making conclusions from the two linear trees (see Figure 1, trees 1 & 2) that were most similar to images typically used in the course. She was not able to transfer her knowledge to the novel tree representations and was uncertain if the content was consistent, because she was not able to recognize the patterns associated among the image structures.

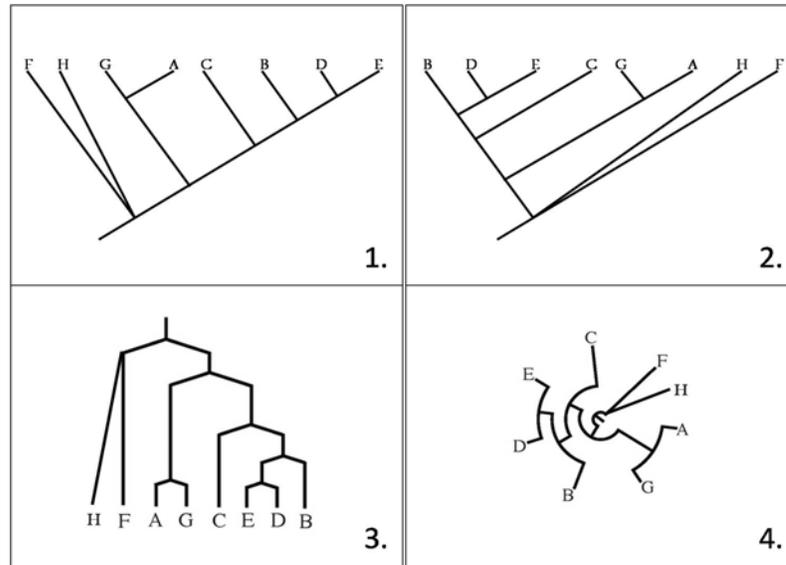


Figure 1. Four tree topologies representing identical evolutionary relationships. When further pressed to comment on the usefulness of these representations,

Melanie remarked that she would be most likely to use an image like one of the first two linear trees.

For me they denote time in better sense. Time is shown, you can see the natural progression you can actually see it moves along the page and you can follow it.

And then on [tree] four you have to weave your way through and you don't know how long it has been because each [branch] is just a little part of a circle.

She claimed that she would not use an image like the bracket tree “because in plants there aren't always clear divisions, there aren't always clear splits you kind of have to be vague about it, but in [image three] you have more defined changes.” However, when Melanie was later asked to construct a model representing relationships among the caminalcules, she constructed a flowchart image tree depicting a linear progression of relatedness from primitive to advanced that directly connected each species, rather than generating a scientifically accepted branching tree similar to the earlier representations she had commented upon.

### *Use of Expertise Knowledge to Solve Systematics Problems*

Scientists have varying approaches toward solving systematics problems. We assumed that the approach used by the instructor of the course could be categorized as an expert knowledge about phylogenetics. We identified this approach by the professor being able to: accurately provide scientifically appropriate responses to questions posed about relationships depicted on a phylogenetic tree, transfer scientifically appropriate understanding across different representations of phylogenetic trees, and using a consistent strategy to build scientifically appropriate phylogenetic trees. While no students used expert phylogenetic knowledge to solve a full range of systematics problems during the course, we found that several students did use expert knowledge when approaching solving select problems upon completion of the course, such as question four, five, and seven in the posttest. Thus, we found that these students had developed expertise in tree-reading but not tree building.

### *Type of Reasoning*

#### *Novice*

*Inconsistent.* Novice students did not use a consistent identifiable reasoning scheme. Rather these students drew upon inaccurate conceptual foundations and irrelevant information to attempt making sense of the phylogenetic representations. Often responses to systematics problems involved frustration with the problem and a high level of uncertainty; students often altered their response repeatedly. Novice students were not able to produce scientifically appropriate responses when asked to interpret phylogenetic trees, could not describe similarities between different tree representations, nor were they able develop trees from given data.

*Intermediate*

*Reliance on Expert Knowledge.* Students that demonstrated low confidence in their responses often relied excessively upon academic resources to provide answers to systematics problems they encountered. Students who used this type of reasoning provided responses to the questions asked. However, they indicated they would utilize experts or expert resources within the discipline before developing reliable conclusions. Jonathan stated that before building a phylogeny incorporating an unknown species,

I would call [my professor] because he has a lot more experience than I do. I have about ten weeks worth, and he has about 20 or 30 years worth... I am sure he uses the exact same resources, unless there is a resource I am not aware of, but he has been doing it for 30 years.

We found that students who relied upon expert knowledge considered that their responses would not be as correct as an expert's. We found that these students did not attempt to solve problems with any strategies other than what were presented during the course and did not develop expertise skills.

*Ecological.* In this type of reasoning, students referred to ecological attributes such as geographic location when interpreting trees and evolutionary relationships, demonstrating a misconception that ecological attributes influence species relatedness. For example, when asked what information scientists used to identify plant species, Daniel indicated that they needed to know the location where the organisms were collected. "Not all species live in the same place. Some [chili peppers] are native to the Amazon region, but now they grow everywhere in the world, but certain chili varieties are not grown all over the world, but are only grown in places like Peru." Daniel had

difficulties incorporating biogeographic information into systematics problems. Experts do not identify species based on location; rather they identify species and mark the location in order to investigate trends in biogeography. Locations of related plant populations can change over time, but this does not necessarily affect evolutionary relationships.

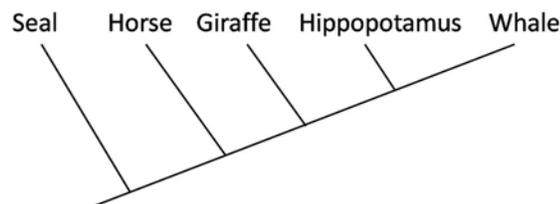
Ecological references that students made indicated that they saw the environment acting directly upon species rather than on individual organisms. Systematics experts would recommend looking holistically at the organism and coupling that information with a genetic analysis, not with ecological attributes, to identify relations among organisms. Students who held the ecological type of reasoning oversimplified the role of the environment upon speciation and relatedness. For example, Doug said that the relationship of organisms could be determined by understanding their habitat, rather than by interpreting phylogenetic relationships. He stated that the “seal and whale are both aquatic, the horse is not,” therefore indicating that the seal and whale should be more closely related (see Figure 2). The scientific explanation derived from the tree indicated that the seal was equally related to both the horse and whale. Likewise Holly stated, “Both the seal and the whale have similar habitats or at least they both are associated with water.” She continued using ecological reasoning in later responses. For example, she remarked that in order to identify plants, “you would need to gather evidence about climate and habitat so you know what types of growing situations you need for that plant.” By referencing ecological elements in connection with species identification, Holly did not apply an evolutionary basis for identifying plants or understanding relatedness. Holly’s reasoning persisted throughout the semester and she continued to

reference ecological attributes to identify relationships on the posttest. Melanie's explanations about interpreting trees and relatedness among species indicated that she also reasoned ecologically. When asked about the relationships of imaginary caminalcules (Gendron, 2000), she stated:

I don't really know how they are related because I can't see how they act or what they eat or how they live. I mean, if you have this guy who's living in a cave with his one eye and can't see very well and then you have [this other one] who has his eyes on the side of his head, he's out on the land and walking around and he has to see a lot of the things around him and [the third one] focused on gathering as much light as possible. . . . If I could see where they were, I could figure out exactly where they fit in the spectrum of what their environmental needs are and how their bodies are adapted to fit it.

This alternative reasoning prevented Melanie from accurately making sense of the phylogenetic problem.

5. Which of the following is an accurate statement of relationships illustrated by this tree?



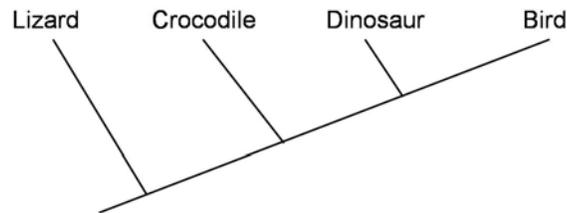
- a) A seal is more closely related to a horse than to a whale
- b) A seal is more closely related to a whale than to a horse
- c) A seal is equally related to a horse and a whale
- d) A seal is related to a whale, but is not related to a horse

Provide an explanation for why you chose your answer.

*Figure 2.* This was question five from the pre/posttest. We derived this question from Baum et al. (2005). Students not only select a response, but we also asked to provide their rationale for their answer.

*Morphological.* The most common reasoning associated with tree-thinking was what we called “morphological” reasoning. We found that students used morphological reasoning in two ways: categorizing or eliminating. Students grouped taxa by looking for commonalities in physical appearance or by eliminating relationship possibilities by searching for differences in physical appearance. Using this reasoning, students ignored genetic evidence and based responses solely on physical characteristics that were stated or that they knew previously. Jessica made her decisions about relatedness based on “obvious knowledge that crocodiles and lizards look similar to each other and not birds” (see Figure 3). She continued with her morphological reasoning when she considered how she would attempt to identify species and their relationships to each other, “Is it a flowering plant or not? How does it produce seeds? What are leaf shapes? What is the root system like? I believe these types of questions are needed in order to classify the plant and place it in the correct group.” While morphological reasoning might make sense for experts who are attempting to group species into trees based only physical traits, this is not an appropriate rationale for expert phylogenetic cladograms. Using morphological reasoning, students did not consider that commonalities could occur between unrelated, or rather distantly related organisms due to convergent evolution.

4. Which of the following is an accurate statement of relationships illustrated by this tree?



- a) A crocodile is more closely related to a lizard than a bird
- b) A crocodile is more closely related to a bird than a lizard
- c) A crocodile is equally related to a lizard and a bird
- d) A crocodile is related to a lizard but not related to a bird

Provide an explanation for why you chose your answer.

*Figure 3.* This was question four from the pre/posttest. We derived this question from Baum et al. (2005). Students not only select a response, but we also asked to provide their rationale for their answer.

*Branch-Influenced.* This reasoning category was demonstrated by students who interpreted relatedness based upon physical characteristics of the tree: distance between branches and reading the proximity of the tips (Baum et al., 2005; Gregory, 2008). Kelly was a senior biology major who had taken multiple college level biology courses, two of which focused on genetics and evolution. Initially it seemed as though Kelly had an understanding that deep time influenced taxonomy, because she believed that scientists study the relationships of organisms in order “to better understand the past and predict the future.” However, the remainder of her responses illustrated that her phylogenetic tree reasoning was branch-influenced. For example, Kelly’s response to question four (Figure 3), “they [the crocodile and the lizard] are closer together on the phylogenetic tree, but crocs are still related to birds” showed branch-influenced reasoning because she made her decision about the relationship among the crocodile, lizard, and bird due to their physical location of the branches on the tree representation. Much like Kelly’s response to question four, Neil, Bobby, Patty, and Lacy also interpreted relationships based upon

which species appeared closer together when looking at the tips of the tree. Neil's explanations for his answers to questions four and five (Figures 2 & 3) stated that, "the crocodile is closer to the lizard than the bird on the tree;" and, "the seal is closer to the horse on the tree." Bobby stated that, "the crocodile's line is closer to the lizard line than it is to the bird," and "seal is closer to horses than it is to whales." Patty also stated that, "the seal and horse are much closer together in the cladogram than the seal and the whale. Thus, they share more apomorphies and are more closely related." Lacy also used branch-influenced reasoning to interpret the relationships illustrated by phylogenetic trees. She stated that in question 4 and 5 (Figure 2 and 3), "All of the organisms are related; each organism is most closely related to the organism next to it."

In addition, as illustrated in Kelly's response to question five was (Figure 4), "When only looking at the tree, we would assume that 'A' is true. However, when we consider the physical characteristics, we see that 'B' seems true. 'D' is obviously false. Seals and horses are more similar because they both diverged from a 'parent' organism, along a similar time-line. It took whales longer to evolve from the first organism." Kelly continued to use branch-influenced reasoning to make sense of the tree. This reasoning was based on the physical location of the branches and species on the tree, not on common ancestry. She was unable to interpret the tree as showing the seal equally related to the horse and whale, the scientifically accepted idea. If Kelly was able to interpret these trees scientifically, her response would have more closely resembled those students who used phylogenetic reasoning.

*Tree Shape-Influenced.* The type of representation used influenced how students interpreted evolutionary relationships among organisms. Students who had challenges

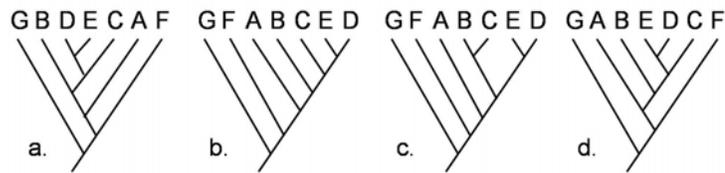
interpreting different styles of phylogenetic trees were aware of how branches related to one another and that nodes were “flippable.” They knew that by flipping the nodes and changing the branch alignment, the depicted relationships among taxa were not altered. However, these students were unable to apply this principle and accurately interpret the relationships when they examined multiple styles of phylogenetic trees. For instance, when describing how to find patterns and interpret relationships shown on similar phylogenetic trees, Ryan stressed the idea that “you just flip the node.” However, he provided varying responses to the same prompt when examining four different styles of trees. The circular tree (see Figure 1, tree 4) was the most confusing and disliked by all of the participants. However, this tree also elicited the most scientifically accurate responses about the depicted relationships. Students were better at verbally describing what they were looking at and how the branches were related as they worked through the “maze” the image portrayed. We concluded that, when the students were given a phylogenetic tree that they had not previously encountered, their schema for interpreting the tree was lacking. This caused them to work critically through the problem without relying upon their alternative prior knowledge.

*Node-Influenced.* The intermediate node-influenced reasoning scheme represents responses that focused on the number and location of nodes that were present between taxa on the phylogenetic tree. While experts interpret phylogenetic trees using nodes to represent common ancestry, students using node-influenced reasoning misused nodes. These students counted nodes to determine evolutionary relationships or only used nodes that fell on the “main branch.” For example, when Doug interpreted the trees in questions four and five on the posttest (Figures 2 & 3) he explained his answers by

stating that a crocodile is more closely related to a bird than a lizard because it has “one common ancestor instead of two” and a seal is more closely related to a horse than to a whale because the “horse is closer to the line and there are less nodes.” Paul also counted nodes when interpreting phylogenetic trees, “The horse has one divergent ancestor before it shares a common ancestor with the seal, where the whale has three.”

Don’s responses referenced node position with respect to a main branch. “The crocodile descended for the bird in a separate manner that the lizard diverging from the bird lineage.” When Don attempted to interpret the phylogenetic tree he viewed the bird lineage as the main branch with the other taxa diverging from it, “each [taxa] branches off the main trunk, so it has some kind of individual characteristic that defines it.” Holly also referenced the idea of a main branch in her response to question nine on the posttest, “I chose ‘B’ because it’s the only one that appears to have all of the branches coming off the main one.” Andy was misled for this same reason. In his response to question nine (figure 4), Andy stated that, “I chose ‘B’ because it doesn’t have secondary branches like, ‘A’, ‘C’, & ‘D’ had.” Ryan was also incorrect in his response to question nine (Figure 4), “None of the organisms [in tree ‘B’] branch off of each other they all branch off of one line, therefore the relationships are different because two different species did not evolved from one branch off of the ancestor.” These explanations indicate that these students thought that phylogenetic trees illustrated species branching off from a main branch. Scientifically, it is accepted that this “main branch” actually represents internal branches or shared lineage history between taxa, and taxa do not branch “off of” one another.

9. Which of the following four trees depicts a different relationship than the others?



Provide an explanation for why you chose your answer.

Figure 4. This was question nine from the pre/posttest. We derived this question from Baum et al. (2005). Students not only select a response, but we also asked to provide their rationale for their answer.

*Quasi-scientific.* Quasi-scientific reasoning is when students used scientifically appropriate reasoning to explain their responses but did not reach scientifically accepted answers. We found that while these students seemed to sound like experts in the field, there was a disconnection between their explanations and the selection of their response. For example, on question six of the pretest, Matthew explained that, “The speciation events leading to seals and horses occurred one after another and suggests great genetic similarity.” Although this statement sounds scientific and logical, Matthew indicated an incorrect answer, selecting response A instead of response C as an expert evolutionary biologist would have selected. Thus, we referred to this as evidence of “quasi-scientific” reasoning.

*Expert*

*Phylogenetic.* When individuals interpret and utilize phylogenetic trees in the same manner as evolutionary scientists, we referred to their reasoning scheme as phylogenetic. For example, when Matthew explained his response to question four in the pretest (see Figure 3), he stated, “If you assume a constant rate of genetic change in all lineages then the two relationships (croc and lizard and croc and bird) share the same

family history and common ancestor, so speciation [leads to] additional speciation.” This reasoning is consistent with that of expert scientists. Similarities to scientific interpretation occurred in one of Doug’s responses as well. Doug explained that a researcher must collect, “genetic evidence. Some plants that are very closely related look nothing alike,” when he discussed the type of evidence needed to identify where a plant belongs on a phylogenetic tree. However, no student showed consistent phylogenetic reasoning throughout the entirety of the data set.

### Discussion

In this study we investigated how students understood and used tree thinking. First, we found that interpretations of the trees influenced how students applied tree thinking to new systematics problems. We classified students’ problem solving abilities on a novice-expert gradient based upon the expert skills identified by Bransford et al. (2000). Novice students lacked all of the expert level skills required to produce viable solutions to phylogenetic problems. These students did not have the conceptual understanding need to develop a cohesive problem solving strategy. Thus, they demonstrated inconsistent reasoning and were unable to produce responses other than disjointed guesses without evidentiary support. Students with intermediate problem solving abilities drew upon some expert skills, but did not possess a complete set of expert skills. Intermediate students used variable reasoning processes based upon various understandings. For instance, some students that were able to identify meaningful patterns associated with phylogenetic trees provided explanations about their answers that were not conceptually accurate. Other students that were unable to recognize patterns and could not interpret phylogenetic trees still understood fundamental systematics

concepts. Only upon achieved a complete set of expert skills, are students able to utilized phylogenetic reasoning for each problem presented. Expert ability, as shown by the professor, was not achieved by any students by the end of the course. However, some students, such as Matthew, were able to access nearly all expert skills and used phylogenetic reasoning to solve select phylogenetic problems requiring tree-thinking but not tree-building. Still, Matthew struggled with the expert abilities needed to apply his understandings to novel problems and be flexible in his problem solving approach. Nearly expert, or advanced intermediate students like Matthew, were able to identify meaningful patterns of information presented on phylogenetic trees, held a large amount of conceptual content knowledge about systematics, were able to retrieve pieces of their knowledge base easily, but were unable to vary their approach and transfer their reasoning process across a variety of problems.

We identified eight major reasoning processes that interrupted students' transition from novice to expertise tree thinking: inconsistent, reliance on expert knowledge, ecological, morphological, branch-influenced, tree shape-influenced, node-influenced, and quasi-scientific. Each of the student participants used one or more of these reasoning processes. For example, over the semester, Holly shifted from using ecological to node-influenced reasoning to interpret phylogenetic trees and solve systematics problems. In another example, Doug transitioned from ecological reasoning to either node thinking or eventually quasi-scientific thinking to interpret and use phylogenetic trees by the end of the semester. However, while some students used multiple reasoning processes throughout the course or an exam, only one reasoning type was used to address each individual problem.

Although we identified misconceptions consistent with those identified previously (such as reading across the tips, main lines and side tracks, similarity versus relatedness, and more intervening nodes equals more distantly related) (e.g., Baum et al., 2005; Gregory, 2008), we also found misconceptions that went beyond misreading the topology of phylogenetic trees. Our results indicate that when students were presented a phylogenetic tree, they did not consider it to contain enough information to solve a systematics problem. Therefore, they relied upon prior knowledge to supplement or overturn phylogenetic reasoning. We found that most students used the seven intermediate categories of reasoning (see Table 1). Because students relied upon non-phylogenetic reasoning to solve most systematics problems, we believe that categorizing student misconceptions based upon responses to multiple choice items may not be an accurate assessment of their understanding. For example, just because students selected ‘A’ to question five on our pretest (see Figure 2), they were not necessarily “reading across the tips” as suggested by Baum et al. (2005) and Gregory (2008). Likewise, ‘B’ responses were not necessarily indicative of students’ comparing nodes or connecting similarity to relatedness. These researchers would suggest that ‘D’ responses indicated misconceptions about a main line and side tracks. However, our findings reveal that students interpreted tree based upon fundamental inaccuracies in their conceptual understandings about phylogenetics. Students selected their responses for one of eight reasons, twice as many as predicted, most of which were based upon non-topology ideas, such as ecological characteristics.

We found that students were resistant to solving problems using abstract tools, such as phylogenetic trees, and had difficulties using expert level skills to interpret

phylogenetic representations. Although the course emphasized tree thinking throughout, no student made reference to tree thinking when explaining responses to questions that did not refer explicitly to a tree. While students attempted to make sense of relationships among unknown organisms and interpret given trees, they did not attempt to use tree thinking to help make sense of new systematics problems. While students were able to interpret representations similar to those presented within the course, they were unable to transfer that knowledge to interpret or generate novel representations. Without this transfer ability, students will not become experts in evolutionary biology (Bransford et al., 2000).

The alternative types of reasoning used by the students influenced their representation-based thinking abilities. For example, our findings showed that students utilized their prior knowledge to make sense of the visual trees in ways that did not align with scientific explanations. Instead of basing interpretations upon genetically determined characters, students' used intermediate reasoning schemes, such as ecological reasoning, and considered ecological elements (e.g., where the organisms lived) rather than using the tree itself to interpret relationships among species. When students attempted to build a visual representation, they grouped species according to ecological similarities rather than focusing on phylogenetic characteristics. This caused students to give inaccurate content description and to generate inaccurate representations (consistent with novice or intermediate level thinking). The multiple types of reasoning about systematics identified stemmed from misconceptions in prior knowledge as well as inability to make sense of the tree representation. This suggests that each of these areas must be addressed explicitly in order to help the learners achieve expertise in the field.

## Implications

The type of reasoning students use can cause them to generate a variety of responses when interpreting and using phylogenetic trees. Current quantitative assessment instruments (e.g., Baum et al., 2005) may uncover apparent categories of student errors, such as those described by Gregory (2008), but they do not uncover the underlying reasoning patterns. Student errors often prevail due to deeper conceptual misunderstandings about the relationships depicted on the tree representation. Thus, while a student may appear to “read across the tips,” they may hold a representational-based misconception, or they may base their ideas upon perceived ecological connections. Such a dualistic interpretation is masked by misconception defined error categories such as “reading the tips”. If instructors target instruction solely toward representation-based misconceptions such as this, instruction may lead to unintended learning outcomes or be fruitless. Rather, our finding about alternative types of reasoning implies that instructors must explicitly design instruction toward evolutionary reasoning in addition to tree interpretations; thereby targeting instruction toward improving the foundational reasoning used as well as overcoming representation-based misconceptions. Thus, instructors who use tree thinking in their courses will also need to understand and challenge student misconceptions in evolution. Much of the current biology curriculum is driven by the use of phylogenetic trees. However, it is clear that novice students do not interpret trees in the same manner as expert evolutionary biologists. The biology curriculum must be altered to recognize the alternative student reasoning types in order to effectively promote development toward expertise. In particular, this is true when considering the role of prior knowledge and the detrimental

effect misconceptions can have on student learning. In addition to identifying and targeting misconceptions about tree interpretations, students must be given the opportunity to explore systematics problems in ways that utilize evolutionary trees. Explicit direction on how to utilize tree thinking thought process is necessary to help students move from a novice status to an expert problem solver.

While very little research about tree thinking, or other representations, exists in biology, studies about student thinking about representations in chemistry and physics provide guidance for instruction and for future research (Gilbert, 2005). These studies highlight the importance of both content knowledge mastery as well as spatial reasoning. Baum et al. (2005) investigated how the topology of phylogenetic trees caused students to fail to see patterns of evolutionary relatedness. However, they did not investigate how students used trees to solve new problems. Their findings suggested that branch proximity was the core reason students failed to interpret relationship patterns illustrated. We found that branch proximity did interfere with some students' reasoning, but this was not the only, or primary, challenge associated with tree-thinking. Our study provides insights into how college biology students interpret and use phylogenetic trees. The lack of literature in this area leads to the need for future research on to the role that representations play in learning biology. By better understanding our students, we will be able to design an informed curriculum that enhances meaningful learning in biology.

#### References

Anderson, K. C., & Leinhardt, G. (2002). Maps as representations: Expert novice comparison of projection understanding. *Cognition and Instruction, 20*, 283-321.

- Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree-thinking challenge. *Science, 310*, 979-980.
- Boster, J. S., & Johnson, J. C. (1989). Form or function: A comparison of expert and novice judgements of similarity among fish. *American Anthropologist, 91*, 866-889.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school* (Expanded ed.). Washington D.C.: National Academy Press.
- Caravita, S. (2001). A re-framed conceptual change theory? *Learning and Instruction, 11*, 421-429.
- Cobern, W. W., Gibson, A. T., & Underwood, S. A. (1999). Conceptualizations of nature: An interpretive study of 16 ninth graders' everyday thinking. *Journal of Research in Science Teaching, 36*, 541-564.
- Cooper, R. A. (2002). Scientific knowledge of the past is possible: Confronting myths about evolution and scientific methods. *American Biology Teacher, 64*, 427-432.
- deGroot, A. D. (1965). *Thought and choice in chess*. The Hague, the Netherlands: Mouton.
- Donovan, S. S. S. (2004). A brief introduction to tree thinking. Retrieved January, 2007, from <http://www.lrdc.pitt.edu/donovan/intro.html>
- Donovan, S. S. S. (2005). *Tree thinking and reasoning about change over deep time*. Paper presented at the National Association of Biology Teachers Convention, Chicago.

- Fullan, M., & Steigelbauer, S. (1991). *The new meaning of educational change* (2nd ed.). New York: Teachers College Press.
- Gendron, R. P. (2000). The classification & evolution of caminalcules. *American Biology Teacher*, 62, 570-576.
- Gilbert, J. K. (Ed.). (2005). *Visualizations in science education*. Dordrecht, The Netherlands: Springer.
- Gregory, T. R. (2008). Understanding Evolutionary Trees. *Evolution: Education and Outreach*, 1, 121-137.
- Hackling, M. W., & Garnett, P. (1992). Expert-novice differences in science investigation skills. *Research in Science Education*, 22, 170-177.
- Hatch, J. A. (2002). *Doing qualitative research in education settings*. New York: State University of New York Press.
- Heyworth, R. M. (1999). Procedural and conceptual knowledge of expert and novice students for the solving of basic problem in chemistry. *International Journal of Science Education*, 21, 195-212.
- Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Thousand Oaks, CA: Sage.
- Meir, E., Perry, J., Herron, J., Maruca, S., Stal, D., & Kingsolver, J. (2005). *How effective are individual-based simulations in EvoBeaker at overcoming misconceptions in evolution?* Paper presented at the ESA Annual Meeting
- National Research Council. (1996). *National science education standards*. Washington D.C.: National Academy Press.
- O'Hara, R. J. (1998). Population thinking and tree thinking in systematics. *Zoologica Scripta*, 26, 323-329.

- Palmer, S. E. (1978). Fundamental aspects of cognitive representation. In E. Rosch & B. B. Lloyd (Eds.), *Cognition and categorization* (pp. 259-303). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Patton, M. Q. (2002). *Qualitative research & evaluation methods*. Thousand Oaks, CA: Sage Publications.
- Simon, H. A., Larkin, J. H., McDermott, J., & Simon, D. P. (1989). Expert and novice performance in solving physics problems. In H. A. Simon (Ed.), *Models of thought* (Vol. 2, pp. 243-256). New Haven, CT: Yale University Press.
- Stake, R. (1995). *The art of case research*. Thousand Oaks, CA: Sage Publications.
- Tabachneck, H. J. M., Leonardo, A., & Simon, H. A. (1994). *How does an expert use a graph? A model of visual and verbal inferencing in economics*. Paper presented at the 16th Annual Conference of the Cognitive Science Society.
- Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, *10*, 159-169.



**Required Textbooks (2, bring to every lecture and lab):**

1. Simpson, M. G. 2006. *Plant Systematics*. Elsevier Academic Press. ISBN: 0126444609.
2. Mohlenbrock, R. H. 2002. *Vascular flora of Illinois*. Third edition. Southern Illinois Univ. Press. Carbondale. ISBN 0-8093-2421-0.

**Optional Texts (2):**

1. Denison, E. 2001. *Missouri Wildflowers*. 5<sup>th</sup> Edition. Missouri Department of Conservation, Jefferson City. ISBN: 1887247289.
2. Harris, J. G. and M. W. Harris. 2001. *Plant Identification Terminology. An Illustrated Glossary*. 2<sup>nd</sup> Edition. Spring Lake Publ. Spring Lake, Utah. ISBN: 0964022168.

**Other Course Materials:** Hand lens (“loupe”, 10x or greater), small field notebook. Drawing Pencils: 2H (or 3H). Eraser. Drawing paper in 3-ring notebook. Dissection kit.

***Teaching and Learning Goals and Objectives***

After completing the course, students should be able to:

1. state, define, and give examples of the components of taxonomy: description, identification, nomenclature, and classification.
  2. describe a plant, using the descriptive terminology of plant morphology and reproductive biology.
  3. draw phylogenetic relationships of the major lineages of plants, indicating their classification and significance of major evolutionary changes.
  4. name, classify, and diagnose several of the major families of flowering plants.
  5. collect, identify, and record field data; create herbarium specimens.
  6. state the principles and rules of plant nomenclature, including how to publish a new taxon name, and know how to use and apply botanical names.
  7. describe the basics of the theory and methodology of phylogenetic systematics and how it is applied in systematic research.
  8. design and implement a project in plant systematic research.
  9. use the major literature sources in plant systematics, including bibliographic surveys.
- Students will be assessed for the above skills by class participation in lecture and lab, graded quizzes, assigned exercises, tests, lab practicals, and a research project.

**Classroom Etiquette**

Please ARRIVE TO CLASS ON TIME and plan to stay for the full period of the class. If you are late for a lecture or lab quiz or exam you will not be given additional time. NO EXCEPTIONS. Be aware that you are responsible for all lecture notes, supplements, and additional readings for the exams. If you miss a lecture or a lab, you are responsible for getting homework assignments and other information you missed. Labs are taken down the following day so if you cannot make your lab session one day we will make reasonable attempts to have you attend another lab on that same day but only with advance notice. Always be neat and clean up your area completely at the end of class. Discussion in class is expected and encouraged, but always interact with instructors and other students in a respectful and civil manner.

## Discussion

This class is *discussion based*, often using the *Socratic method*, so it is important that you read and study a topic ahead of time. (Part of your grade is assigned for your initiation of discussions and asking questions.) The "topic" will generally correspond to all or part of a book chapter or a research article. Occasionally, the instructors will have you get into groups of 2-4 people and discuss, recite, or review material. We welcome feedback as to the most effective and interesting way to learn.

## ***Homework Assignments***

Some type of homework assignment will be given each week. Homework will vary from reflection activities given online to answering select Chapter Review Questions. Occasionally, other assignments will be given. Homework assignments are due at the start of each period or as specified if online, and there are no make-ups. Class participation and homework assignments account for 10% of your grade (a "freeby"), and doing the homework in a timely fashion will help you on the exams.

## ***Quizzes***

There will be quizzes in lecture and lab interspersed between the midterms and final exams. Like the homework, their purpose is test your knowledge and to help you to keep up with the material in the course. Quizzes usually start at the beginning of class and there are no make-ups for being late or ill. Please arrive to class on time.

## ***Exams***

These will consist of a lecture exam and a lab practical for each third of the class. Lecture exams cover BOTH facts and concepts of BOTH lecture and lab material (especially where lecture and lab intergrade). The exams may include questions directly or modified from the chapter review questions. We often ask students to come up with exam questions as well. Some questions will demand a degree of synthesis. The typical format for lecture exams may include a mix of rote questions (definitions, true/false, matching), short answer, short essay, and usually one longer essay question that requires synthesizing information from several fields of biology. Grading for essay questions will be based in part on organization, grammar, and prose. Thus, it is strongly suggested that you spend a minute or two jotting down an outline of what you wish to say before you begin writing. Lab practicals consist of on-site identification of plants and plant parts, including identification of major groups, families, and/or taxa. The first portion of the lab practical consists of a number of stations with general questions such as: what is the name of the structure indicated? To what major group/family does this species belong? The second portion of the lab practical may include keying out an unknown species, material for dissection and identification and a more lengthy elaboration of features of that material.

## ***Plant Identification***

With each plant family we study, we may select at least one and often several taxa to learn, usually from lecture and lab demonstrations or cultivated plants on campus. We will keep a running list of these taxa through the semester. You are responsible for knowing the scientific name of each (correctly spelled) and the family or group to which they belong.

### ***Herbarium Collection***

Each student will be required to collect plants and to properly process them (with labels) toward making herbarium specimens. Students do not get to keep their collection, as specimens become part of the research and teaching collections. Details on collections will be given later, but some opportunity for extra credit may be available at the discretion of the instructors.

### ***Laboratory Notebook, Drawings and Photography***

You will need to keep a laboratory notebook for the duration of the course. This notebook should contain illustrations that you make during lab, primarily those that are listed for you to draw in the laboratory exercises. The notebook should have 3-hole punched white paper placed in a 3-ring notebook so that select drawings may be removed. We will evaluate your drawings early in the semester to give you suggestions for improvement. The laboratory notebook is due thrice during the semester, on the day of each lab practical. Another goal is for you to learn digital photography. During several labs, we will designate students to photograph and upload images of whole plants/organs or dissected material.

### ***Research Project***

A final goal of the course is to apply knowledge of plant systematics in the form of a project. Everybody will work on a research project focused on the Brassicaceae (Mustard Family). You will collect and prepare illustrations and/or photographs of taxa in this family, including aspects of vegetative and reproductive morphology (flowers and flower parts from whole and variously dissected specimens). In addition, you will write about the family, including keys, circumscription, apomorphies, phylogenetic relationships, and economic, biogeographic, and ecological significance (as well as other data that you may collect and describe). As individuals or in groups, you will also give a powerpoint presentation in lab. We will have the class as a whole contribute to making a "rubric", a list of characteristics of a good presentation. Graduate students can discuss alternative research projects with the instructors.

### ***Field Trips***

We have only organized ONE field trip during lab time. If we have time and sufficient interest, we may arrange for some optional (yet to be scheduled) fieldtrips outside of lab time.

### ***Grading for 4 credit course***

Homework Assignments/Participation	10%	100 points
Quizzes (e.g., weeks 3, 8, 12 lecture and lab)	10%	100 points
Midterm Exam #1 (week 5 lecture and lab)	20%	200 points
Midterm Exam #2 (week 9 lecture and lab)	20%	200 points
Research Project	10%	100 points
Herbarium Collection	10%	100 points
Final exam (lecture and lab - semicumulative)	<u>20%</u>	<u>200 points</u>
	100%	1000 points total

### **Additional Resources for Further Study**

*Guide to Flowering Plant Families* by W. B. Zomlefer; University of North Carolina Press. This is a very well illustrated (line drawings) overview of about 100 flowering plant families that follows the classification of Thorne, rather than Cronquist. It also includes a useful, abbreviated illustrated glossary. Although it lacks information on the non-flowering plants and supplemental supporting information about the science of taxonomy, the illustrations and family descriptions for flowering plants are superb. It is a great book, and very reasonably priced.

*Plant Systematics: A Phylogenetic Approach* 2<sup>nd</sup> ed. by Judd, Campbell, Kellogg, and Stevens. Sinauer Associates, Inc. This book has a good introduction to systematics as a science, basic morphological terms, a CD-ROM with pictures of representative species for many families, and cites a lot of current research. The plant families covered include descriptions, economic uses and interesting biology, and line illustrations.

*Vascular Plant Taxonomy* 4<sup>th</sup> ed. by D. R. Walters & D. J. Keil; Kendall/Hunt Publishing. A good general introduction to plant taxonomy with both family descriptions and information on the science of taxonomy. Follows the older Cronquist system for the flowering plant hierarchy and family circumscriptions. Has simple illustrations for many families.

*Contemporary Plant Systematics* 3<sup>rd</sup> ed. By D. W. Woodland; Andrews University Press. Another good general book, this one with a CD-ROM with photographs for many of the families. Cronquist's system for the flowering plants is also followed in this book. The background information on systematics and morphological terms is very good, family treatments concise, but illustrations are not all that great.

*The Plant Book: A Portable Dictionary of the Higher Plants.* 2<sup>nd</sup> ed. By D. J. Mabberley; Cambridge University Press, Cambridge.

#### Books in lab:

*Flora of Missouri*, Volumes 1 and 2.

*Trees of Missouri* and *Trees of Missouri Field Guide*

*Shrubs and woody vines; Missouri Orchids; Missouri Wildflowers* and other resources.

*Websites:* Google "Angiosperm Phylogeny Website" which is an excellent resource that also has links. Also google "Flora of North America" and "Flora of Missouri" to begin looking for project ideas.

### **Statement for ADA**

If you need accommodations because of a disability, if you have emergency medical information to share with me, or if you need special arrangements, please inform me immediately. Please see me privately after class, or arrange to meet me at my office. Reasonable efforts will be made to accommodate your needs. To request academic accommodations (for example, a note taker or extended time on exams), students must also register with the Office of Disability Services (<http://disabilityservices.missouri.edu>), S5 Memorial Union, 882-4696. It is the campus office responsible for reviewing documentation provided by students requesting academic accommodations, and for planning accommodations in cooperation with students and instructors, as needed and consistent with course requirements. For other MU resources for students with disabilities, go to "Disability Resources" on the MU homepage.

### **MU Statement on Academic Dishonesty and Student Conduct**

Academic honesty is fundamental to the activities and principles of a university. All members of the academic community must be confident that each person's work has been responsibly and honorably acquired, developed, and presented. Each student is expected to conduct all work within the letter and spirit of the MU academic honesty policy. Any effort to gain an advantage not given to all students is dishonest whether or not the effort is successful. In particular, when a student uses a purchased research paper, the work of another, the ideas or words of another, or portions there from, and represents this as his or her own work without giving the originator proper credit, then that student has plagiarized the source. Cheating on assignments or exams, plagiarism, obtaining exam questions prior to the examination, and other academic misconduct may result in a failing grade on the particular assignment or exam, a failing grade in class. The academic community regards academic dishonesty as an extremely serious matter, with serious consequences that range from probation to expulsion. When in doubt about plagiarism, paraphrasing, quoting, or collaboration, consult the course instructors. Also, students are referred to Chapter 200 of the Collected Rules and Regulations of the University of Missouri (<http://www.umsystem.edu/ums/departments/gc/rules/programs/200/>) for other rules applicable to this class that govern student conduct.

### **Emergency Information for Tucker Hall**

In the lab and online we have posted emergency contact information for this building (Tucker Hall), which includes a description of the building, assembly points and shelter locations. This handout does not include specific instructions on what to do in an emergency but those can be found by going to <http://ehs.missouri.edu/other/er>. As emergency planning is an on-going effort at the MU, you may receive a subsequent e-mail in the coming weeks or months with that updated information. We strongly encourage you if you have not already done so to register your cell phone with MU's Mass Notification System. This will ensure that you will be notified via your cell phone in the event of a campus-wide emergency. Instructions on how to register your cell phone can be found on MU Alert at <http://mualert.missouri.edu>, and to register your cell phones with the system through MyZou. If at any time you should have questions about the Mass Notification System, or Emergency Planning in general at MU please do not hesitate to contact Chad Pfister at 882-5508 or [pfisterc@missouri.edu](mailto:pfisterc@missouri.edu).

***Tentative Course Schedule – weeks 1-5***

<b>Wk</b>	<b>Date</b>			<b>Lecture Period Topic/Reading</b>	<b>Lab Period Topic/Activity/Reading</b>	<b>Assignment:</b>
1A	Tu	Jan	22	Plant Systematics: Overview (assign Ch 1 in class); what is systematics?	Introductions; Greenhouse visit; diversity of plants; facets of taxonomy (Ch 1)	<b>Ch 1 and Appendices Homework 1 assign</b>
1B	Th	Jan	24	Introduction to Phylogenetics: Microevolution to Macroevolution Discuss chapter 1	Pre-Test (30-45 minutes), Consent forms How to do a lab notebook; Grading Criteria (Appendix 1 and 2)	<b>Ch 2 and Ch 9 vegetative parts</b>
2A	Tu	Jan	29	Phylogenetic Systematics Overview (Ch 2); Intro to Tree terminology, Representations; pre-test ideas	Plant Morphology: Vegetative Characters (Ch 9) Overview of required terminology to know Last Day to register/add/change sections	<b>Godfrey article Ch 9 finish Homework 2 assign</b>
2B	Th	Jan	31	Phylogenetic Systematics: History Discuss chapter 2 Discuss Godfrey article	Flower morphology, inflorescences (Ch 9) How to do a lab notebook/illustration review	<b>Baum article Ch 3-4 assign</b>
3A	Tu	Feb	5	Evolution and Diversity of Green Land Plants (Ch 3) & Vascular Plants (Ch 4) Discuss Baum article	Fruits and seeds (Ch 9) Grocery Store Botany Morphology/Terminology review: describe Salvia (Ch 9 and Appendices finished)	<b>Ch 15 assign Study for quizzes Homework 3 assign</b>
3B	Th	Feb	7	<b>Lecture Quiz (Ch 1, 2, 9, lecture)</b> Discuss Baum article and Class Activity: Mobiles Chapter 2 Cladogram construction	<b>Lab Quiz (Ch 9, Appendices 1 and 2, lab)</b> Constructing keys: mythical creatures and/or Hypothetical plants or Winter twigs/gymnosperms Research Project handouts	<b>Ch 5-6 and online lectures; Hypothetical plants matrix/key;</b>
4A	Tu	Feb	12	Evolution of Seed Plants and Flowering Plants; angiosperm apomorphies (Ch 5-6 overview) Darwin's "abominable mystery".	Family characters/keying/herbarium sheets Key Brassicaceae taxa Hypothetical plant key exercise	<b>Friis paper; exam ?s, Homework 4 (Ch 6) Hypothetical plants</b>
4B	Th	Feb	14	Discuss and Turn in Exam 1 Questions Hypothetical Plant Key & Tree Exercise	Family descriptions/keying/herbarium sheets Discuss lab exam Research Project	<b>Ch 6 homework concept map; Exam study guide</b>
5A	Tu	Feb	19	Review chapter 6 angiosperm apomorphies and "concept map" it; Discuss Friis paper, exam preview	Family descriptions/keying Review for lab practical	<b>Homework 5 Study for exam</b>
5B	Th	Feb	21	<b>Lecture Exam #1 [Simpson Ch 1, 2, (3-5) 6, 9, 15 and papers (e.g., Godfrey, Baum, Friis), and lecture/ lab materials]</b>	<b>Lab Practical #1 [Ch 9 terminology, plant parts, families; Lab Notebooks Due]</b>	<b>Assign chapter 14 and give notes; Online DNA Lecture</b>

***Tentative Course Schedule – weeks 6-9 (subject to change)***

6A	T	Feb	26	Review Midterm exam/Feedback; DNA systematics; (Ch 14) Issues of molecular systematics (Homology, chloroplast capture, hybridization and introgression, molecules vs. morphology, data types, chloroplast vs nuclear gene trees, etc).	Exam reviews, Current class grade <b>(drop dates deadline is Monday February 25)</b> Family characters/keying/herbarium sheets: Key winter twigs and/or gymnosperm genera Research Project	Ch 14 Online lecture? Research Project reading <b>Homework 6 assign</b>
6B	Th	Feb	28	Class Activity: molecules vs. morph-WHIPPO and/or Brassicaceae exercise Incongruence issues 1	Family characters/keying/herbarium sheets Research Project	<b>Assign Ch 7 part 1 assign pp 137-153</b>
7A	T	Mar	4	Evolution of “Basal” Angiosperms: Magnolias and wild gingers (Ch 7 part 1) Set up Thursday Cracraft discussion	Family characters/keying/herbarium sheets Start keying using Mohlenbrock’s Flora !	<b>Incongruence article</b> Research Project reading <b>Homework 7</b>
7B	Th	Mar	6	Exam questions due Discuss incongruence article and relevance to Brassicaceae project Molecules vs. morphology debate cont’ Missing data issues	Family characters/keying/herbarium sheets: Lab Quiz preparation/review Research Project	<b>Finish Ch 7 on monocots Quiz study</b>
8A	T	Mar	11	<b>Lecture Quiz</b> Origin of Monocots: aquatics, yams, lilies, irises, and orchids; Synapomorphy of commelinids (Ch 7 monocot overview)	<b>Lab Quiz</b> Family characters/keying/herbarium sheets:	<b>Cracraft article Ch 7 finish</b> Online lectures? <b>Homework 8 (Ch 7/8)</b>
8B	Th	Mar	13	Why does phylogenetics matter? Systematics and Society Discuss Cracraft paper Online midcourse evaluation (& SALG)	Family characters/keying/herbarium sheets: Research Project TA mid course evaluation (in future)	<b>Assign Ch 8 part 1 pp. 227-252</b> <b>Next exam questions</b>
9A	T	Mar	18	Basal Eudicots: Ranunculids: buttercups; Caryophyllids: carnations, cacti, and chenopods (Ch 8 intro) Turn in questions and exam review	Family characters/keying/herbarium sheets PowerPoint of weedy/garden plants not to collect Plant Collection handout/give out presses Ch. 17-18? Plant Collecting & Documentation	<b>Ch 8 part 2 pp. 252 – 289 and homework?</b> <b>Homework 9 Exam Study Guide</b>
9B	Th	Mar	20	<b>Lecture Exam #2 [Simpson Ch 7, 8, 14, 17, &amp; papers, and lecture/lab materials]</b>	<b>Lab Practical #2 [Ch 9 terminology, plant parts, families; Lab Notebooks Due]</b>	
	Sat	Mar	22	<b>SPRING BREAK 22 – 30</b>	Field Collections and Research Project	Read Ch 13/Hapeman

***Tentative Course Schedule – weeks 10-16 (subject to change)***

10A	T	April	1	Review midterm; midsemester evaluations, grades; Intro to Pollination biology/Coevolution (Ch 13 and set up journal article)	Review midterm; evaluations, and explain grades; Family characters/keying/herbarium sheets	<b>Read Ch 13 and Hapeman article Research project Homework 10</b>
10B	Th	April	3	Discuss Hapeman article and Ch 13; convergent evolution (molecules vs. morphology debate); Ancestral States; Evidence for evolution Reconnect micro- to macroevolution	Family characters/keying/herbarium sheets PowerPoint of mapping and collecting Plant Press Demo: See Ch 18 for collection help <b>Research Project Data Collection done?</b> (April 7 last day to withdraw from course)	<b>List evol'n evidence Assign Doebley 2006 domestication paper</b>
11A	T	April	8	Speciation lecture and introduction to domestication syndromes; Artificial selection vs nat selection How environment influences genes	Family characters/keying/herbarium sheets <b>Research Project write-up?</b>	<b>Doebley article Rosids project Homework 11</b>
11B	Th	April	10	Discuss Doebley et al. 2006 review paper on Plant Domestication	<b>RESEARCH PROJECT POWERPOINT PRESENTATIONS</b>	<b>Turn in presentation homework and first pressed plant; Finish Ch 8 reading</b>
12A	T	April	15	Overview of Rosids (Ch 8) Folk taxonomy/pre-survivor preparation	Family characters/keying/herbarium sheets <b>First plant of plant collection due!</b>	<b>Study for quiz Assign Ch 8 homework for rosids and asterids Homework 12</b>
12B	Th	April	17	<b>Lecture Quiz (Ch 8 and 1 paper)</b> Overview of Asterids (Ch 8)	<b>Lab Quiz</b> Demo Pollination syndromes	<b>Assign 6 final exam questions over weekend</b>
13A	T	April	22	<b>Plant Taxonomy Survivor!</b>	<b>Field Trip to Hearn Hill Optional Herbarium Visit</b>	<b>Work on Plant Collections Homework 13</b>
13B	Th	April	24	Plant Biogeography – Earth and life evolve together; Fossil evidence and plate tectonics paradigm	Family characters/keying/herbarium sheets Work on herbarium collections of 5 sheets	<b>Assign 6 final exam questions</b> Finish Collections! Lab exam study
14A	T	April	29	Phylogenomics: Deep Green-to-Conservation ? Plant oddities, carnivores, and systematic puzzles	Family characters/keying/herbarium sheets	<b>Lab final study Homework 14</b>
14B	Th	May	1	<b>4-6 Student Research Presentations</b>	Family characters/keying/herbarium sheets TA Evaluations	

15A	T	May	6	Adaptive Radiations; review Student supplied exam question.	<b>Phylogenetic Post-test (30-45 minutes); Review for lab final exam</b>	<b>Homework 15</b>
15B	Th	May	8	Adaptive Radiation, Overview of final exam study guide (student questions); <b>Course evaluations</b>	<b>Lab Practical Final (Semicumulative; keying) Plant/Herbarium Collections Due Friday morning, May 9)</b>	<b>Lecture final study</b>
16	??	May	??	<b>Final Exam #1: 10:30 AM-12:30 PM 18 Tucker (Ch 3, 4, 5, 8, 18 and papers) plus semicumulative</b>	<b>Semicumulative (focus on last third of course; see study guide that includes student-generated exam questions)</b>	<b>Final grades due ??</b>
	Sat	May	12	<b>Commencement Weekend</b>		

APPENDIX C. CONSENT FORM



University of Missouri

**MU Science Education Center**  
 Kristy L. Halverson, Doctoral Candidate

321-O Townsend Hall  
 Columbia, MO 65211-2400  
 VOICE (573) 884-5370  
 FAX (573) 884-2917

Winter 2008

Dear BIO SC 3210 Student,

I am a doctoral student in science education at the University of Missouri-Columbia (MU) conducting a research investigation on college biology majors' understanding and using of tree thinking in a plant systematics course. Science educators, like myself, have focused upon what to teach and how to teach it. However, not much is known about what's going on in students' mind when they try to make sense of new taxonomy concepts. Professors can teach better if they know how to help students thought processing, but we need your assistance in helping us determine what is effective for students. Tree thinking is a foundation for learning major systematic concepts. Thus, learning plant systematics requires more than reading the textbook and listening to the lecture. I believe that a person's thinking processes can make his/her learning more effective. I hope you will be interested in contributing to this project. I'm asking for volunteers to provide me with your insights into how you develop your understandings and thinking skills while working through plant systematics problems.

Your participation is totally optional. The professor will not know who is or is not participating. However, if you are willing to participate, you can choose to do so at one of two levels:

	Type of Study Participation	Your Time Commitment
<b>1</b>	Provide access to your answers on: (1) homework assignments, reflective journals, and exams, and (2) basic demographic information (grade level, major, etc.)	NONE!
<b>2</b>	Provide access to your answers on: (1) homework assignment and exams, and (2) basic demographic information (grade level, major, etc.) PLUS share with me your thought process while working through plant taxonomy problems during 2 interviews	Two interviews (1~1½ hour each) during the semester

The problems used in the interview are aligned with this course. This interview may benefit you by refreshing and reorganizing concepts you have learned from the class as well as examine new problems. The interviews will be scheduled at a time and location convenient to you. These interviews will be video and audio taped to ensure accurate data collection and to facilitate data analysis. These data files will be stored in a secure location and will be kept on file for no more than three years.

**You must be 18 years old to participate in this study and your participation is completely voluntary.** If you agree to participate, you may choose not to answer any question. You may withdraw from the study at any time without consequences to you. Your confidentiality will be strictly protected. Your name will be replaced with a code. Only the researcher (Kristy Halverson) will have access to the master list that matches your name with the code. Video and audio files from interviews will be transcribed by the student investigator or a university transcriptionist. As soon as the transcriptions are complete, all files will be securely stored. The study is being conducted to provide a better understanding of how students apply their knowledge toward plant systematics problems. Eventually we would like to publish findings. NO results will be reported in a manner that would allow a reader to associate any responses to you. You will not be purposely deceived, nor does this project does not pose physical danger. Participating in the study will subject you to no risks greater than those you normally encounter in everyday life.

Please feel free to ask any question during or after your participation in this study. If you have questions or concerns about this study, you may contact me:

Kristy Halverson  
321-O Townsend Hall  
University of Missouri – Columbia  
Columbia, MO 65211  
e-mail: [klhf25@mizzou.edu](mailto:klhf25@mizzou.edu)  
phone: (573) 884-5370

For questions concerning human subjects research, you may contact the MU Campus Institutional Review Board at:

Campus IRB Compliance Office  
483 McReynolds Hall  
Columbia, MO 65211  
(573) 882-9585

You also may email the Campus IRB Compliance Office at [umcresearchcirb@missouri.edu](mailto:umcresearchcirb@missouri.edu).

Your signature on the attached consent form indicates that you have received a copy, read, and understand this letter that describes the study. The informed written consent is required by IRB for your participation.

Thank you!  
Sincerely,

Kristy Halverson, Ph.D. Candidate  
Science Education

Sandra Abell, Professor, Science  
Education  
Dissertation Supervisor

\*\*If you return the Informed Consent Form (regardless of participation) you will be entered into a raffle to win (1 of 2) \$75.00 gift certificates (venue chosen by the researcher) - drawing to be held at the end of the semester. If you volunteer for this study you will be given an additional entry for the raffle drawing. If you volunteer for the interview series and are not selected to participate at this level you will still be given two additional entries into the raffle drawing. If you choose to volunteer for the interview series and are selected to participate at this level, you will be given two additional entries into the raffle drawing and upon completion of both interviews you will receive a \$20.00 gift certificate (venue chosen by the researcher).

**Informed Consent Form**  
**Investigating the Development and Use of Phylogenetic Thinking in College Undergraduates**

**Please indicate what your decision is regarding participation in this study by checking one box indicating your choice, signing and then dating the consent form.**

I AGREE TO PARTICIPATE in the ‘Investigating the Development and Use of Phylogenetic Thinking in College Undergraduates’ study being conducted by a graduate student investigator, Kristy Halverson, at the University of Missouri – Columbia. I understand that my participation is voluntary and that I may withdraw at any time without consequences to me. I know that my participation has no bearing upon my course grade.

**Circle a number below to indicate your level of participation:**

- 1** I agree to grant access to my answers on (1) homework assignments and exams, and (2) basic demographic information (grade level, major, etc.). I understand that there will be NO extra time commitment on my part.
  
- 2** I agree to grant access to my answers on (1) homework assignments and examines, (2) basic demographic information (grade level, major, etc.) **and** share my thinking process while working through plant taxonomy problems in two 1 ~ 1½ hour interviews to be scheduled at my convenience during the semester (and if selected, will receive compensation upon completion of both interviews).

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Date

\_\_\_\_\_  
Name (Please Print)

\_\_\_\_\_  
Student number

\_\_\_\_\_  
Email address

\_\_\_\_\_  
Phone number

I DECLINE TO PARTICIPATE in the ‘Investigating the Development and Use of Phylogenetic Thinking in College Undergraduates’ study being conducted by a graduate student investigator, Kristy Halverson, at the University of Missouri – Columbia. I know that my decision has no bearing upon my course grade.

\_\_\_\_\_  
Name (Please Print)

\_\_\_\_\_  
Date

APPENDIX D. PRETEST INSTRUMENT

Name: \_\_\_\_\_ Date: \_\_\_\_\_

Grade: (Please circle) Freshman      Sophomore      Junior      Senior      Graduate

Major: \_\_\_\_\_

1. Briefly explain what evolution means and how some flower species pollinated by butterflies with long mouth parts evolved longer flower tubes.



2. What type of variation in organisms is passed on to the offspring?
- a) Any behavior that was learned during the organism's lifetime.
  - b) Characteristics and behaviors that are useful or beneficial.
  - c) Characteristics that are genetically determined.
  - d) Any characteristics that were influenced by the environment.
  - e) Characteristics that influenced where the organism lived.

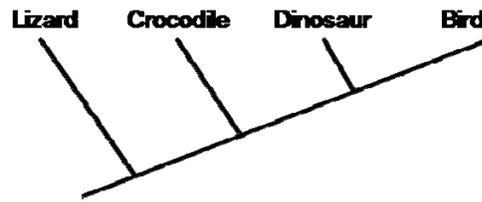
Explain why you selected this answer:

3. What information do scientists use when categorizing organisms into evolutionary related groups? (circle as many type of information as appropriate)

- |   |                          |
|---|--------------------------|
| Genetic Sequences                       | Geographic Location      |
| Environmental Conditions                | Physical Characteristics |
| Behavior                                | Chemical Make-up         |
| Time of Collection                      | Fossils                  |
| Genome Organization (e.g. chromosome #) | Surrounding Organisms    |
| Habitat (e.g. lake, cave, etc.)         | Other _____              |

Explain why the information you selected is important to use when developing categories:

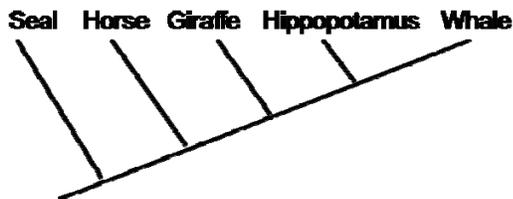
4. Using the image below, which of the following is an accurate statement?



- a) A crocodile is more closely related to a lizard than a bird
- b) A crocodile is more closely related to a bird than a lizard
- c) A crocodile is equally related to a lizard and a bird
- d) A crocodile is related to a lizard but not related to a bird

Provide an explanation for why you chose your answer:

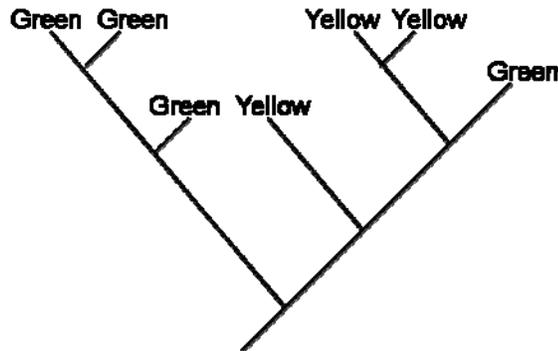
5. Using the image below, which of the following is an accurate statement?



- a) A seal is more closely related to a horse than to a whale
- b) A seal is more closely related to a whale than to a horse
- c) A seal is equally related to a horse and a whale
- d) A seal is related to a whale, but is not related to a horse

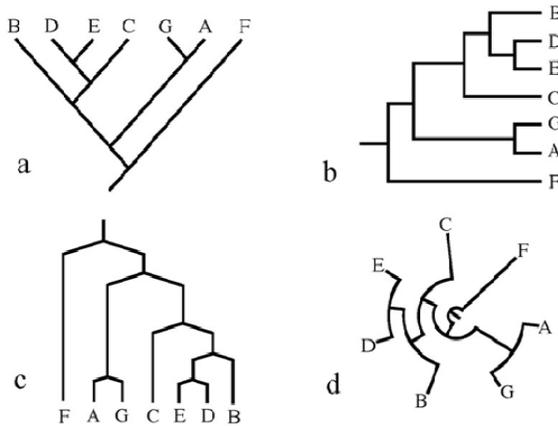
Provide an explanation for why you chose your answer:

6. Below is an image that depicts the color of fruits from different plant species. Use this image to respond to the following items.



- A) Indicate the oldest and most recent parts of this image.
- B) How many times did the Green color evolve? Explain your answer.
- C) Indicate on the image where the Green and Yellow characteristics originated.
- D) Explain why the branches are different lengths.

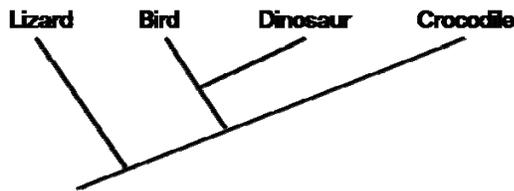
7. Although sea urchins and humans appear to have little in common, scientists recently found new evidence that relates sea urchins (B) with humans (E) and other vertebrates (D). This finding also suggests that sea urchins are not as closely related to beetles (C) and clams (G). Which tree below does *not* represent this new evidence?



Provide an explanation for why you chose your answer:

8. Pretend you are on a field trip to the Amazon and find a new plant that is not listed in any field guide. Your task is to figure out what evidence you need to gather from this new species in order to group it with currently known plants. Discuss the types of evidence you would want to collect and your reason for selecting each type of evidence.

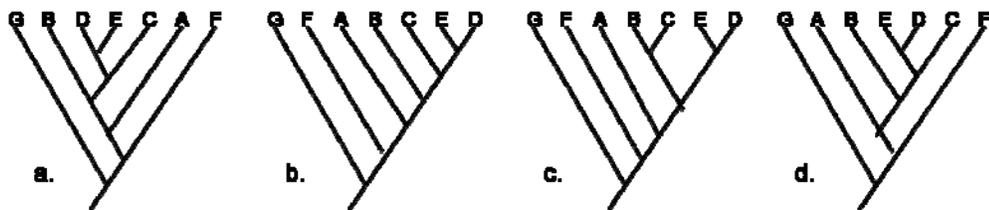
9. Using the above tree, which of the following is an accurate statement of relationships?



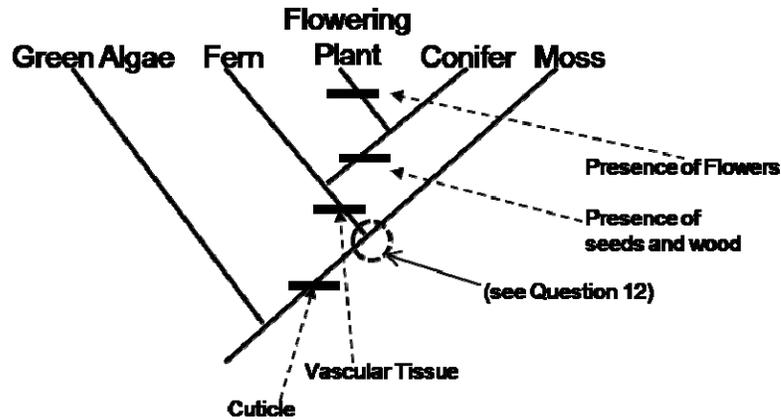
- a) A crocodile is more closely related to a lizard than a bird
- b) A crocodile is more closely related to a bird than a lizard
- c) A crocodile is equally related to a lizard and a bird
- d) A crocodile is related to a lizard but not related to a bird

Provide an explanation for why you chose your answer:

10. Which of the following four evolutionary trees depicts a different pattern of relationships than the others?



Provide an explanation for how the tree you chose is different from the others:



11. Consider the tree above. Based on the tree and assuming that all changes in these characteristics are shown, what characteristics might a Moss have?

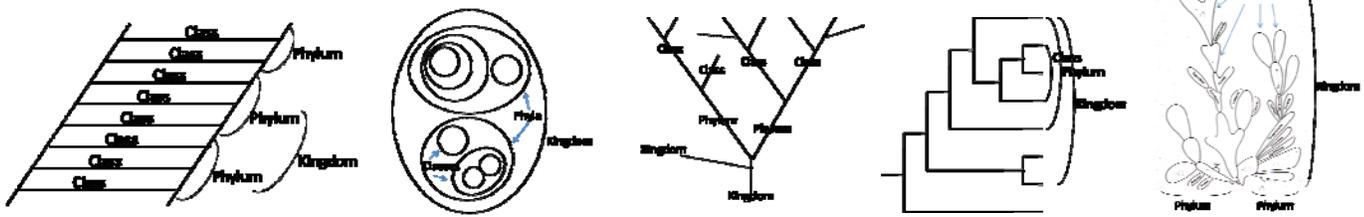
- a) Nonvascular tissues, flowerless, seedless, and a cuticle
- b) Vascular tissues, flowerless, woody, and a cuticle
- c) Nonvascular tissues, flowerless, seeds, and no cuticle
- d) Vascular tissues, flowers, woody, and a cuticle
- e) Nonvascular tissues, flowerless, seedless, and no cuticle

Provide an explanation for why you chose your answer:

12. Using same tree from question 11, what characteristics would you expect the organism indicated by the circle to have?

- a) Nonvascular tissues, flowerless, seedless, and a cuticle
- b) Vascular tissues, flowerless, woody, and a cuticle
- c) Nonvascular tissues, flowerless, seeds, and no cuticle
- d) Vascular tissues, flowers, woody, and a cuticle
- e) Nonvascular tissues, flowerless, seedless, and no cuticle
- f) There is not enough information provided to answer this question

Provide an explanation for why you chose your answer.



13. Sometimes when scientists use different kinds of images (examples above) to categorize organisms into related groups, they come to different conclusions about relationships among organisms. Explain why this might happen.

14. Consider what you already know about these 16 organisms:

- |          |        |           |        |
|----------|--------|-----------|--------|
| Bat      | Onion  | Dolphin   | Parrot |
| Oak Tree | Fern   | Pine Tree | Slug   |
| Daisy    | Human  | Trout     | Algae  |
| Mushroom | Turtle | Crab      | Fly    |

Use the space below to draw a visual representation that helps you understand how these organisms are related to one another. *Please include a written narrative* explaining your image.

APPENDIX E. POSTTEST INSTRUMENT

Name: \_\_\_\_\_ Date: \_\_\_\_\_

Grade: (Please circle) Freshman      Sophomore      Junior      Senior      Graduate

Major: \_\_\_\_\_

1. Briefly explain what evolution means and how some flower species pollinated by butterflies with long mouth parts evolved longer flower tubes.



2. What type of variation in organisms is passed on to the offspring?
- a) Any behavior that was learned during the organism's lifetime.
  - b) Characteristics and behaviors that are useful or beneficial.
  - c) Characteristics that are genetically determined.
  - d) Any characteristics that were influenced by the environment.
  - e) Characteristics that influenced where the organism lived.

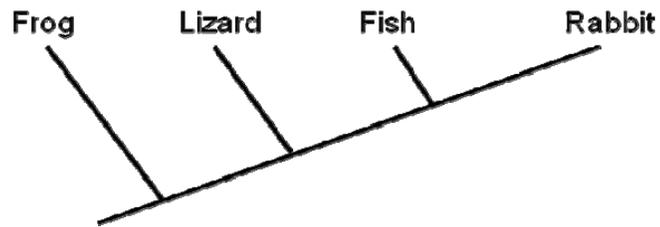
Explain why you selected this answer:

3. What information do scientists use when categorizing organisms into evolutionary related groups? (circle as many type of information as appropriate)

- |   |                          |
|---|--------------------------|
| Genetic Sequences                       | Geographic Location      |
| Environmental Conditions                | Physical Characteristics |
| Behavior                                | Chemical Make-up         |
| Time of Collection                      | Fossils                  |
| Genome Organization (e.g. chromosome #) | Surrounding Organisms    |
| Habitat (e.g. lake, cave, etc.)         | Other _____              |

Explain why the information you selected is important to use when developing categories:

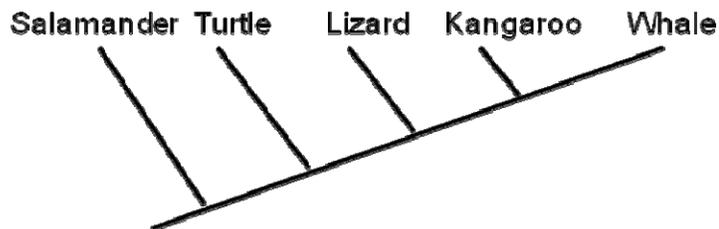
4. Using the image below, which of the following is an accurate statement?



- a) A lizard is more closely related to a frog than a rabbit
- b) A lizard is more closely related to a rabbit than a frog
- c) A lizard is equally related to a frog and a rabbit
- d) A lizard is related to a frog but not related to a rabbit

Provide an explanation for why you chose your answer:

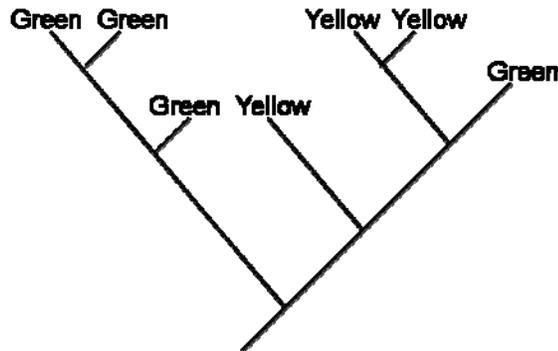
5. Using the image below, which of the following is an accurate statement?



- a) A salamander is more closely related to a turtle than to a whale
- b) A salamander is more closely related to a whale than to a turtle
- c) A salamander is equally related to a turtle and a whale
- d) A salamander is related to a whale, but is not related to a turtle

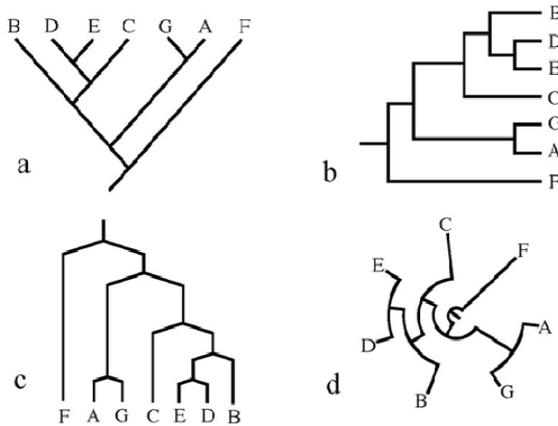
Provide an explanation for why you chose your answer:

6. Below is an image that depicts the color of fruits from different plant species. Use this image to respond to the following items.



- A) Indicate the oldest and most recent parts of this image.
- B) How many times did the Green color evolve? Explain your answer.
- C) Indicate on the image where the Green and Yellow characteristics originated.
- D) Explain why the branches are different lengths.

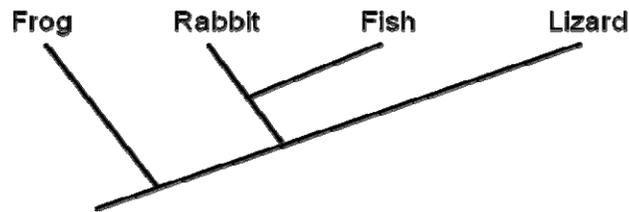
7. Although sea urchins and humans appear to have little in common, scientists recently found new evidence that relates sea urchins (B) with humans (E) and other vertebrates (D). This finding also suggests that sea urchins are not as closely related to beetles (C) and clams (G). Which tree below does *not* represent this new evidence?



Provide an explanation for why you chose your answer:

8. Pretend you are on a field trip to the Amazon and find a new plant that is not listed in any field guide. Your task is to figure out what evidence you need to gather from this new species in order to group it with currently known plants. Discuss the types of evidence you would want to collect and your reason for selecting each type of evidence.

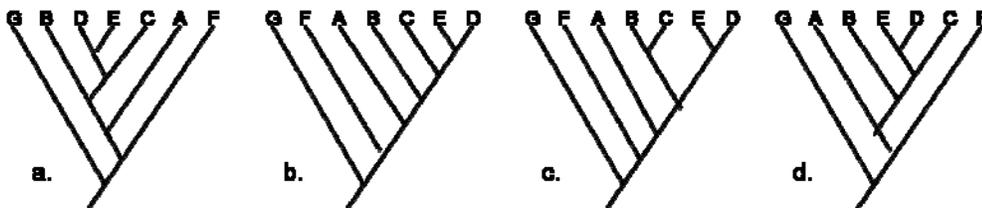
9. Using the tree below, which of the following is an accurate statement of relationships?



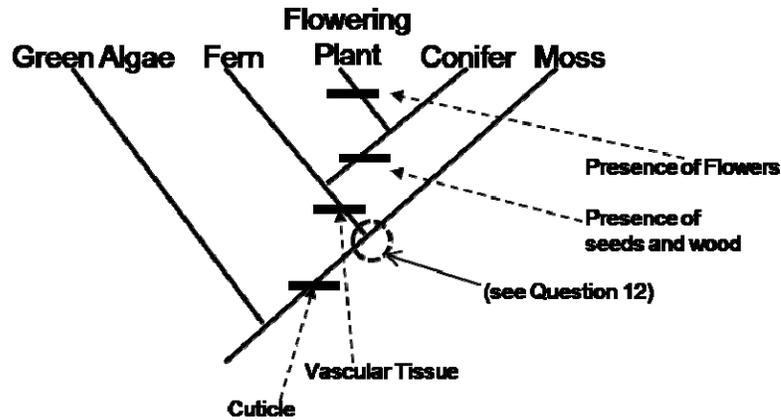
- a) A lizard is more closely related to a frog than a rabbit
- b) A lizard is more closely related to a rabbit than a frog
- c) A lizard is equally related to a frog and a rabbit
- d) A lizard is related to a frog but not related to a rabbit

Provide an explanation for why you chose your answer:

10. Which of the following four evolutionary trees depicts a different pattern of relationships than the others?



Provide an explanation for how the tree you chose is different from the others:



11. Consider the tree above. Based on the tree and assuming that all changes in these characteristics are shown, what characteristics might a Moss have?

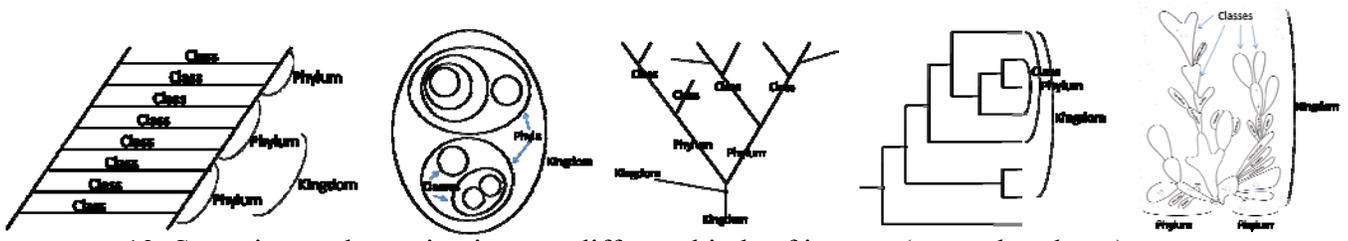
- a) Nonvascular tissues, flowerless, seedless, and a cuticle
- b) Vascular tissues, flowerless, woody, and a cuticle
- c) Nonvascular tissues, flowerless, seeds, and no cuticle
- d) Vascular tissues, flowers, woody, and a cuticle
- e) Nonvascular tissues, flowerless, seedless, and no cuticle

Provide an explanation for why you chose your answer:

12. Using same tree from question 11, what characteristics would you expect the organism indicated by the circle to have?

- a) Nonvascular tissues, flowerless, seedless, and a cuticle
- b) Vascular tissues, flowerless, woody, and a cuticle
- c) Nonvascular tissues, flowerless, seeds, and no cuticle
- d) Vascular tissues, flowers, woody, and a cuticle
- e) Nonvascular tissues, flowerless, seedless, and no cuticle
- f) There is not enough information provided to answer this question

Provide an explanation for why you chose your answer.



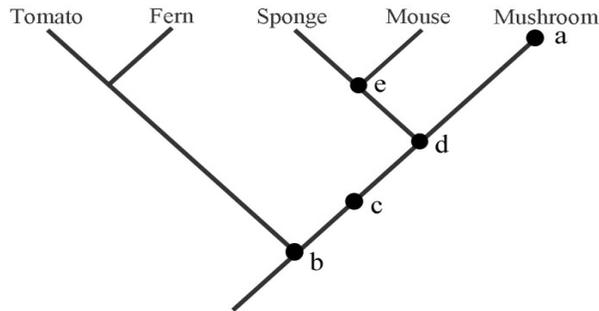
13. Sometimes when scientists use different kinds of images (examples above) to categorize organisms into related groups, they come to different conclusions about relationships among organisms. Explain why this might happen.

14. Consider what you already know about these 14 organisms:

- |          |       |           |          |        |
|----------|-------|-----------|----------|--------|
| Bat      | Onion | Dolphin   | Parrot   | Turtle |
| Oak Tree | Fern  | Pine Tree | Daisy    | Fly    |
| Human    | Trout | Algae     | Mushroom |        |

Use the space below to draw a visual representation that helps you understand how these organisms are related to one another. *Please include a written narrative* explaining your image.

15. Look at the tree below to answer this question. Which of the five marks in the tree above corresponds to the most recent common ancestor of a mushroom and a mouse?



- a) a
- b) b
- c) c
- d) d
- e) e
- f) the mushroom and mouse do not share a common ancestor

Provide an explanation for why you chose your answer.

16. How would you summarize your views of the truth of evolution (as contrasted with, for example, creationism)

- a) I believe that evolution happened as scientists say
- b) I suspect that evolution happened, but I need to know more to be sure
- c) I suspect that evolution did not happen, but I am open to being convinced otherwise
- d) I believe that evolution did not happen as scientists claim and do not expect to have my mind changed
- e) Other: explain \_\_\_\_\_

17. Which of the following would an evolutionary biologist be most likely to say about the evolution of humans?

- a) Humans evolved from chimpanzees
- b) Humans and chimpanzees share a recent common ancestor
- c) The human species evolved because they could out-compete chimpanzees
- d) Humans have accumulated superior features, which other primates have not yet acquired
- e) Humans evolved due to an intrinsic tendency for advanced features to accumulate.

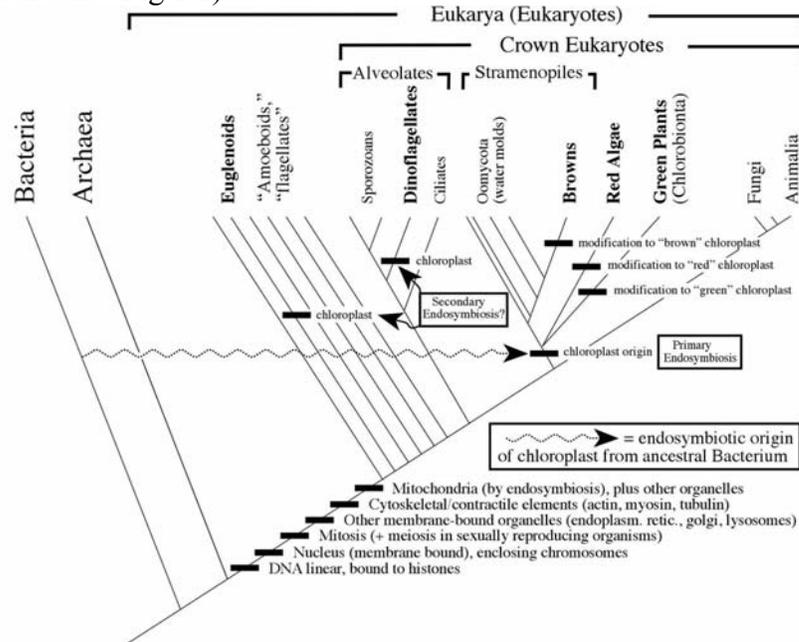
18. Imagine you could travel backwards through time and examine the last common ancestor of a human and a chimpanzee. What would it be?

- a) A chimpanzee
- b) A human
- c) A gorilla
- d) A species that cannot be classified as any of the above
- e) There is no common ancestor between a human and a chimpanzee

APPENDIX F. SELECTED WEEKLY REFLECTION QUESTIONS

Week 2

*Question 1.* What past experience have you had working with these images? (see attached figure from your text - Fig 1.1)



*Question 3.* A. What new things did you learn about interpreting this image of a tree since you've been in this course (again, refer to Fig 1.1)? B. Identify who or what helped you in learning more about interpreting trees (for example: did a fellow student/small group help explain the tree to you, etc.)?

*Question 4.* Presently, what questions do you have about interpreting trees (refer to Fig 1.1 or an example from the pretest)? Include at least two questions in your response.

Week 3

*Question 1.* Refer to Fig 1.1 and/or 1.3 in your text to help you answer this question.

List the key features used when interpreting a phylogenetic tree.

In your answer star (\*) the things you already knew before the semester started and underline the new items.

*Question 2.* Reflect upon your readings and the lecture about chapter 2.

In your response be sure to include:

1. An explanation of Figures 2.2, 2.8, and 2.11 and how they are similar/different from one another. (e.g., what is at the tips, what groupings are present, what is a root, etc.)

2. How did you study/approach reading chapter 2?

3. What questions do you still have about chapter 2 and/or phylogenetics in general?

*Question 3.* We had an interesting discussion in class last week (Tuesday) about the Flargle question from Week 1 Reflection. Chris explained how he approached the question, which was different from the way that many of you approached it. Compare how you interpreted and approached the problem with how Chris approached it. (The question is repeated below for your reference.)

One night after class you head back to your room and your roommates are discussing some imaginary characters brought up in a novel they were reading. They are attempting to relate one of the characters, a flargle, to known organisms. It is safe to assume that all of the evidence presented is accurate.

**Bob:** I think that a flargle would be most closely related to bacteria. The novel says that these critters can reproduce without having sex. I know that is how bacteria reproduce.

**Sally:** I think that a flargle would be most closely related to a mammal. It says in the novel that the flargle has fur, a complex organ system, and gives birth to live young.

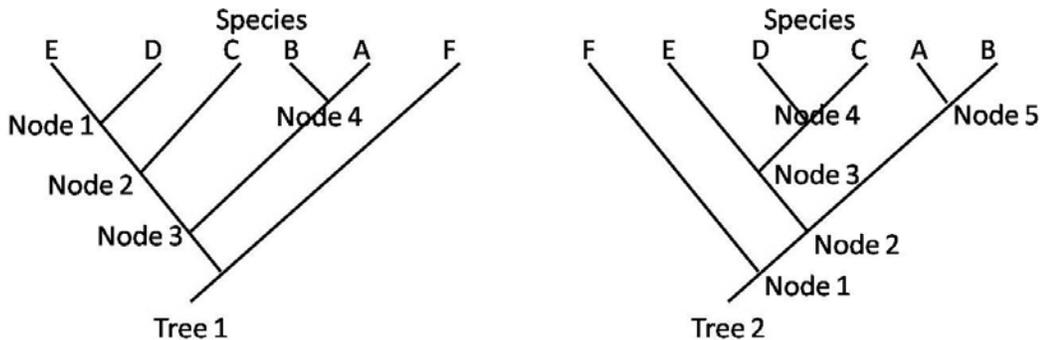
**Jill:** I think that a flargle would be most related to a bird. The novel says that these guys make their nests in trees close to eagles and can fly. They also migrate south when it starts to get cold.

**John:** I think that a flargle would be more closely related to a plant. It says in the novel that the flargle is always found by plants, it's green, and it makes its own food if it can't find food to eat for over a week.

*Question 4.* During class this past week, we discussed how scientists can “flip” tree branches so that while the tree may look different the information contained within the representation remains consistent. Pretend you were trying to explain why this is possible to a freshman college student, non-science major.

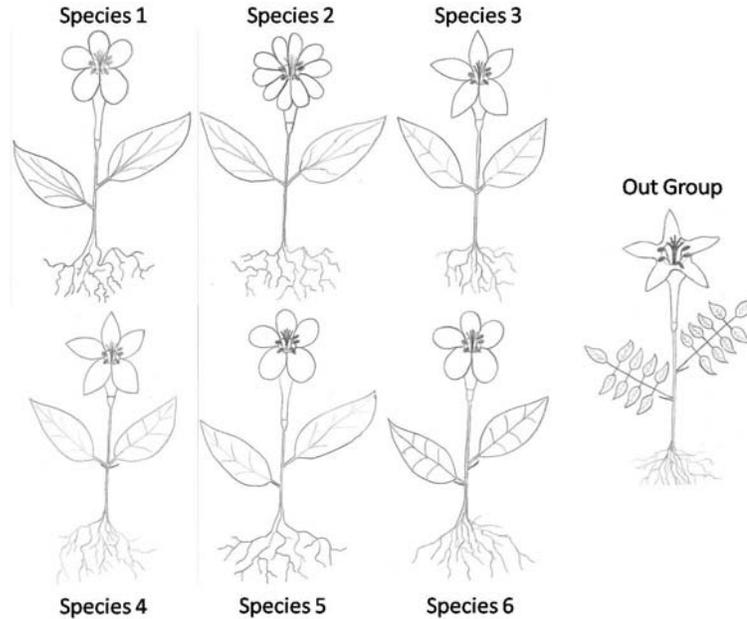
Week 4

*Question 2.* Explain how these two attached tree are the same or different (Be very explicit in explaining how you know this). Use the Species letters and Node numbers as reference when providing your explanation.



*Question 3.* Consider the pipe cleaner model you used in class last week to answer this question. In what ways is this model helpful for showing evolutionary relationships, and what are some limitations of the pipe cleaner model?

*Question 4.* Build a tree based on the attached image



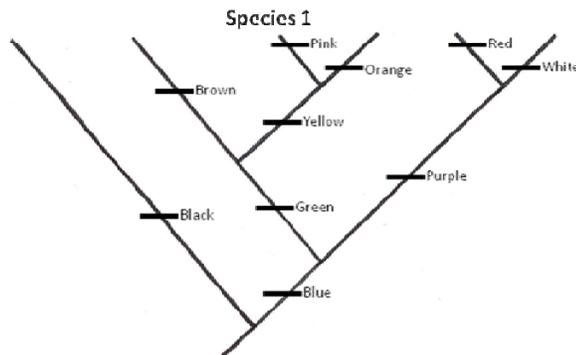
In your response include the steps you took to develop your tree, include the information you used to determine relationships of organisms.

A bit of history about the plants: Outgroup and species 1,2,3 are diploid (2n), Species 4-6 are tetraploid (4n), Outgroup, Species 3 and 4 live in rocky soil, Species 1, 5, and 6 live in prairies, Species 2 lives in woody meadows.

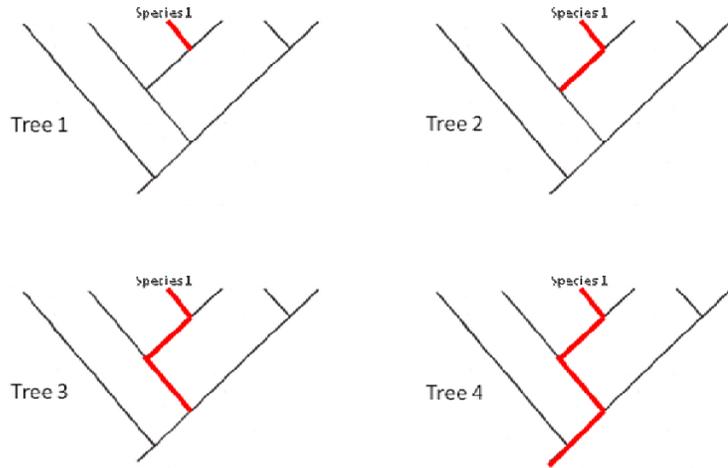
\*\**(You will need to attach an image file in addition to your response to this reflection prompt)*  
There are multiple acceptable ways to create this tree. Thus, you will receive full points for being thorough in your response.

Week 7

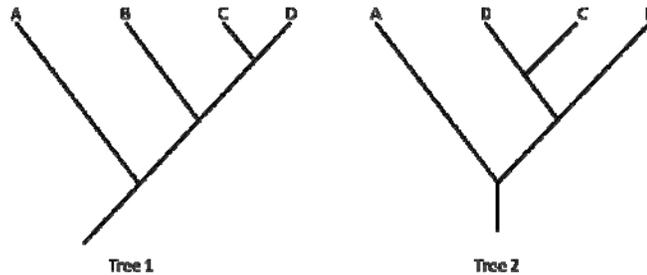
*Question 1.* After looking at the attached tree: List the derived character state(s) that you would find in Species 1.



*Question 2.* Which attached tree most appropriately represents Species 1 lineage (as highlighted in red). Explain why the other 3 images are not suitable for illustrating this lineage.



*Question 4.* Review the 2 attached trees. Consider these statements: Tree 1 illustrates a phylogenetic progression in the extant taxa with Species ‘D’ offering the most derived and advanced evolutionary traits so the ancestral trait is more likely similar to taxa ‘A’. Although tree 2 illustrates the same relationships among taxa (A-D) it indicates that there is no progression of taxa so the ancestral state is just as likely similar to the monophyletic group ‘B, C, & D’ as it is taxa ‘A’. Write a paragraph reflection upon these trees and include a rationale for why you agree or disagree with these two statements.

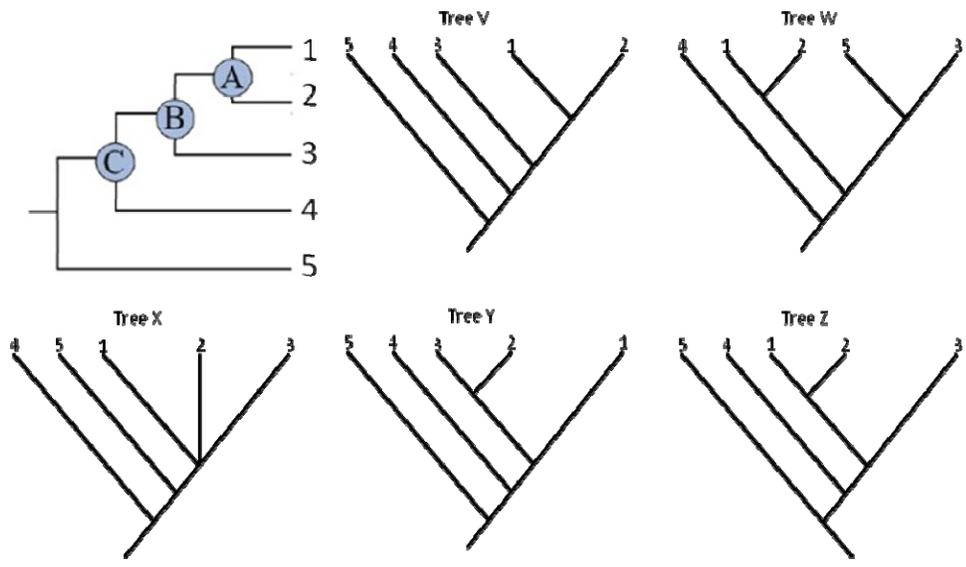


Week 8

*Question 2.* Due to limited availability of fossils and molecular data scientists have not been able to compile a complete data set for all of the taxa being examined in the WHIPPO activity (for example: scientists have not found usable skeletal evidence for whale taxa). How would you propose that scientists overcome this dilemma? (Select one response from a-d and include the reasoning for your answer)

- a. Use only the data sets that have information for all taxa being examined. (for example using the homework activity, exclude the skeletal data set entirely because there was no information available from whale taxa)
- b. Use only the taxa that have all of the data sets of interest. (for example, exclude extinct taxa because there is no molecular data available)
- c. Use all of the data sets and taxa regardless of missing information. (for example, develop a “supertree” that illustrates a consensus of all of the available data)
- d. Do not use any data sets or taxa until complete information is obtained.

*Question 4.* For the last homework you were asked to find supporting evidence in data sets (hypothetical trees) for the nodes presented in the first attached tree. Look at the rest of the trees (trees V, W, X, Y, and Z) attached. Which tree(s) supports Clade B?



*Question 5.* What in class activities have been most helpful in your efforts to interpret, use, and build phylogenetic trees? In your response be sure to include at least:

- 2 examples of how the in class activity(s) helped your tree-thinking abilities
- 2 examples of what you might change about the activity(s) to improve its usefulness

Week 11

*Question 1.* Consider the content you have read in chapter 7 about basal angiosperms and monocots. In these chapters you have been presented multiple trees and evidence for evolution that has created the diversity we can observe today. Describe what is meant by diversity and how these trees represent variations in flora.

Week 12

*Question 1.* Read the “tree thinking” handout posted in Week 11 Lecture Course Documents. How has this handout influenced your understanding of phylogenetic trees? (Include specific examples in your response!)

Week 13

*Question 1.* Pretend you have been asked to give a lecture in Bio 1010 (a biology lecture course for non-majors) over understand tree-thinking. Provide a narrative explaining how you would teach one of these students how to read phylogenetic trees. (Include the content and define each of the terms you are teaching)

\*\*If you need to upload/use images to help your explanations please use this week’s drop box. There are several images available or you may upload your own.

*Question 2.* The instructor thought you did such a great job lecturing on tree thinking that you were asked to come back and provide an additional lecture on tree-building. Provide a narrative explaining how to build trees. (Include and explain all steps taken)

## APPENDIX G. INTERVIEW ONE PROTOCOL

Q1: On a scale of 1-10 (with 10 being expert level knowledge) How well would you rate your understanding of evolution and systematics when you began this class? Can you please elaborate or give me an example.

Q2: How did the pretest go for you? Where did you draw your ideas from as you answered the questions?

Q3: Talk to me about how you study for this class?

What activities/assignments/study techniques/group work/etc. have helped you understand phylogenetic representation so far? How?  
What have you found most challenging so far? Why?

Q4: Take a look at this plant (Purple passion velvet plant), Talk me through the steps you would take to go about finding a suitable family to group this plant into. (Probe steps)

What information or tools would you like to have to help you with this task?  
How would this information/tool [use an example given above] help you identify this plant I gave you?  
How does this task compare to what you do in class?

Q5: This class seems to focus a lot on trees and keys. What differences or similarities do you see between trees and keys?

Probe: Describe the role of phylogenetic tree in plant systematics.  
Describe the role of dichotomous keys in plant systematics.  
How do these relate to one another? How do they represent systematics?

Q6: This is a representation that you constructed on the pretest. (Give image to student) Talk me through how you developed this representation (Probe 1<sup>st</sup> step, 2<sup>nd</sup>, 3<sup>rd</sup>, last, etc.)

Explain what your image is illustrating and the most important features. (probe)  
Is there anything about this image that you would change now? Why?

Q7: I'm going to show you a series of different models. For each image, explain the purpose of the model. I'm interested in your thinking about biology models not right or wrong answers. (Review 10 models – attached at end of protocol)

Probe: Explain what this representation (Show each image: 1 at a time) is illustrating. (Check criteria)  
Explain the different parts of this representation. (Probe scientific terms and features of image)  
Where are you drawing this knowledge from?

Q8: Let's take a step back to this plant we talked about earlier. Scientists have been able to build a phylogeny and found that this plant belongs to the Asteraceae family or "A." Explain the relationship of this plant to the others indicated by letters "B"- "H" on these models.

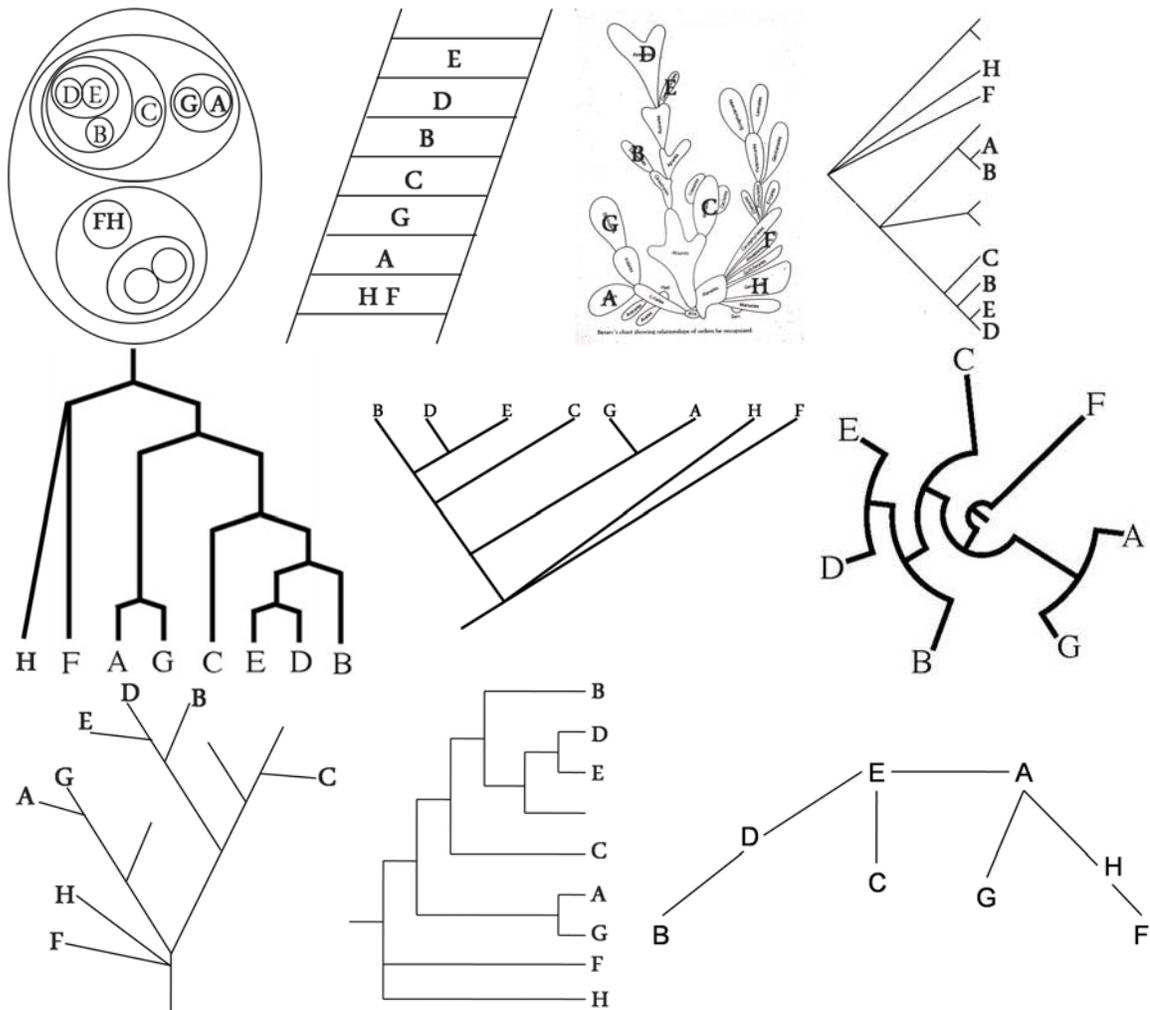
Probe: Which organism is the closest relative? Which is the least related?

Q9: Which model(s) are you using to draw your conclusion?

Describe how you are interpreting information illustrated by this model. (probe Features!)

Justify your reason behind why you think this model(s) is(are) better than the others to help you make conclusions and represent this type of information? (What's different/better about this model than the others?)

Do you have any questions for me?  
Thank you for your time!



## APPENDIX H. INTERVIEW TWO PROTOCOL

### Reflection Task

Think back to the beginning of the course. How have your views of phylogenetic trees changed

Probe: What has helped you alter your ideas about phylogenetic trees? How have these events/experiences helped you alter your ideas?

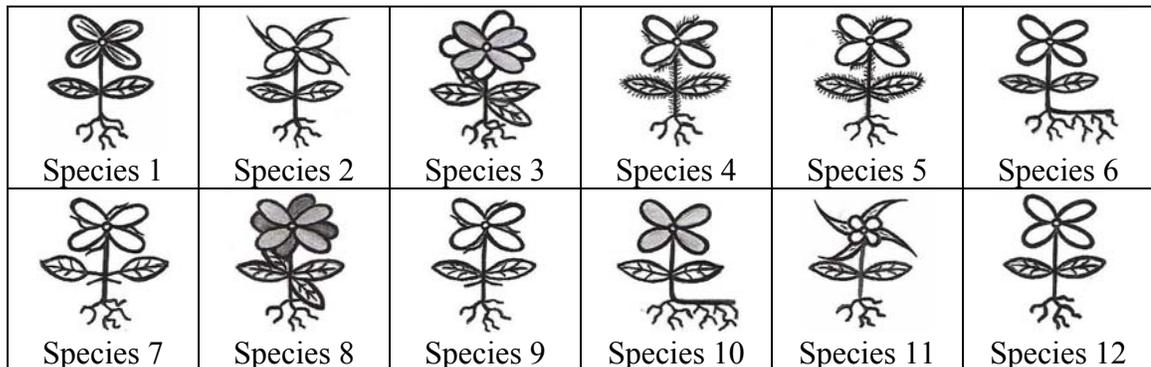
Probe: How has [a specific experience] helped you with your tree reading/building?

What do you consider to be the differences between tree reading and tree building?

### Building Task

Categorize these Pseudocot flowering plant cards based on how you think they are related to one another and talk me through the steps you are taking as you sort them.

Possible probes: What are you thinking through right now? Why are you arranging the cards how you are?



What types of evidence would you like to help you complete this task?

\*Data available to provide to the student if requested:

- Fossil Record (if selected have student incorporate 3 extinct species into task)
- DNA Sequence
- Ecological/Collection Information
- Out Group

*Optional Data (Available in Interpreting Pseudocot Phylogeny activity in Appendix L)*

How are you using this evidence to inform your interpretation of the Pseudocots?

Use this blank paper to build a model showing how these species are related to one another and explain your steps as you draw.

Probe the steps taken to develop the representation (e.g. What is the meaning of drawing an initial diagonal line? What are you struggling with? What is the

hardest part about building your model? What evidence are you looking at to reach this conclusion?)

Probe: Have student indicate time on the representation.

There is late breaking news. Scientists have discovered a new species, *Species 24*, which they believe belongs in the Pseudocot clade. How can you accommodate this new data into your model?

Interpret Task

Based on your model, which of the species are most closely related?

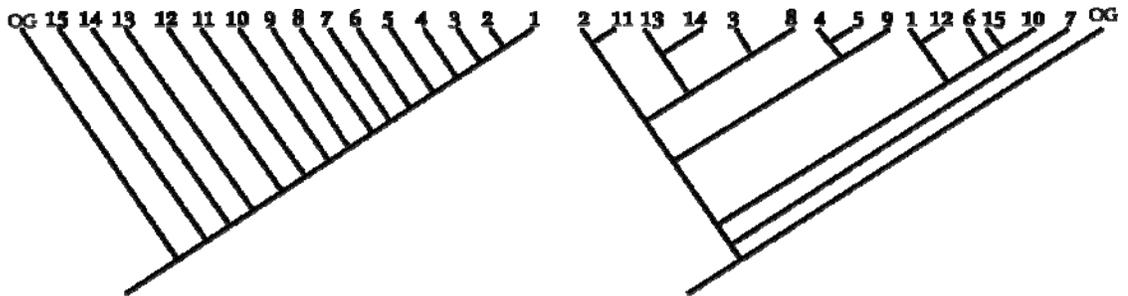
Probe: How did you come to that conclusion?

Optional probes: explain terms, consensus nodes,

Comparison Task

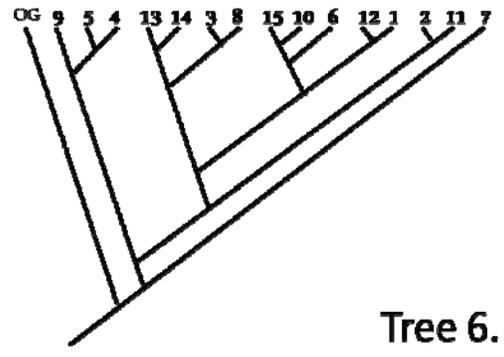
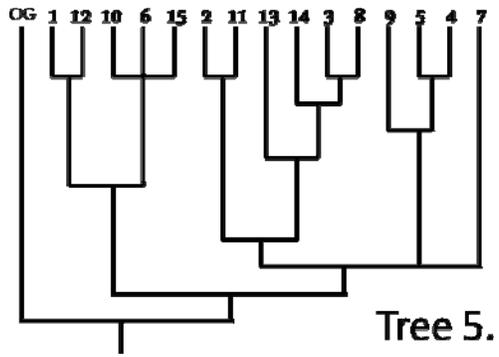
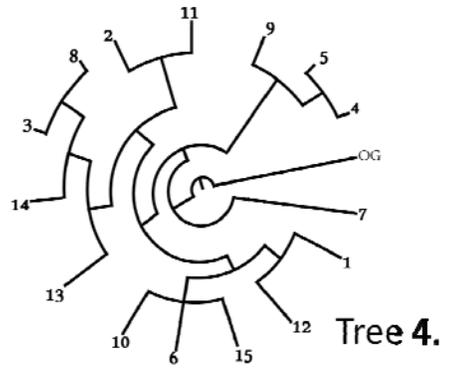
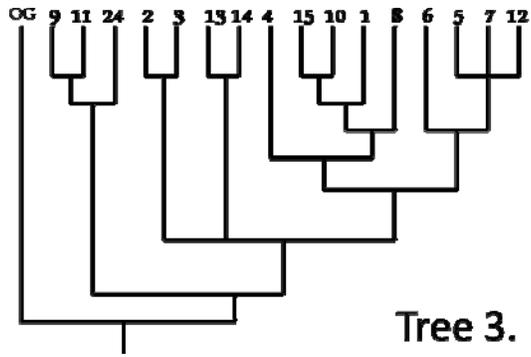
I gave this task to six other people. Compare your model to these 6 other models indicate where your model supports each one of these, if at all.

Optional probe: How does your model support this other model?



Tree 1.

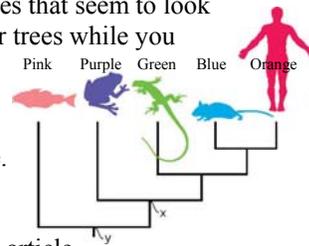
Tree 2.



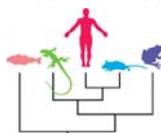
## APPENDIX I. PIPE CLEANER INSTRUCTIONAL INTERVENTION

Name: \_\_\_\_\_

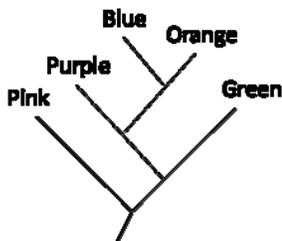
You read the following article: Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree thinking challenge, *Science*, 310, 979-980. In this article the author asks you to consider two trees that seem to look quite different from each other. Work through the following questions using pipe cleaner trees while you discuss the article.



1. Orient your pipe cleaner tree so that it looks like the first tree in Baum's article.
2. Transform your pipe cleaner tree so that it looks like the second tree in Baum's article.



3. Describe what you did to your pipe cleaner tree to change the tree's topology.
4. Describe the differences and similarities between these two trees.
5. What bends/intersections on your pipe cleaner tree are informative about evolutionary relationships? What do you think the informative portions represent?
6. Describe what you think is the significance for making the "edges" multiple colors.
7. Straighten the inter-nodal edges and branches and set the pipe cleaner tree at a 45° angle.
  - a. Draw what this tree looks like below.
  - b. Explain how this tree is different/similar to the previous trees.
8. Describe how you would transform your pipe cleaner tree into the image below.



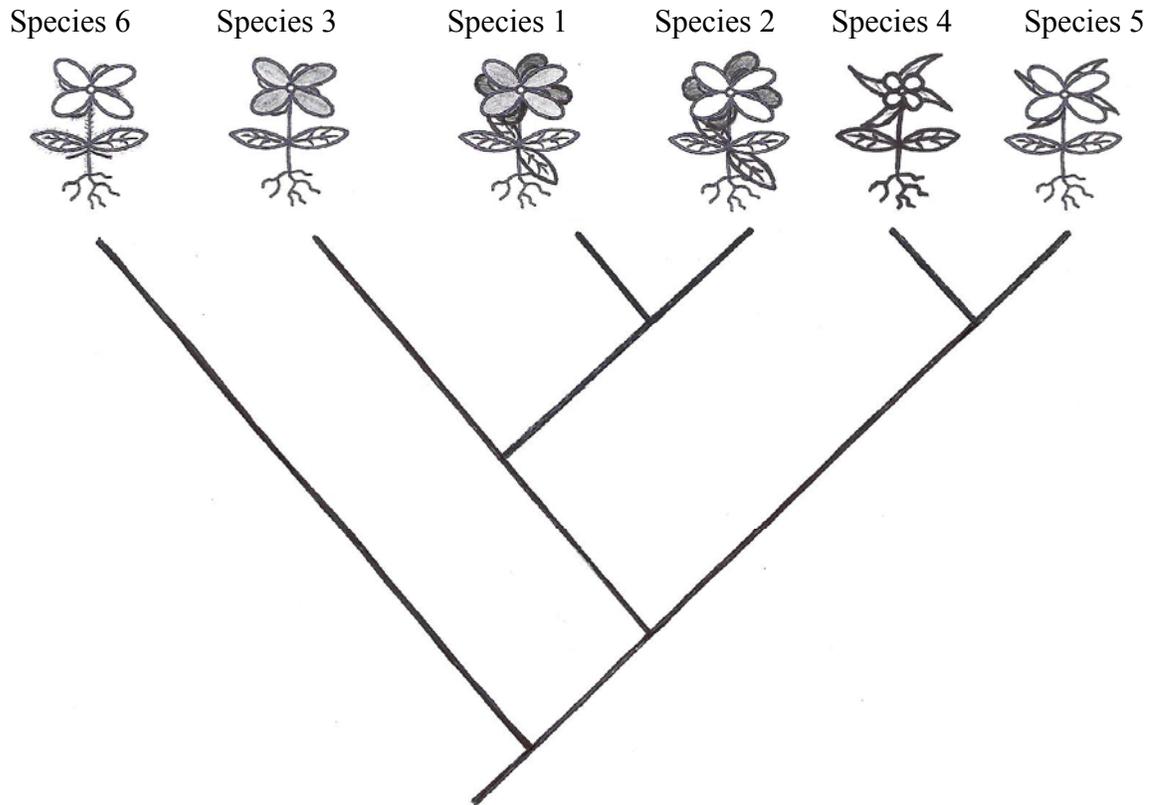
9. How is this tree different/similar from the original trees in Baum's article?
10. Describe how you would add in a newly discovered species to this tree.
11. What questions about phylogenetic trees has this activity made you think about?

APPENDIX J. PSEUDOCOT FOSSIL INSTRUCTIONAL INTERVENTION

Pseudocot Fossil Activity Handout 1:

Name \_\_\_\_\_

Extant Species:

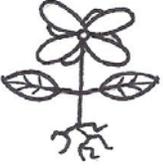


1. Fill in the character states on this Cladogram above.
2. Draw what you expect the most ancestral plant to look like:
3. Explain how you decided upon the character states shown in your drawing above?

Pseudocot Fossil Activity Handout 2

Name \_\_\_\_\_

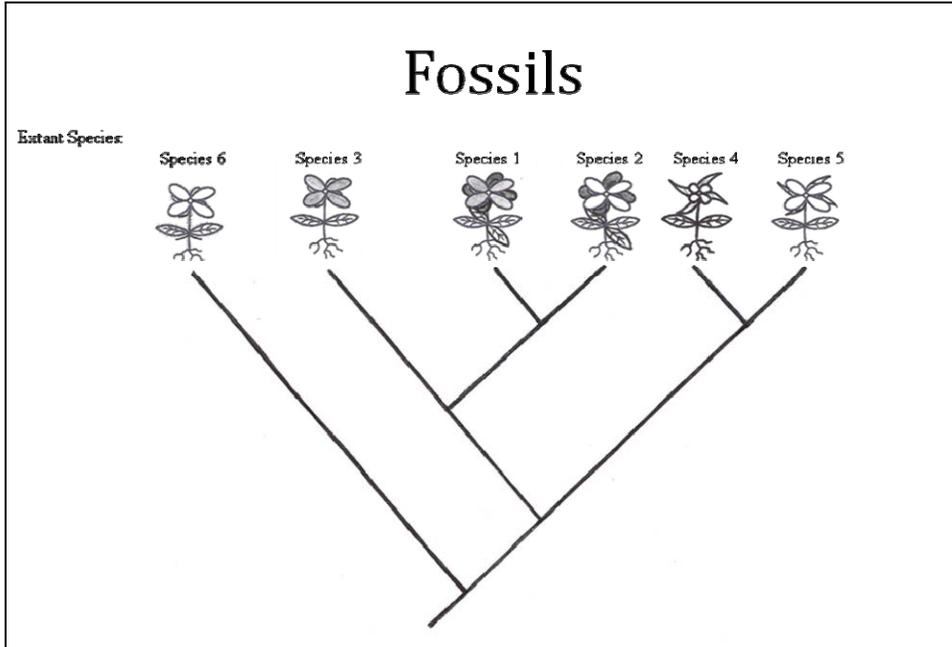
Review this Fossil record that scientists have uncovered: (Species 1-6 are extant, Species 7-15 are extinct)

 <p>Species 1 5 MYA</p>	 <p>Species 2 1 MYA</p>	 <p>Species 3 16 MYA</p>	 <p>Species 4 4 MYA</p>	 <p>Species 5 7 MYA</p>
 <p>Species 6 17 MYA</p>	 <p>Species 7 25 MYA</p>	 <p>Species 8 6 MYA</p>	 <p>Species 9 14 MYA</p>	 <p>Species 10 2 MYA</p>
 <p>Species 11 18 MYA</p>	 <p>Species 12 13 MYA</p>	 <p>Species 13 9 MYA</p>	 <p>Species 14 11 MYA</p>	 <p>Species 15 20 MYA</p>

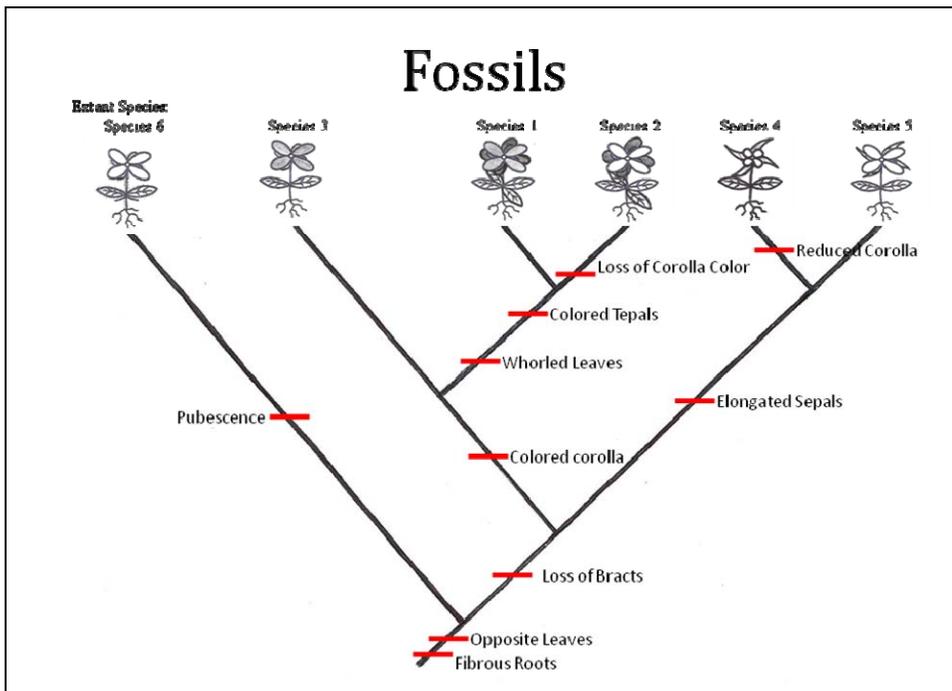
- Without changing your original drawing from Handout 1, how did your prediction compare to the fossil record?
- Explain why this oldest fossil found may or may not be indicative for how the earliest ancestor for this group of plants appeared.
- Using your insights from the Crisp & Cook 2005 reading, explain how erroneous reconstruction of ancestral states could occur. (For example see species 6 in the tree from Handout 1)
- Redraw a Cladogram incorporating all 15 species (extant and extinct):

Include: character states, a time scale, and species labels in your tree

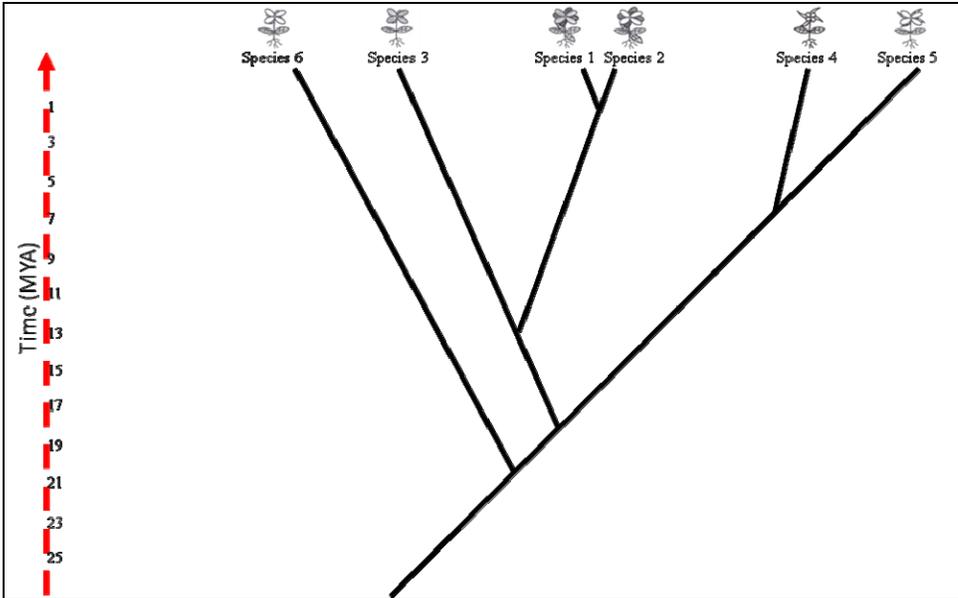
This is the accompanying review for the pseudocot fossil activity:



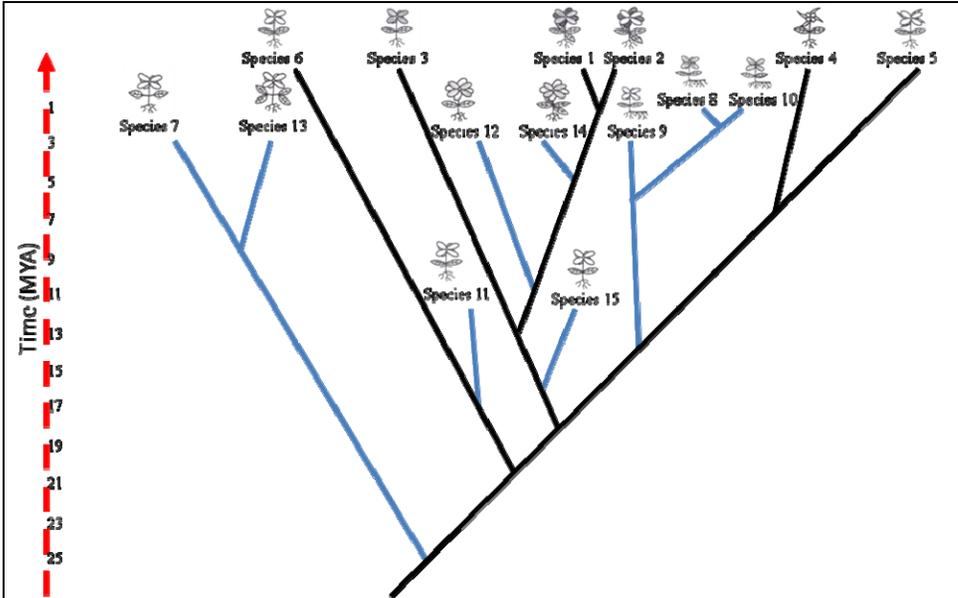
Slide 1. This is the tree as presented in the original handout



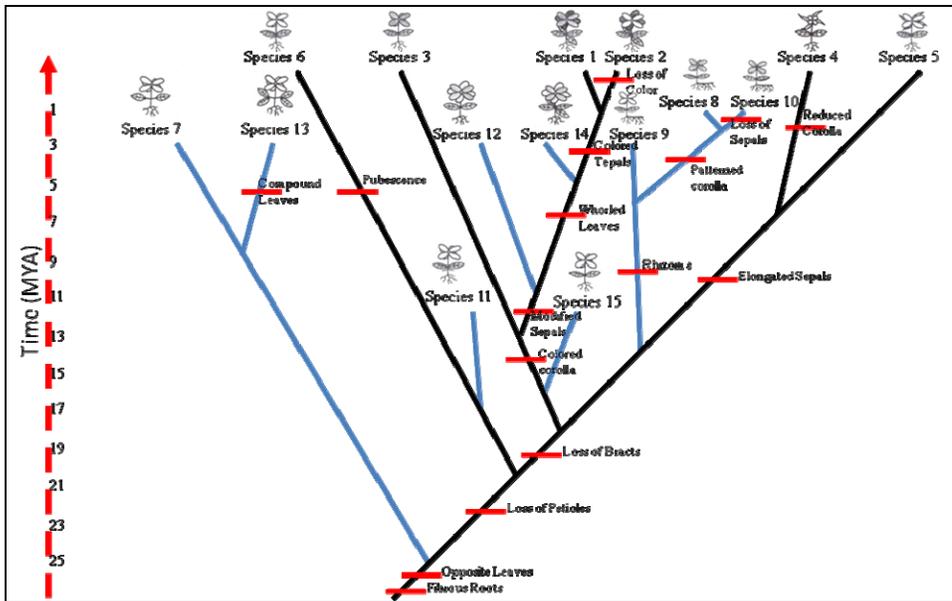
Slide 2. This is the tree with several apomorphies added (might not be all inclusive).



Slide 3. Same tree scaled to time (after first review of fossil data).



Slide 4. Fossils of extinct species added (note the extinct species do not go all the way to the top of the tree)



Slide 5. Apomorphies added back in (again not all inclusive).

## APPENDIX K. WHIPPO INSTRUCTIONAL INTERVENTION

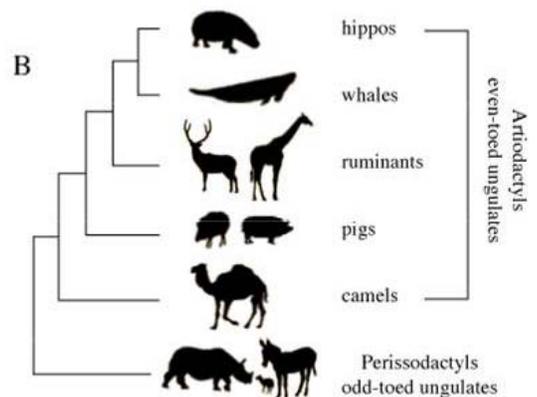
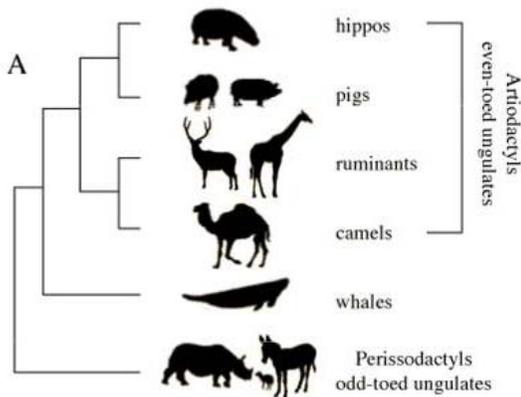
### WHIPPO Activity

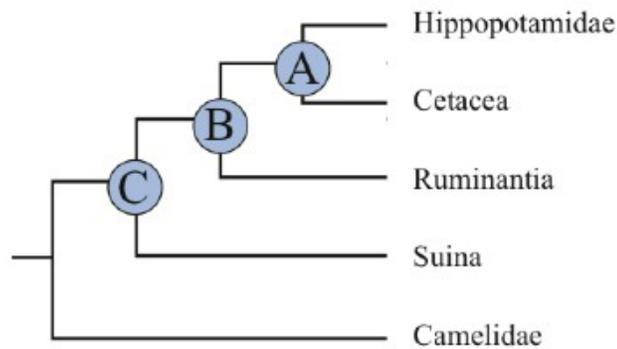
\*Data retrieved from BioQuest [http://www.bioquest.org/bedrock/problem\\_spaces/whippo/](http://www.bioquest.org/bedrock/problem_spaces/whippo/)

Name: \_\_\_\_\_

Taxa Key:	Bovidae – Cattle (ruminants)	Cervidae – Deer (ruminants)
	Griaflidae – Giraffe (ruminants)	Tragulidae – Mouse Deer (ruminant)
	Camelidae – Camels	Hippopotamidae – Hippopotamus
	Suidae – Pigs	Tayassuidae – Peccary
	Delphinoidae – Dolphin	Ziphiidae – Beaked Whale
	Physteridae – Sperm Whale	Mysticeti – Baleen Whale
	Perissodactyla – Horses (odd-toed ungulates - outgroup)	

1. Scientists have compiled multiple data sources and developed two arguing hypotheses about the evolutionary relationships among the whales and various ungulates. Examine following two trees (A and B). In your own words what are the evolutionary relationships illustrated between Cetacea (Whales and Dolphins) and Artiodactyls (Even-Toed Ungulates)





2. Review the above hypothesis. What do the labels 'A,' 'B,' and 'C' represent? Is it possible to have support for Clade B if Clade A is not supported? Explain how or why not?

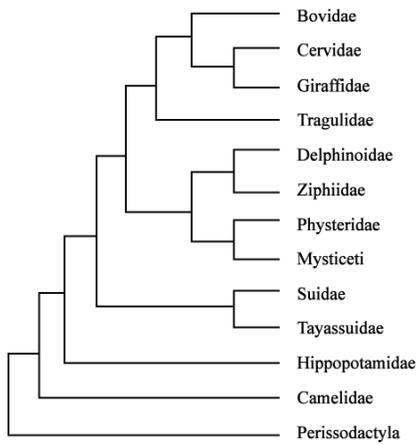
3. Examine the attached six trees developed from different types of data to answer these questions:

- A. Which of the attached trees support A?
- B. Which of the attached trees support B?
- C. Which of the attached trees support C?
- D. Which of the attached trees support the hypothesis presented above?

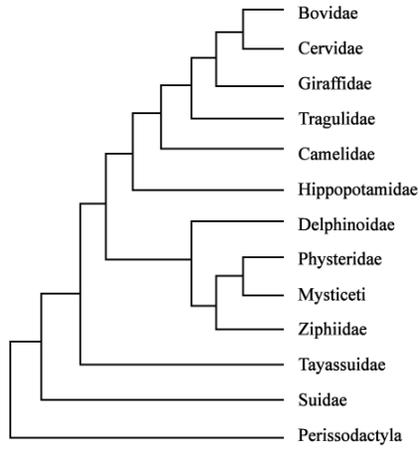
4. Consider your reading assignment (Gatsey & O'Leary, 2001) and look at the tree they presenting in Figure 1.

- A. How does this tree relate to the hypothesis presented in Question 2?

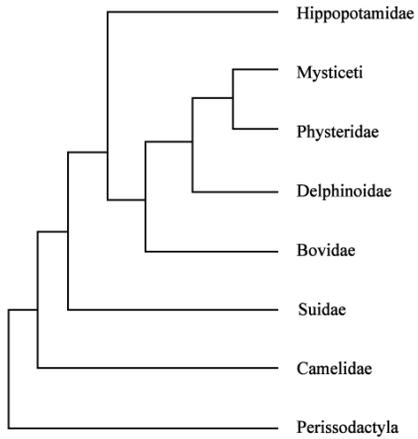
- B. How does this tree relate to the two trees presented in Question 1?



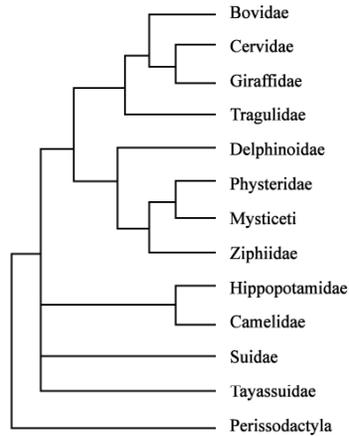
cytochrome b



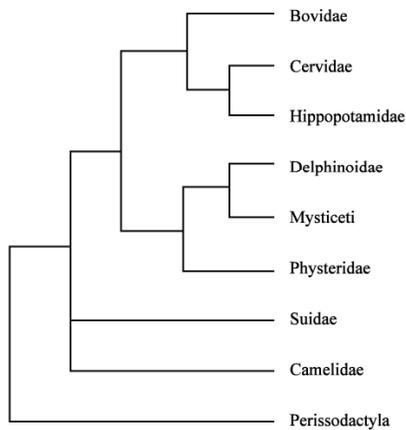
12S rDNA



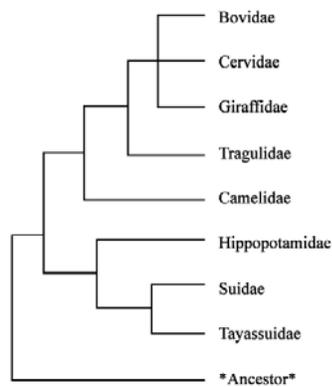
vWF



16S rDNA

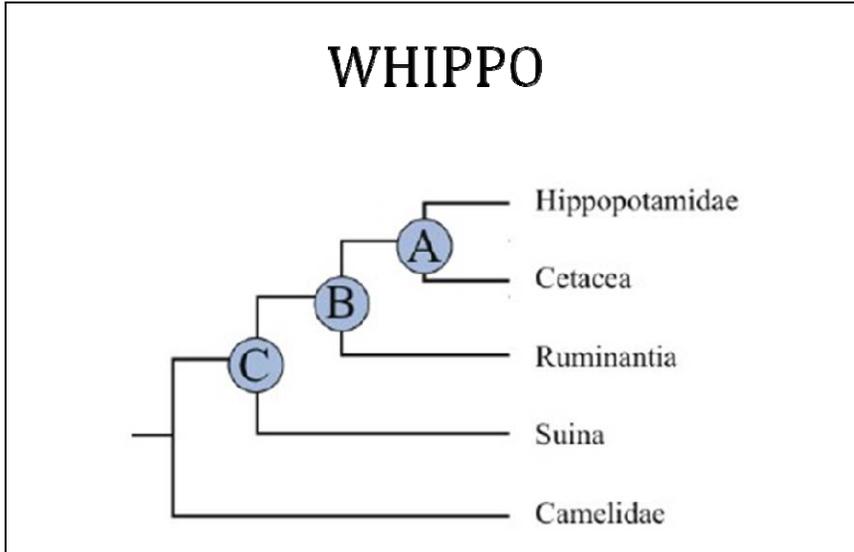


$\alpha$ -hemoglobin

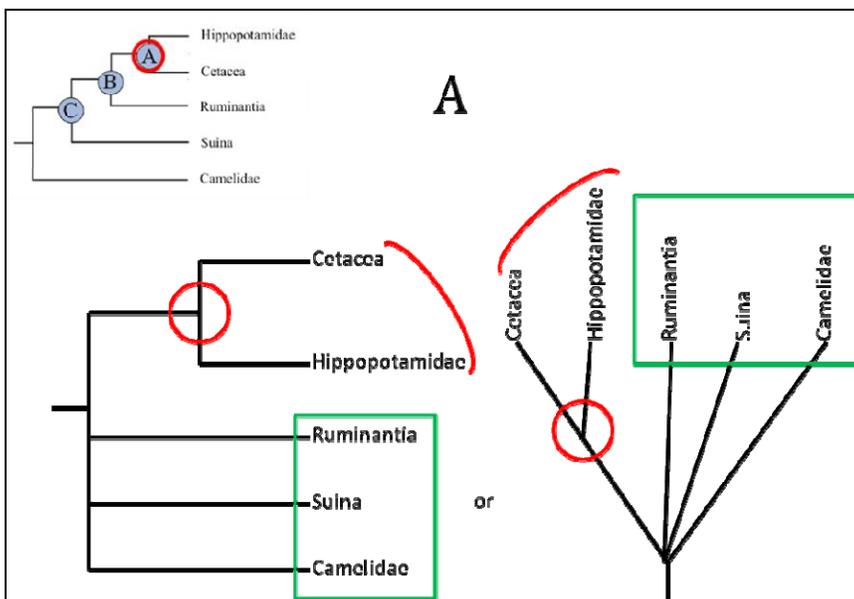


skeletal/dental

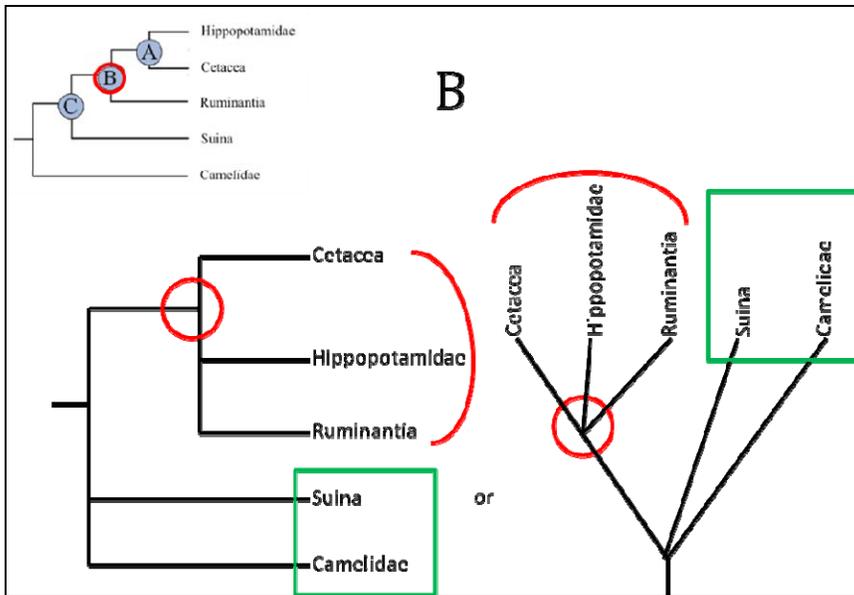
These are selected slides from the accompanying review for the Whippo activity:



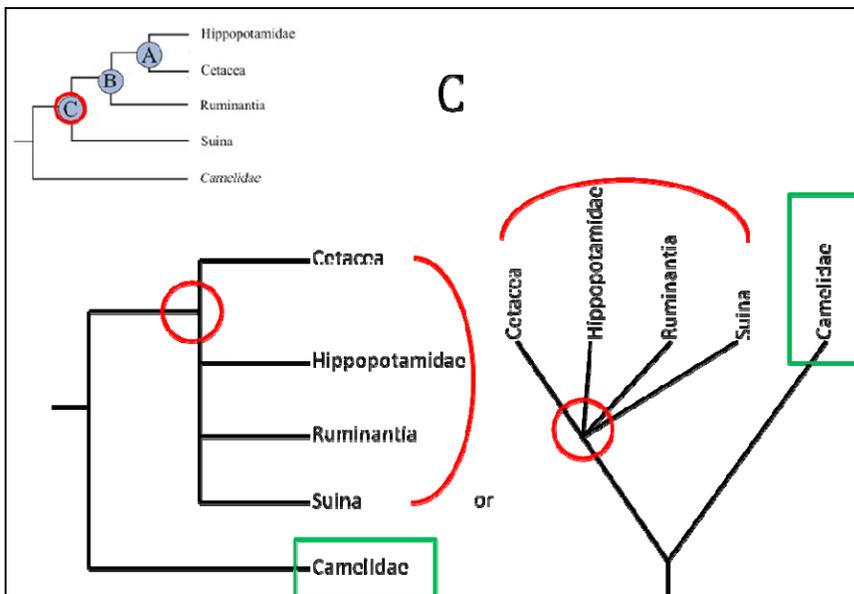
Slide 1. This is the hypothesized tree as presented in the original handout. We are looking for support of nodes A, B, and C.



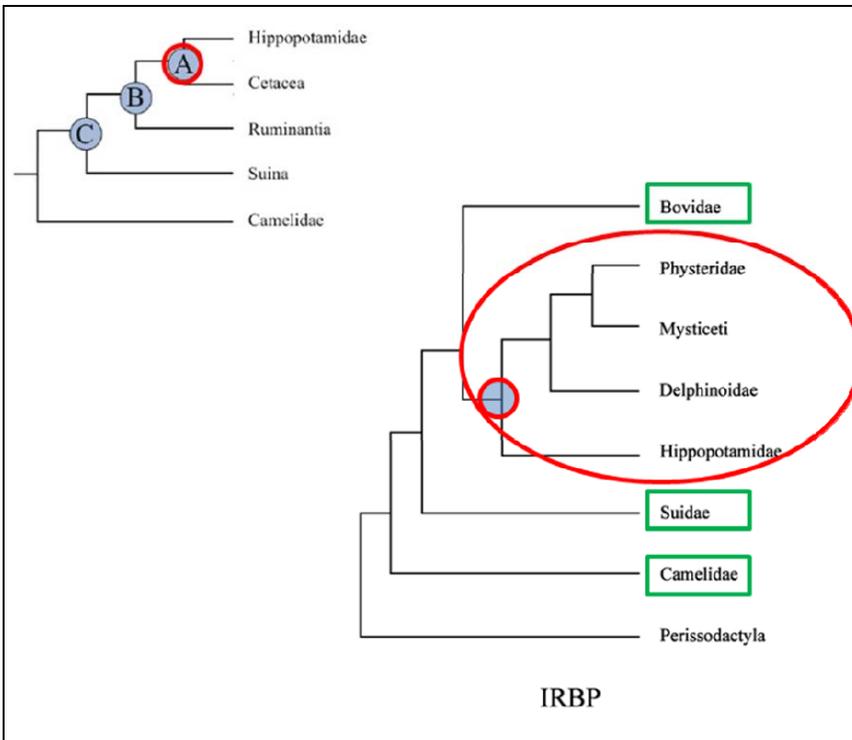
Slide 2. This illustrates what scientists would look for as supportive evidence for Node A (Red Circle = monophyletic group; Green Box = Out group).



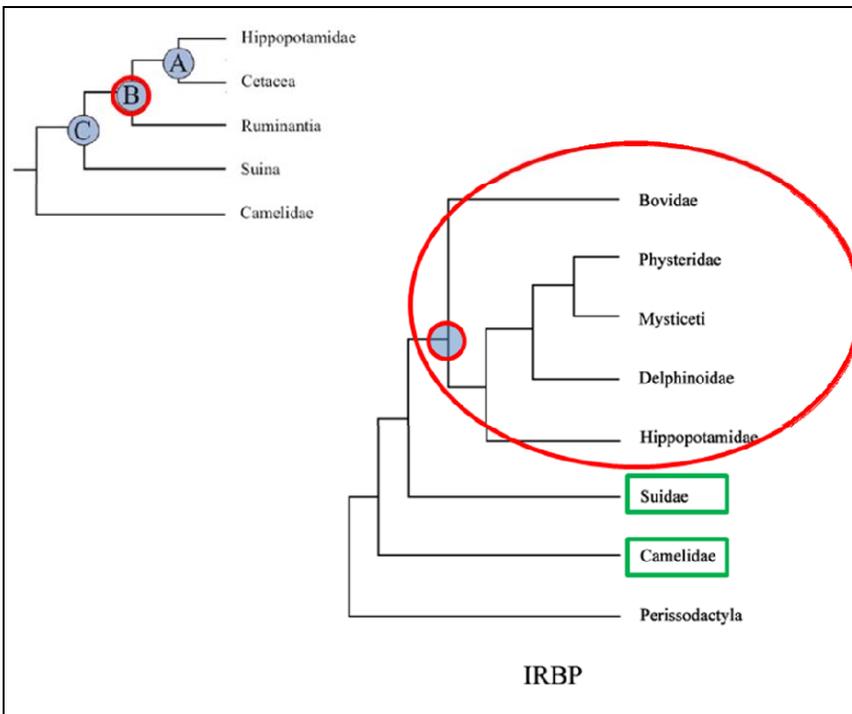
Slide 3. This illustrates what scientists would look for as supportive evidence for Node B.



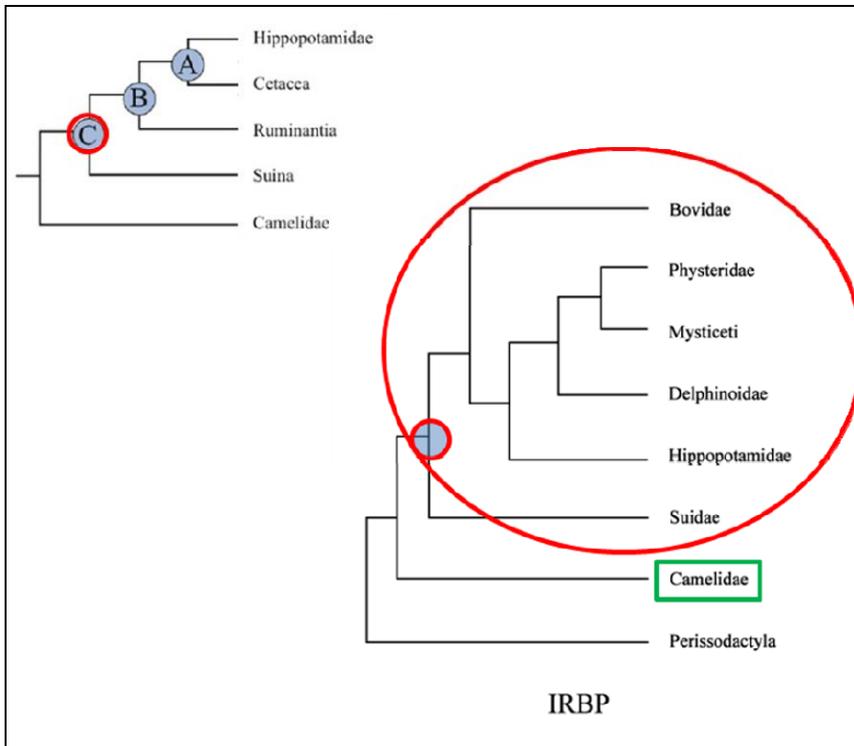
Slide 4. This illustrates what scientists would look for as supportive evidence for Node C.



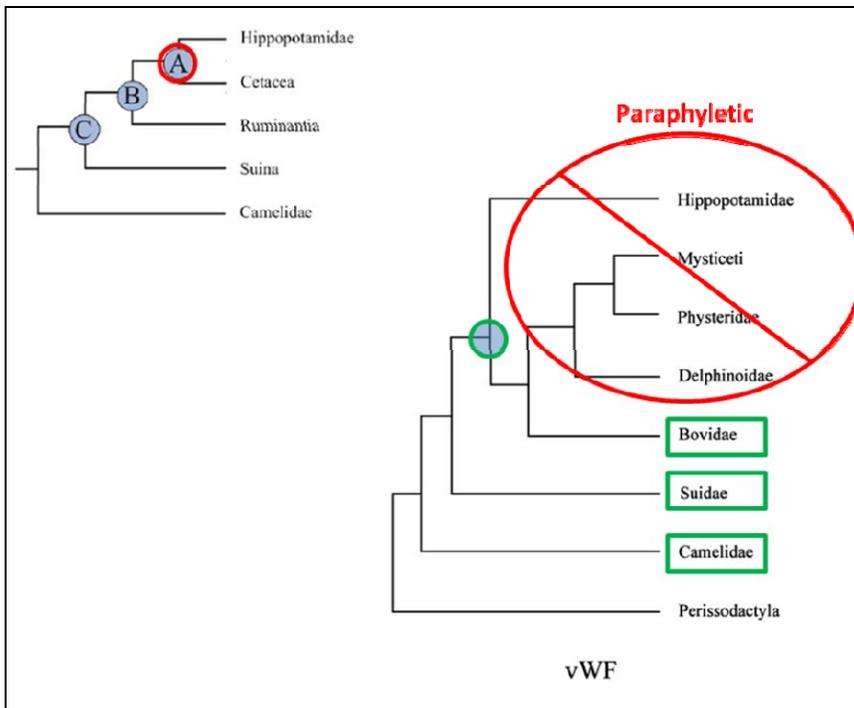
Slide 5. This tree is supporting node A because of the monophyletic group indicated by the small red circle.



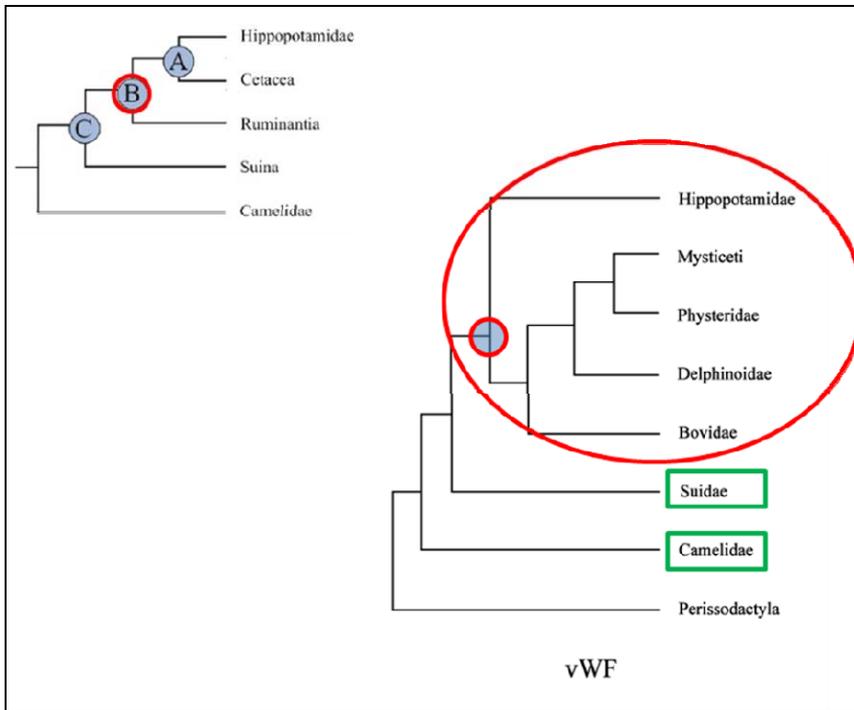
Slide 6. This tree is supporting node B because of the monophyletic group indicated by the small red circle.



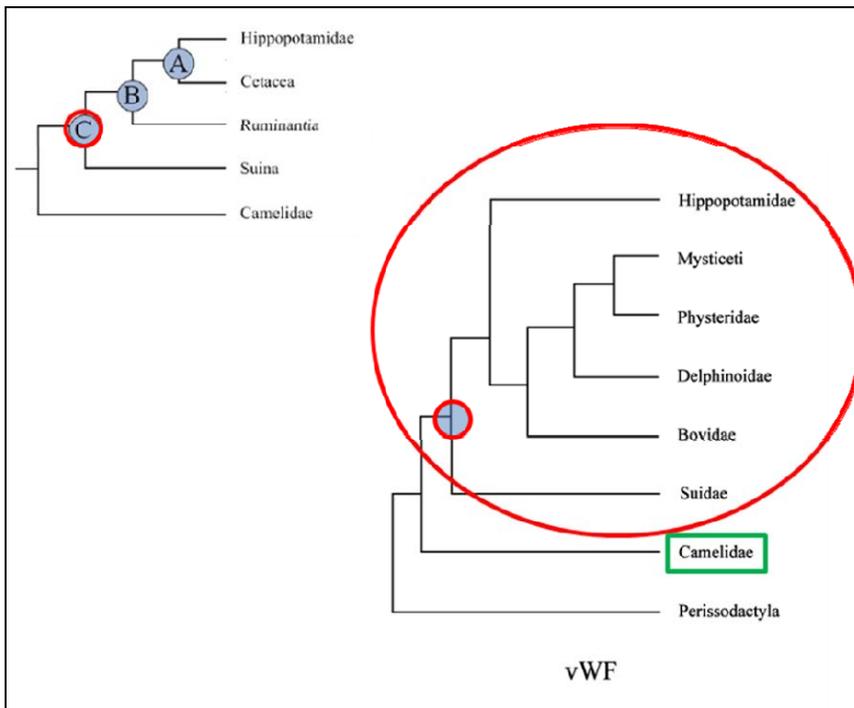
Slide 7. This tree is supporting node C because of the monophyletic group indicated by the small red circle.



Slide 8. This tree does not support Node A because the hippos and whales form a paraphyletic group (not monophyletic)



Slide 9. This tree does support Node B because of the monophyletic group indicated by the small red circle.



Slide 10. This tree does support Node B because of the monophyletic group indicated by the small red circle.

## APPENDIX L. MODIFIED INSTRUCTIONAL INTERVENTIONS

### Pipe Cleaner Phylogeny Lesson Plan

Grade Level: High School through Post Secondary Courses

(vocabulary and objectives can be modified for use with younger grades)

Subject: Biology – Evolution (tree thinking)

Duration: 45-75 minutes – can be adjusted to fit one class period

Description: After conducting an extensive research study I found that students struggle with interpreting phylogenetic trees regardless of their past science experiences. I synthesized findings from my study and current “tree-thinking” literature to identify the most common challenges students encountered. I developed a pipe cleaner model to provide an instructional intervention. This model allowed students to interact with the manipulative and think deeper about evolutionary relationships represented in phylogenetic trees. My instructional activity forces students to examine lineage mapping, impacts of superficial structural changes, and applications to problem solving. For instance, these models helped students shift away from drawing conclusions using “tip-thinking” toward drawing more scientifically appropriate conclusions by looking at common ancestry and using “node-thinking.” Students provided positive feedback about the activity and enjoyed the interactive nature of the pipe cleaners.

Goals: Our goal with this lesson is to explicitly address and overcome known misconceptions associated with phylogenetic tree thinking.

*Common misconceptions addressed:*

Main line and side tracks

Reading across the tips

Different Lineage Ages for Modern Species

More intervening nodes equals more distantly related

Reasoning outside of the representation

Altering the format or orientation of the tree alters the relationships depicted

Reading left to right

These misconceptions were identified from studies reported in the following resources:

Baum, D. A. & Offner, S. (2008). Phylogenies and tree thinking. *American Biology Teacher*, 70, 222-229.

Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree-thinking challenge. *Science*, 310, 979-980.

Gregory, T. R. (2008). Understanding Evolutionary Trees. *Evolution: Education and Outreach*, 1, 121-137.

Halverson, K. L., Pires, J. C., & Abell, S. K. (2008). *Undergraduates' abilities to use representations in biology: Interpreting phylogenetic tree thinking*. Paper presented at the National Association for Research in Science Teaching.

Meir, E., Perry, J., Herron, J., Maruca, S., Stal, D., & Kingsolver, J. (2005). How effective are individual-based simulations in EvoBeaker at overcoming misconceptions in evolution? Paper presented at the ESA Annual Meeting

Omland, K. E., Cook, L. G., & Crisp, M. D. (2008). Tree thinking for all biology: The problem with reading phylogenies as ladders of progress. *BioEssays*, 30, 854-867.

Objectives:

- Students will be able to recognize similarities and differences in patterns of relationships across trees with different topographies, formats or orientations.
- Students will understand that flipping branches around a node does not affect the relationships depicted by the representation.
- Students will be able to trace an entire organism's lineage to the root of the tree.
- Students will become familiar with the key features of a phylogenetic tree and gain an understanding of what they represent.
- Students will be able to recognize what bends/intersections on a phylogenetic tree are informative about evolutionary relationships.
- Students will learn how to use a tool that can manipulate to assist additional phylogenetic tree thinking problems.

Prerequisites: Here are some terms to be familiar with to help improve this lesson

Apomorphy – a derived character state unique to one lineage

Branch – illustrates the different lineages after speciation events

Character – a specific heritable trait described in terms of its state

Common Ancestor – an ancestral organism shared by two or more descendent lineages

Lineage – a continuous line of descent

Monophyletic – a grouping of a common ancestor and all of the descending lineages

Node – a hypothetical common ancestor or speciation event

Phylogenetic tree – an evolutionary tree (shows evolutionary relationships among organisms)

Root – the ancestral lineage

Synapomorphy – a derived character state shared by a monophyletic group of organisms

Terminal Tip – descendants of an ancestor, this can be a species, taxa, gene, etc.

Optional homework to complete prior to class: Read the following article: Baum, D. A., Smith, S. D., & Donovan, S. S. S. (2005). The tree thinking challenge, *Science*, 310, 979-980. In this article the author asks the reader to consider two trees that seem to look quite different from each other but depict identical relationships.

Materials: Two-sided hard copies of worksheets (see end of lesson plan)  
Assembled pipe cleaner models (one per student/group)  
Additional pipe cleaners (e.g. yellow, one per student/group)  
Colored pencils/markers (optional)

To assemble pipe cleaner phylogenetic trees to use with this activity, use 5 different colored pipe cleaners (specific colors do not matter as much as ensuring all of the trees use the same colors and the relationships or ordering of monophyletic groupings is identical across models). See figure 1 for a completed model used for this lesson.

- First: Make sure all the pipe cleaners are gathered together and flush at each end
- Second: Twist all of the pipe cleaners together for about 2" so they are intertwined and will not fall apart.
- Third: Separate the "pink" pipe cleaner from the others and twist the remaining pipe cleaners together for another 1½"-2"

- Fourth: Continue this process until all of the pipe cleaners have been isolated
- Fifth: Bend the pipe cleaners so that they appear identical to the first image in the worksheet (or see Figure 1)

Figure 1. Sample Pipe Cleaner Phylogenetic Tree  
(Pink Purple Green Blue Orange)



Potential modifications to use with the model: Cut out images of different species and put a hole punch at the top and bottom in order to slide the image onto the pipe cleaner tree. This can provide students a more concrete tool with biological organisms directly associated with the colors rather than strictly abstract.

#### Lesson Procedure:

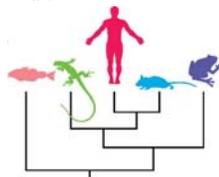
This lesson begins with an activity that elicits students' prior ideas. Using the images presented in Baum et al. (2005, p. 979) pose the following question to the students in order to get them to start thinking about their ideas on how they interpret phylogenetic tree representations.

- On the basis of this tree, is the frog more closely related to the fish or the human?



Take a few minutes and allow the students to express their answers and how they have reached their conclusions. Then show this next image.

- Does the tree change your mind?

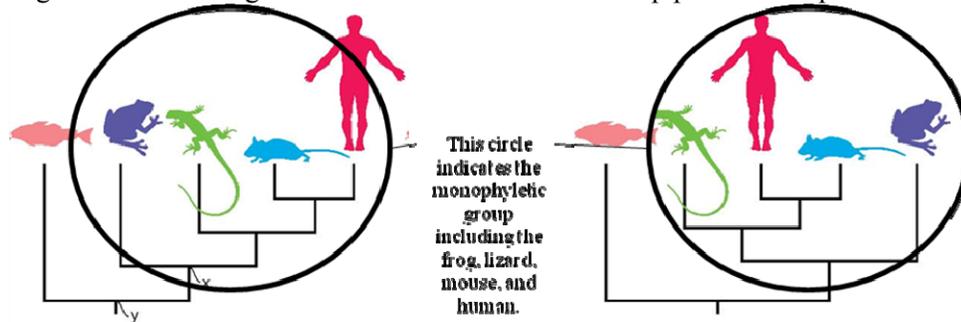


Again, take a few minutes and allow the students to express their answers and how/why they have reached their current conclusions.

Following student discussion allow 5-10 minutes for an overview of the question and discussion about key features of phylogenetic tree used to interpret these representations.

- Both of the trees show the same relationship among the species. The frog being most closely related to the human in each representation (see figure 2).  
(Depending upon the level of understanding indicated by the students a description about monophyletic groups may be needed at this point. Otherwise this portion may be skipped.)

Figure 2. These images show how the same relationship pattern transposed on both trees.



- Phylogenetic trees can be thought of as a mobile. The branches can swivel around a node without altering the monophyletic groupings (or rather the relationship illustrated). - *Demonstrate how branches swivel with a pipe cleaner model*

At this point, hand out the pipe cleaner models to the students and have them form small groups (2-3 students per group) to work through the attached worksheet. During the activity, assess students progress by observing individual groups and asking questions to probe thinking. This interaction also helps keeps students on task.

Figure 3. Students manipulating their pipe cleaner trees as they work through this activity.



Once students begin finishing the worksheet (you will be able to tell by the students interaction with the models, they tend to start forming new shapes and use them in unique manners (see figure 4) – note: this interaction is beneficial as long as they are still thinking about how it affects the information shown in the tree, and it is fun for the students), have them turn in their worksheet and hand out the single pipe cleaners to prepare for a follow-up activity.

Figure 4. A student has vered from the worksheet. “So I can make the branches look like this but the relationships show are all still the same.”



*Follow-up:* Pose this problem to the students – this can be done in groups or as a class.

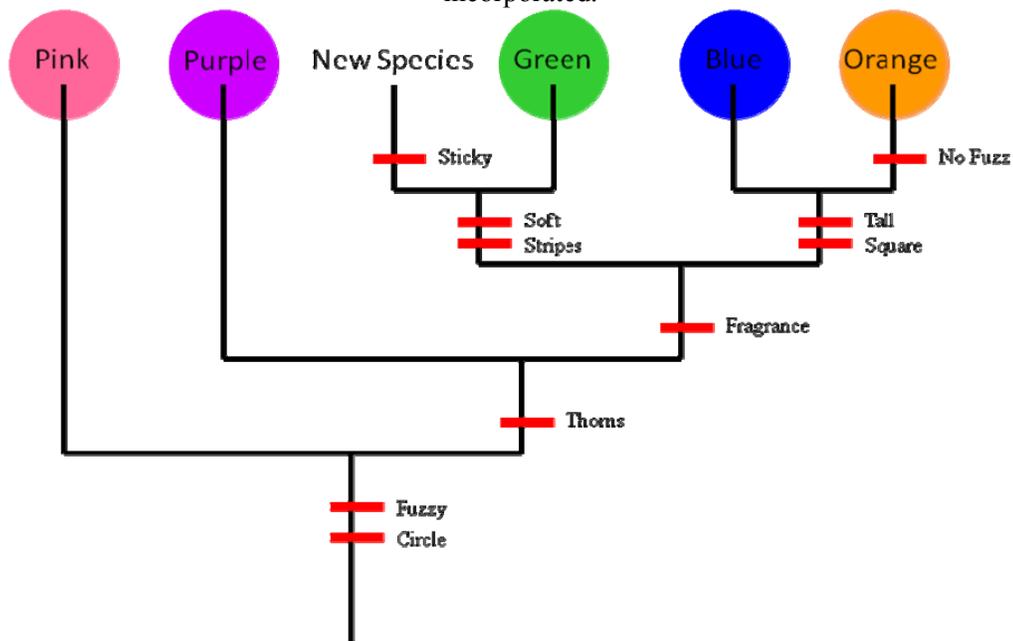
- Consider that you went on a field trip to the Amazon and found a new species that has never been described before. Compare these character states to determine which color is most closely related to the new species.

Species	Characters
Pink	Hard, Short, Not Sticky, No Fragrance, No Thorns, No Stripes, Fuzzy, Circle
Purple	Hard, Short, Not Sticky, No Fragrance, Thorns, No Stripes, Fuzzy, Circle
Green	Soft, Short, Not Sticky, Fragrance, Thorns, Striped, Fuzzy, Circle
Blue	Hard, Tall, Not Sticky, Fragrance, Thorns, No Stripes, Fuzzy, Square
Orange	Hard, Tall, Not Sticky, Fragrance, Thorns, No Stripes, Smooth, Square
New Species	Soft, Short, Sticky, Fragrance, Thorns, Striped, Fuzzy, Circle

- After you have determined the closest relationship, your task is to incorporate this new species onto your phylogenetic tree.

Optional evaluation for follow-up: Have the students draw a phylogenetic tree that incorporates all of the colors, the new species, and the character states in appropriate places (e.g. Figure 5). Otherwise discuss as a class and you can gather evidence to see if they reached the objectives on a later exam.

Figure 5. This is an example of a tree with character states labeled and the new species incorporated.

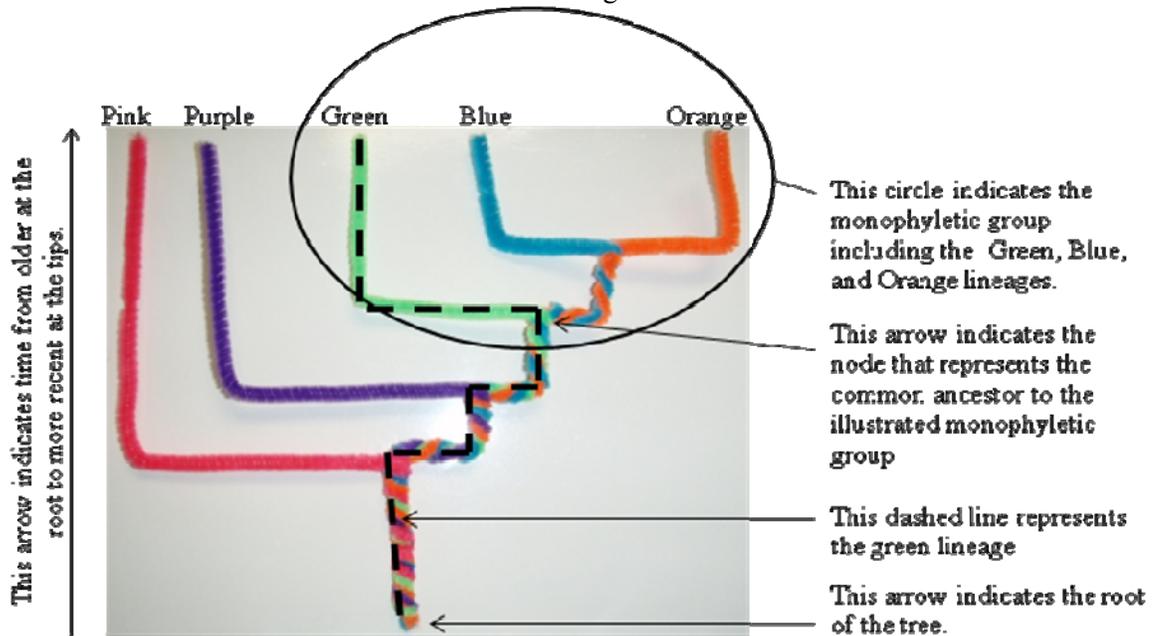


(For younger grades you may want to adapt this follow-up as stated: Consider that you went on a field trip to the Amazon and found a new species that has never been described before. Based upon genetic and morphological data you have concluded that this new species is most closely related to the green species. Your task is to incorporate this new species onto your model.)

Assessment and Evaluation: This lesson provides a strong foundation for investigating future units based upon interpreting phylogenetic trees and a start to helping students gain the necessary skills for tree building.

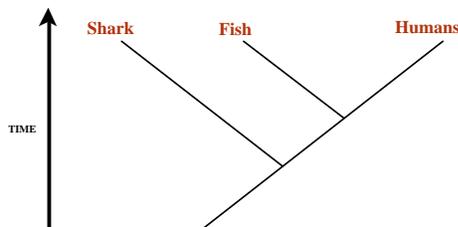
- Have students hand in their completed worksheets at the end of the class period. While assessment should be taken throughout the class period, the worksheet is one way to gather evidence for summative assessment.

Figure 5. This example of shows a model with the full green lineage (from root to tip) indicated by a dashed line and depicts the smallest inclusive monophyletic group and most recent node for this lineage.

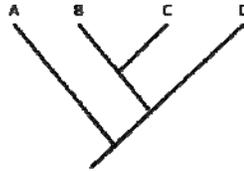


Future Follow-up Evaluation: Evaluation does not have to stop upon completion of this activity. Here are some potential exam questions that draw from the same skill set explored with this lesson.

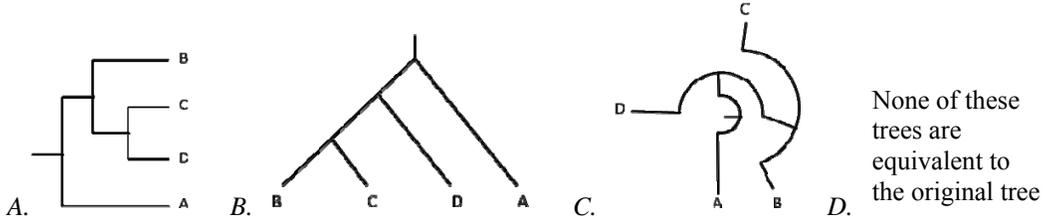
*Question 1. Given the phylogeny on the right, are fish more closely related to sharks, humans, or equally related to both? Explain your answer using appropriate terminology.*



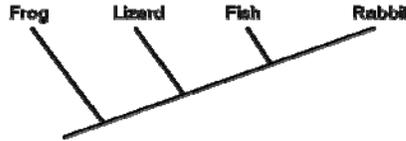
Question 2. Interpret the relationships depicted in the following tree:



Indicate which of these trees below illustrates the equivalent relationships to the tree above (you may circle more than one answer).

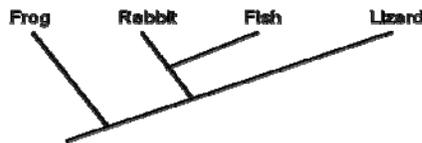


Question 3. Using the image below, which of the following is an accurate statement?



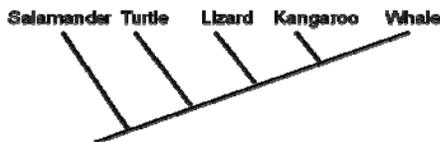
- a) A lizard is more closely related to a frog than a rabbit
- b) A lizard is more closely related to a rabbit than a frog
- c) A lizard is equally related to a frog and a rabbit
- d) A lizard is related to a frog but not related to a rabbit

Question 4. Using the tree below, which of the following is an accurate statement of relationships?



- a) A lizard is more closely related to a frog than a rabbit
- b) A lizard is more closely related to a rabbit than a frog
- c) A lizard is equally related to a frog and a rabbit
- d) A lizard is related to a frog but not related to a rabbit

Question 5. Using the image below, which of the following is an accurate statement?

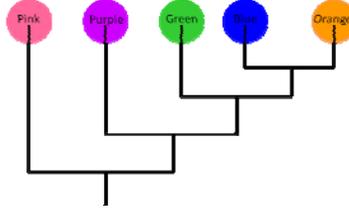


- a) A salamander is more closely related to a turtle than to a whale
- b) A salamander is more closely related to a whale than to a turtle
- c) A salamander is equally related to a turtle and a whale
- d) A salamander is related to a whale, but is not related to a turtle

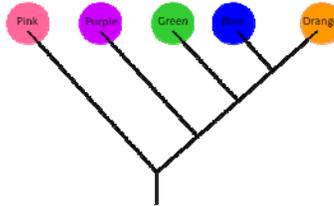
Name: \_\_\_\_\_

Date: \_\_\_\_\_

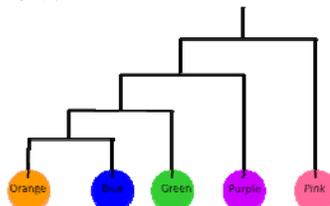
1. Orient your pipe cleaner tree so that the branches and nodes are arranged as shown below. Then use this tree to work through the following questions and reflect upon how this activity relates to tree thinking.



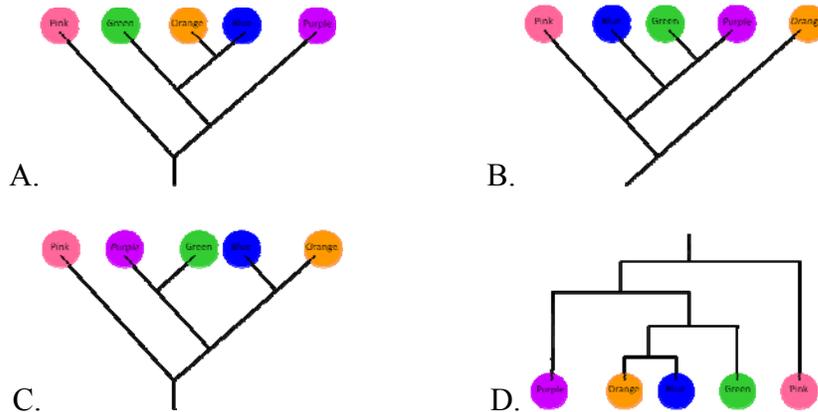
2. Without altering any of the branches, rotate your tree in all directions. How has this action changed the relationships of colors to one another? (Consider these questions in your response: Have the arrangements of nodes changed? Has the direction of time changed? If so how?)
3. Straighten the branches and intermodal regions of your model so they resemble the tree below.



- a. Explain how this tree is different/similar to the previous tree in question 1.
  - b. How has this action changed the relationship of colors to one another? (Consider these questions in your response: What bends/intersections on your pipe cleaner tree are informative about evolutionary relationships? What do you think these informative portions represent?)
4. A lineage refers to the entire evolutionary history of a species or taxa. Using this definition and your model for assistance. Indicate (by tracing) the green lineage on the tree illustrated below.



- Describe what you think is the significance for making the “edges” on your model multiple colors by intertwining the pipe cleaners.
- At the beginning of class we discussed how branches on a phylogenetic tree can swivel around nodes. Swivel the purple, blue, and orange branches on your model and draw the new topology of your tree below.
- Describe the differences and similarities between the tree drawn in question 6 to the initial tree in Question 1. (Consider these questions in your response: Have the monophyletic groups been changed? Have the relationships depicted altered? How can you indicate time on each tree?)
- Reorient your pipe cleaner model so that the branches and nodes are arranged as initially shown in question 1. Compare your model to the trees below. Circle the tree(s) that depict a different set of relationship among the colors.



- How are the relationships of colors in the tree(s) you selected in question 8 different from your pipe cleaner model?
- Describe what you would have to do to transform your model so that it depicted the same relationships as the tree(s) you selected in question 8?

## Interpreting Pseudocots Lesson Plan

Halverson, K. L. (2008, October) *Using hypothetical flowering plants to develop fundamental phylogenetic tree building skills*. Presented at the annual meeting of the National Association of Biology Teachers, Memphis, TN.

Grade Level: Post Secondary Courses

(vocabulary and activities can be modified for use in upper level high school courses)

Subject: Biological Sciences- Evolution (phylogenetics and tree building)

Duration: Two class periods with homework between classes.

Description: In order for students to develop expertise in phylogenetic systematics and become efficient problem solvers, students must cultivate representational competency associated with tree-thinking. However, representations have not been well studied in the biological sciences. This lesson helps students build some fundamental skills for reading and building phylogenetic representations expected upon completing a plant systematics course. The skills identified include: appropriate use of evidence, identification of key tree features, understanding of significant patterns, transferability across representations, and ability to verbally describe illustrated relationships. This lesson uses hypothetical flowering plants to assess and instruct essential phylogenetic tree-building skills. I gave students a set of hypothetical flowering plants, Pseudocots, and associated supplemental materials to complete a series of tasks that require using the identified fundamental skills. This lesson includes tasks such as: selecting appropriate data sources to group taxa into monophyletic groups (clades), constructing a phylogenetic tree representing these clades, adjusting the representation to incorporate new taxa, comparing their tree to other hypothesis, and forming predictions about historic and future character states.

Goals and Objectives: This lesson explicitly addresses and helps overcome the following challenges associated with phylogenetic tree building:

1. Lumping organisms based on single characteristics rather than looking holistically at the organisms.
2. Ignoring critical data & using uninformative evidence to construct trees.
3. Difficulties transferring empirical data into a visual representation illustrating evolutionary relationships.
4. Creating consensus nodes to address discrepancies.
5. Altering the format or orientation of the tree alters the relationships depicted.
6. Generating a comb-like branching structure without incorporating hierarchical lineages.
7. Using trees to reconstructing ancestral states.
8. Identifying the most likely tree by comparing representations

\*\*These challenges were identified from findings reported in the following resources:

Gendron, R. P. (2000). The classification & evolution of Caminalcules *American Biology Teacher*, 62, 570-576.

Halverson, K. L., Pires, J. C., & Abell, S. K. (2008). *Undergraduates' abilities to use representations in biology: Interpreting phylogenetic tree thinking*. Paper presented at the National Association for Research in Science Teaching.

Perry, J., Meir, E., Herron, J. C., Maruca, S., & Stal, D. (2008) Evaluating two approaches to helping college students understand evolutionary trees through diagramming tasks. *CBE-Life Sciences Education*, 7, 193-201.

Objectives:

- Students will be able to identify informative data that can be used to build a phylogeny.
- Students will be able to generate a phylogenetic tree from hypothetical data.
- Students will be able to alter phylogenetic models to accommodate new data.
- Students will be able to compare phylogenetic tree and determine how different models provide support or dispute their phylogeny.

Prerequisites: It helps if students are familiar with reading phylogenetic tree prior to this lesson. Thus I suggest that the Pipe Cleaner Phylogeny lesson or similar tree-reading unit be implemented prior to this lesson.

Here are terms to be familiar with:

Apomorphy – a derived character state unique to one lineage

Branch – illustrates the different lineages after speciation events

Character - a specific heritable trait described in terms of its state

Consensus Tree (or node) - a phylogenetic tree derived by combining common features in multiple trees, often leading to undefined relationship hierarchies of sister taxa.

Internode - a shared lineage between speciation events

Lineage - a continuous line of descent

Monophyletic (Clade) - a grouping of a common ancestor and all of the descending lineages

Node - a hypothetical common ancestor or speciation event

Out Group - a distantly related species that resides outside of the clade of interest

Pseudocot - hypothetical flowering plant clade

Phylogenetic tree - an evolutionary tree (shows relationships among organisms)

Materials:     Hard copies of worksheets (see end of lesson plan)  
                  Hard copies of Supplementary Data (one set per student/group)  
                  Scissors  
                  Colored pencils/markers (optional)

Lesson Procedure:

**This lesson is very dependent upon the timing when data is introduced to the students. It is important be aware of when to hand out the different portions of supplementary data or unintended outcomes may result.**

*Day 1:*

Begin by engaging students with a scenario: “You are part of research team that has just made an amazing discovery of some unique looking flowering plants. The lead investigator of your research team thinks that this new group of species is evolutionarily different that currently known plants and they are a new clade he is calling Pseudocots. It is your job to determine how these plants species are related to each other and the closest currently described flowering plant (a potential out group) by building a phylogeny.”

Once you have presented the scenario and engaged the students, allow them to talk about how they might want to proceed to create a phylogeny. This is a good step to assess what

students know about phylogenies before beginning the lesson. Most students will probably never have encountered this type of task previously and will need a lot of guidance. If you have some students with tree building experience, you may want to group them accordingly.

Have students form groups of 2-3 students per group (students can also complete this activity individually and discuss as a class). Hand out *Worksheet 1a, Sissors*, and the data for the *12 living Pseudocots and field notes*. Have the students cut out the images of the Pseudocots (be sure to keep the species number attached to each image) so they can physically arrange them how they think they might go together. Give students time to group the species and think about how they might be related. As you observe the students have them consider what types of evidence they are using to organize their plant species and why that evidence is informative (e.g., are they using the field notes and/or morphological data – why?).

**\*\*It is important to have students indicate the evidence they used for their classification method to ensure they are not basing the relationships on uninformative ecological data.**

*(Optional adaptation: Depending upon how familiar your students are with phylogenies, you can reduce the number of species used in this activity to six, using only species: 1, 2, 5, 6, 7, 11).*

Students often think that the ancestral characters states are a primitive regardless of the evidence presented. Thus, once students have settled upon a classification scheme, have them predict what the most ancestral Pseudocot might look like and draw this prediction on their worksheets. Images will vary quite a bit at this point.

Once they have committed to their prediction, hand out *Worksheet 1b and the Fossil Record*. Allow students time to compare and discuss the fossil record and work through the two problems on this worksheet. Have students discuss differences/similarities in their previous prediction and their current ideas. This is an optimal point to discuss issues with ancestral state reconstruction as a class.

**\*\*Note:** The oldest fossil may or may not be indicative of the ancestral states for multiple reasons (e.g., we might not have a complete fossil record and there could be older fossils not yet found, there could be ancestral states that have been lost prior to the fossilized species).

By the end of the class period, students should have completed Worksheets 1a and 1b. You can collect these or let students keep them for reference as the work on the homework portion of this lesson. Regardless, all students should make note of their original species grouping and should keep the species images to assist with the homework and bring them to class the next period as well. These images are extremely helpful with all portions of the lesson.

*Homework (or completed at the end of Day 1 or beginning of Day2 if time allows):* Give students (or post online) the *Homework* worksheet and *Genetic Data*. Instruct the students to fill out the data matrix with 0's and 1's (and 2's if necessary when there are three variations). 0's represent traits present in the out group or "ancestral" traits.  
*(Optional adaptation: If you are only using six species then reduce the genetic data to the following codons: A, D, F, G, H, I, J, K)*

**Day 2: Constructing a Phylogenetic Tree**

This is the most challenging portion of this activity. Students have already organized morphological character states and genetic data of the Pseudocots in a data matrix. This step helps them translate the matrix information into a phylogenetic tree and should be done as a class. \*\*Students may have differing matrices, so begin by creating a single consensus matrix as a class and use this to complete *Worksheet 2a*.

There are 5 Steps that you can use to help provide a scaffold for students to be able to translate raw evidence into a phylogenetic tree:

- Step 1: Begin with a Data Matrix that organizes raw evidence (Previous homework)
- Step 2: Reorder Matrix so that it is easier to see patterns of apomorphies (optional)
- Step 3: Create Venn Diagram of Species
- Step 4: Add Branches, connect lineages, and root tree
- Step 5: Compare trees in search of support

\*\* Have students record these steps on their worksheets as a reference.

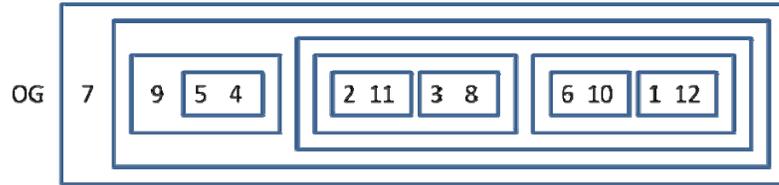
**Step 1: Data Matrix**

	A	B	C	D	E	F	G	H	I	J	K	L	M
Species 1	1	1	0	1	0	0	1	0	1	0	1	0	0
Species 2	1	0	0	0	0	1	1	0	1	0	0	0	2
Species 3	1	0	2	0	1	0	1	0	1	0	1	0	2
Species 4	1	0	0	0	0	0	1	1	1	0	0	0	1
Species 5	1	0	0	0	0	0	0	1	1	0	0	0	1
Species 6	1	2	0	0	0	0	1	0	1	0	1	1	0
Species 7	0	0	0	0	0	0	0	0	1	0	0	0	0
Species 8	1	0	1	0	1	0	1	0	1	0	1	0	2
Species 9	1	0	0	0	0	0	0	0	1	0	0	0	1
Species 10	1	2	1	0	0	0	1	0	1	0	1	1	0
Species 11	1	0	0	0	0	1	1	0	1	1	0	0	2
Species 12	1	1	0	0	0	0	1	0	1	0	1	0	0
Out Group	0	0	0	0	0	0	0	0	0	0	0	0	0

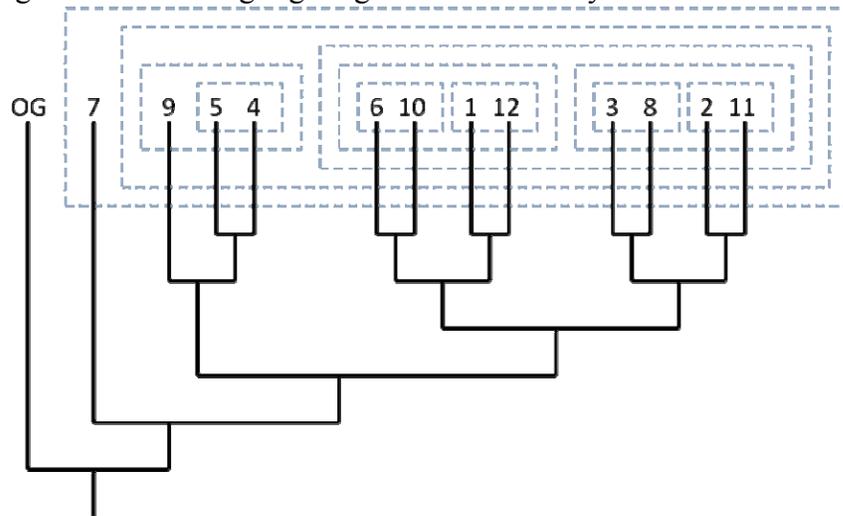
**Step 2: Reorganize Data Matrix**

	I	A	G	K	H	F	E	L	J	D	M	C	B
Species 12	1	1	1	1	0	0	0	0	0	0	0	0	1
Species 1	1	1	1	1	0	0	0	0	0	1	0	0	1
Species 10	1	1	1	1	0	0	0	1	0	0	0	1	2
Species 6	1	1	1	1	0	0	0	1	0	0	0	0	2
Species 8	1	1	1	1	0	0	1	0	0	0	2	1	0
Species 3	1	1	1	1	0	0	1	0	0	0	2	2	0
Species 11	1	1	1	0	0	1	0	0	1	0	2	0	0
Species 2	1	1	1	0	0	1	0	0	0	0	2	0	0
Species 4	1	1	1	0	1	0	0	0	0	0	1	0	0
Species 5	1	1	0	0	1	0	0	0	0	0	1	0	0
Species 9	1	1	0	0	0	0	0	0	0	0	1	0	0
Species 7	1	0	0	0	0	0	0	0	0	0	0	0	0
Out Group	0	0	0	0	0	0	0	0	0	0	0	0	0

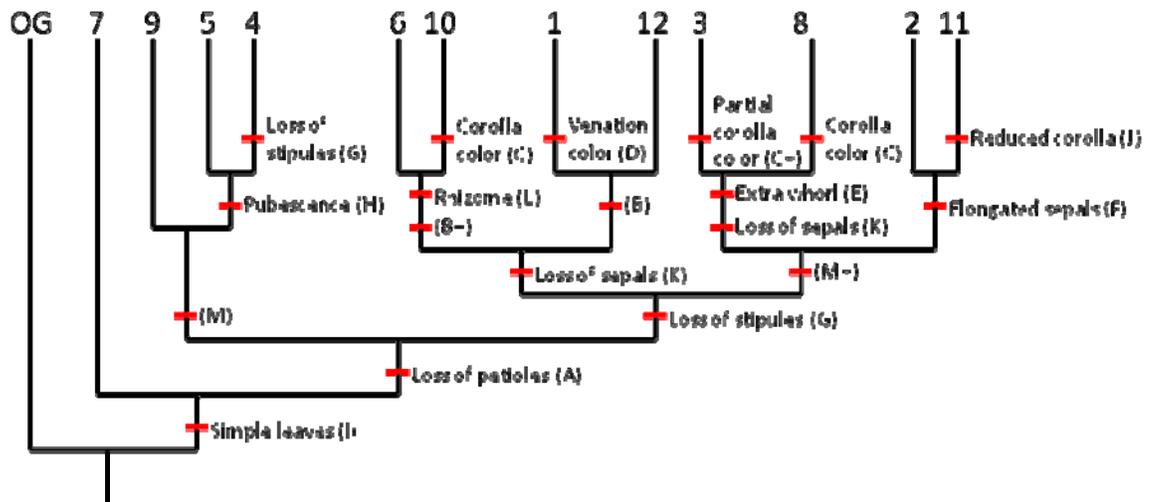
**Step 3:** Assist students with splitting the species into monophyletic groups by focusing on apomorphies. Isolate each species (or sister group) into its own circle with the most related nested in the most circles.



**Step 4:** Once the clades have been identified from the evidence provided, students can begin drawing branches and highlighting common ancestry.

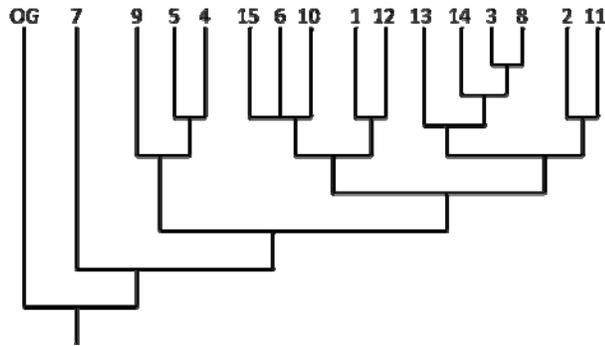
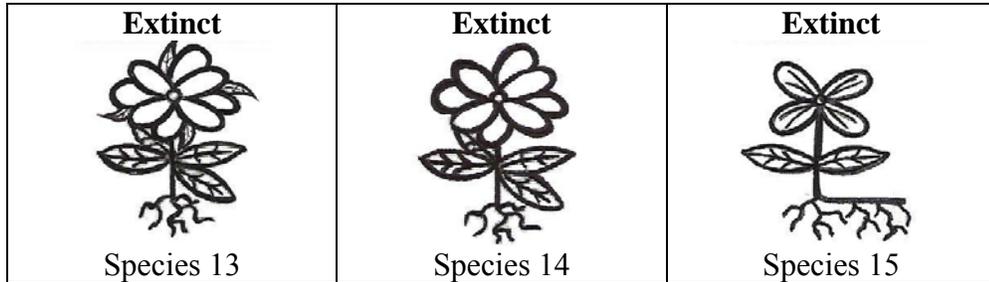


By adding character states and rooting the tree, students will have built a phylogeny from the data they used.



**\*\*Note:** This activity has some character states (e.g., loss of stipules and corolla color) that evolved more than once. Also, it's perfectly fine if the species are in a different order as long as the groupings are the same. For more information about this – see a tree-reading lesson.

(Optional adaptation: Include these extinct Pseudocot species from the fossil record when constructing the Pseudocot phylogeny \*\*\*Note: if you are using fossils in your phylogeny, then they will not have DNA data. This is a good discussion point for class – why we don't or have difficulties obtaining DNA evidence from extinct species. You can have students add in morphological evidence to help these species fit in very easily.):



(Optional adaptation: If electing to use smaller sample set, then see the following images to see potential phylogeny):

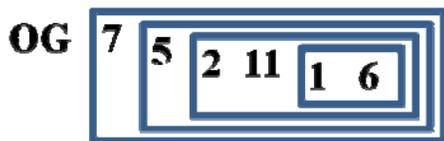
Step 1: Data Matrix

	A	D	F	G	H	I	J	K
Species 1	1	1	0	1	0	1	0	1
Species 2	1	0	1	1	0	1	0	0
Species 5	1	0	0	0	1	1	0	0
Species 6	1	0	0	1	0	1	0	1
Species 7	0	0	0	0	0	1	0	0
Species 11	1	0	1	1	0	1	1	0
Out Group	0	0	0	0	0	0	0	0

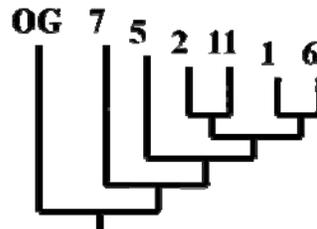
Step 2: Reorganized Data Matrix

	I	A	H	G	F	J	K	D
Species 1	1	1	0	1	0	0	1	1
Species 6	1	1	0	1	0	0	1	0
Species 11	1	1	0	1	1	1	0	0
Species 2	1	1	0	1	1	0	0	0
Species 5	1	1	1	0	0	0	0	0
Species 7	1	0	0	0	0	0	0	0
Out Group	0	0	0	0	0	0	0	0

Step 3: Venn Diagram



Step 4 & 5: Adding Branches & Rooting Tree

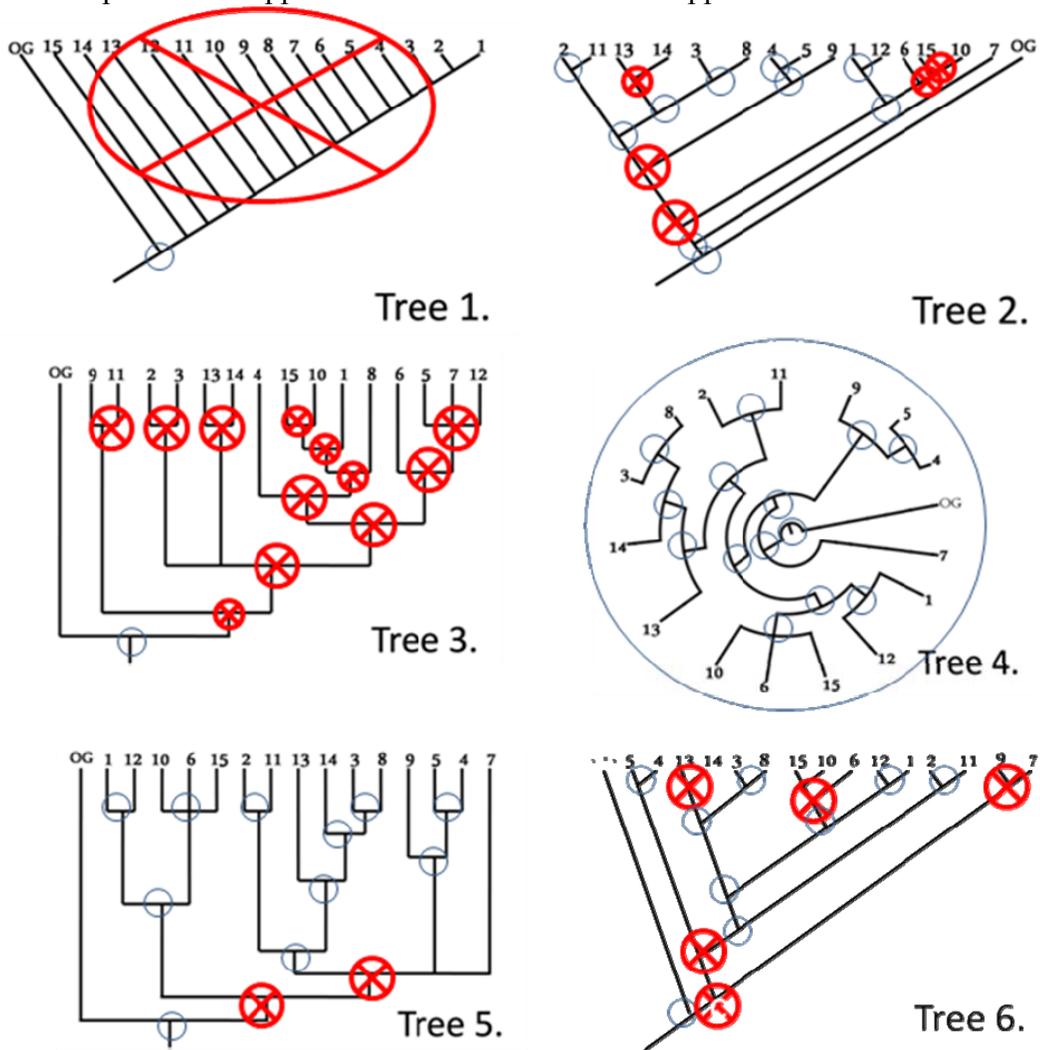


(Optional adaptation: To further assess students tree building abilities you may have them build a tree from their personal matrix if different than the one presented in class or build a tree from the remaining species if you did not include all in the original tree.)

**Step 5:** Compare trees in search of support

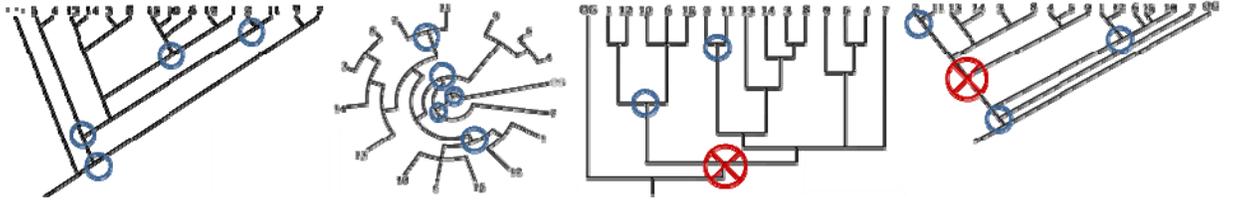
After the class has constructed the Pseudocot phylogeny, hand out *Worksheet 2b*. The clades organized as a class can be tested against other phylogenetic trees. Have students circle the monophyletic groupings on each tree and compare clades, or “collapse branches to the nodes.” If only the species of interest are included, then there is support, if a different species is included within the clade, then there is no support.

Here are examples comparing 6 phylogenies to the tree generated *including fossils*. These examples show supported nodes circled and non-supported nodes crossed out.



For another example of how to compare phylogenies see:  
 BioQUEST Curriculum Consortium. (2008, October 4). BEDROCK: Whippo Problem Space. Retrieved October 15, 2006 from [http://www.bioquest.org/bedrock/problem\\_spaces/whippo/](http://www.bioquest.org/bedrock/problem_spaces/whippo/)

*(Optional adaptation: If electing to use smaller sample set, then see the following images to see how the developed phylogeny compares to some of the trees presented to the students.):*



*(Optional adaptation: You can opt to have students compare their tree to all or a subset of the trees provided. Or, if you have students develop trees individually after the example completed by the entire class have students compare their trees with a neighbor. How these trees compare will vary based upon how the students grouped the species.)*

Follow-up:

One way to assess students' tree-building skills is by having them apply their knowledge to an example that relies upon conceptual understanding of phylogenies. This follow-up example presents a problem similar to those faced by scientists on a regular basis - New data is introduced that they have to accommodate in their understanding.

Late breaking news: Two scientists were on a collecting exhibition in the Amazon (where there is limited sunlight and poor soil available) and found a new, Pseudocot species (#24). Accommodate this new data and incorporate this new species into your phylogenetic tree.



New Species (#24)

Coding Sequence: ATG, ATA, CGT, TAA, AAC, TGC, TAA, ACC, AGT, ATA, CAA, ATT, CTG

**\*\*Note:** Students may have to readjust the current relationships they had predicted in order to fit this species into the phylogeny. Have them build a tree and turn it in for evaluation.

## Worksheet 1a: Interpreting the Pseudocot Phylogeny

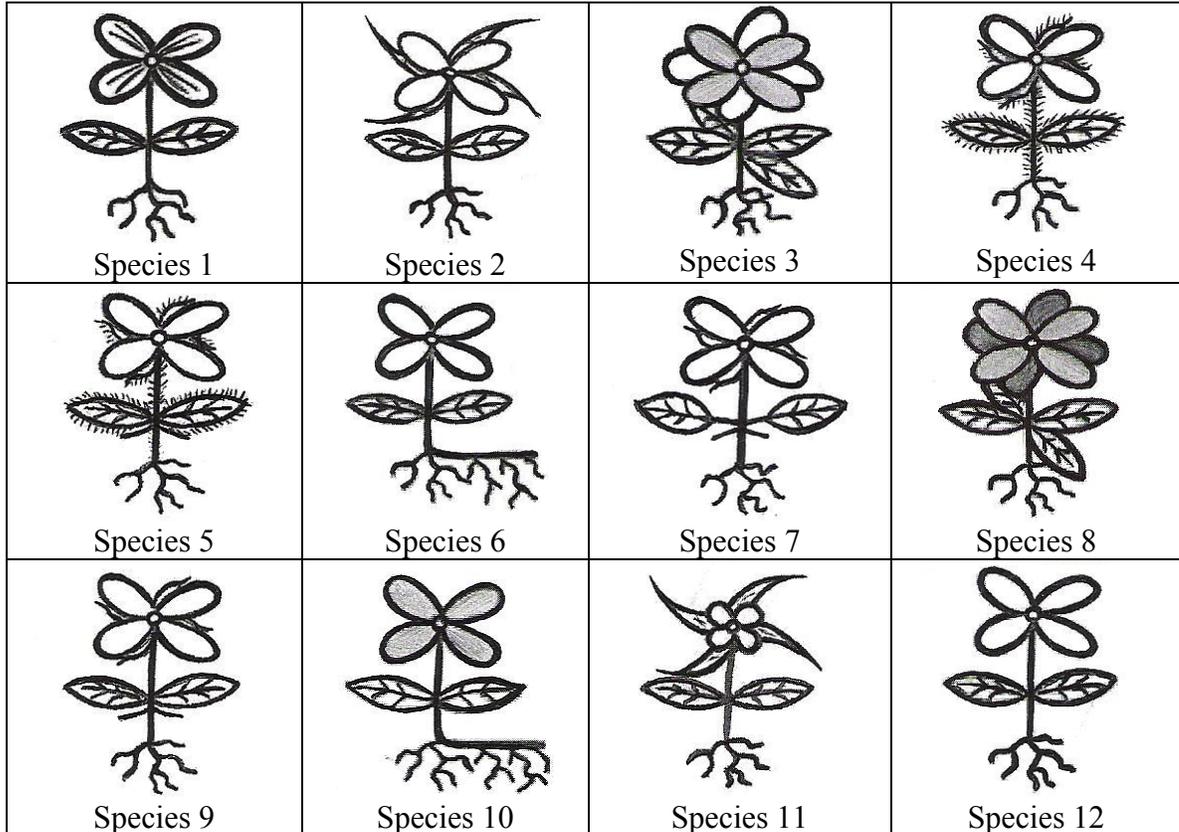
Name: \_\_\_\_\_

Date: \_\_\_\_\_

1. You are part of a research team investigating some hypothetical flowering plants called Pseudocots. You have collected 12 extant species from across North Americas (see field notes for environmental data). Your current task is to cut out the images of the living Pseudocots (Species 1-12) and group them into categories indicating how you think they are related to one another. In the space below, write down the groupings you finalized. Explain what evidence you used to organize these species and how you think these groups are related.

2. Based upon your categories of Pseudocots, describe/draw what you think the most ancestral Pseudocot would look like.

Living Pseudocots:



**Field notes:**

Species 1: Collected from a rocky meadow by a stream in the Midwest (US), shady conditions, fertile soil (found by #10)

Species 2: Collected from an upland forested area in Eastern US, limited sunlight available, poor soil (found by #3)

Species 3: Collected from an upland forested area in Eastern US, limited sunlight available, poor soil (found by #2)

Species 4: Collected from a swampy wetlands area in the Midwest (US), shady conditions (found by nonpseudocots)

Species 5: Collected from a desert in Southwest (US), full sun conditions (found by #7 & #12)

Species 6: Collected from a tall grass prairie in the Midwest (US), full sun conditions

Species 7: Collected from a desert in Southwest (US), full sun conditions (found by #5 & #7)

Species 8: Collected from a rocky meadow by a stream in the Northeast (US), shady conditions, fertile soil (found by nonpseudocots)

Species 9: Collected from a tropical rain forest in Southern Mexico, limited sunlight, poor soil

Species 10: Collected from a rocky meadow by a stream in the Midwest (US), shady conditions, fertile soil (found by #1)

Species 11: Collected from a tropical rain forest in Southern Mexico, limited sunlight, poor soil

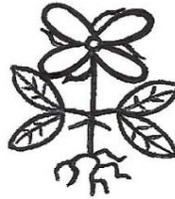
Species 12: Collected from a desert in Southwest (US), full sun conditions (found by #5 & #7)

Worksheet 1b: Interpreting the Pseudocot Phylogeny

Name: \_\_\_\_\_

Date: \_\_\_\_\_

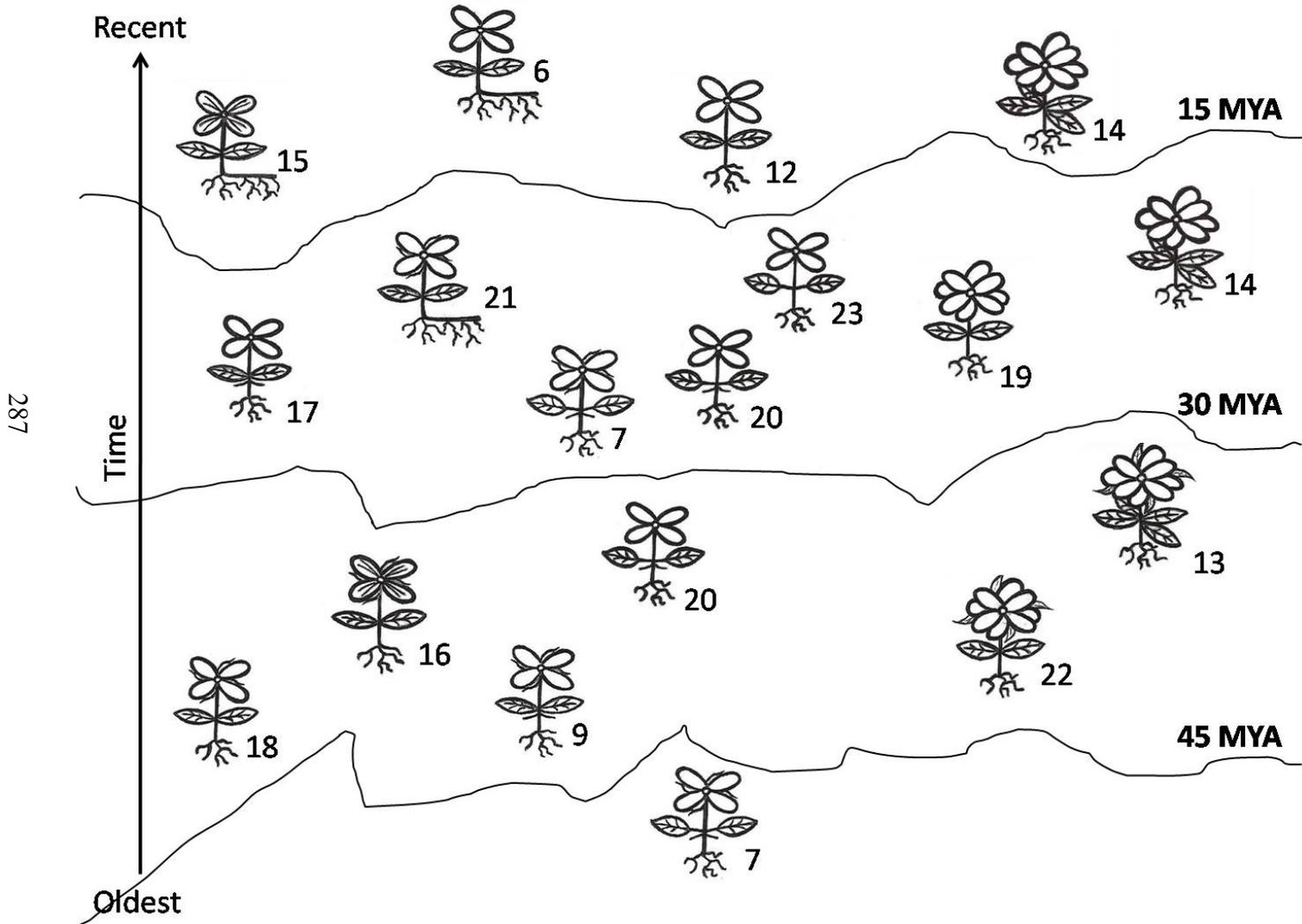
1. Review the Fossil record that scientists have uncovered and the outgroup species: (Species 1-12 are extant, Species 13-23 are extinct). Without changing your original drawing from Question 2, be specific in explaining how your prediction compared to the fossil record.



Out Group

4. Explain why this oldest fossil found may or may not be indicative for how the earliest ancestor for this group of plants appeared.

Fossil Record (Species 1-12 are extant (still living), Species 13-23 are extinct):



Homework:

Name: \_\_\_\_\_ Date: \_\_\_\_\_

Pretend you have been allowed access to a DNA sequencing laboratory and gathered genetic data for each of these living species and an out group. Review the coding sequences and complete the following matrix using '0' for ancestral states and '1' for derived characters (use '2' if there are more than 2 traits).

Fill in the Matrix:

	A	B	C	D	E	F	G	H	I	J	K	L	M
Species 1													
Species 2													
Species 3													
Species 4													
Species 5													
Species 6													
Species 7													
Species 8													
Species 9													
Species 10													
Species 11													
Species 12													
Out Group													

6. Revisit the categories you created in Worksheet 1a, Question 1. After reviewing this new data (fossils, DNA, and out group) have you altered the way you believe these species are related to one another? In the space below, write down the groupings you finalized. Explain what evidence you used to organize these species and justify any changes you have made to your groupings, if any.

Genetic Data:  
Coding Sequence: (Codon Sequences Labeled)

	A	B	C	D	E	F	G	H	I	J	K	L	M
Species 1	A T G	T A C	G C A	A T T	A A C	T G C	T A A	A C C	A G T	A T A	G C C	A T T	C T C
Species 2	A T G	A T A	G C A	T A A	A A C	A C T	T A A	A C C	A G T	A T A	C A A	A T T	C C T
Species 3	A T G	A T A	C C T	T A A	T T T	T G C	T A A	A C C	A G T	A T A	G C C	A T T	C C T
Species 4	A T G	A T A	G C A	T A A	A A C	T G C	T A A	A A A	A G T	A T A	C A A	A T T	C T G
Species 5	A T G	A T A	G C A	T A A	A A C	T G C	A T G	A A A	A G T	A T A	C A A	A T T	C T G
Species 6	A T G	T A A	G C A	T A A	A A C	T G C	T A A	A C C	A G T	A T A	G C C	G C C	C T C
Species 7	G G C	A T A	G C A	T A A	A A C	T G C	A T G	A C C	A G T	A T A	C A A	A T T	C T C
Species 8	A T G	A T A	C G T	T A A	T T T	T G C	T A A	A C C	A G T	A T A	G C C	A T T	C C T
Species 9	A T G	A T A	G C A	T A A	A A C	T G C	A T G	A C C	A G T	A T A	C A A	A T T	C T G
Species 10	A T G	T A A	C G T	T A A	A A C	T G C	T A A	A C C	A G T	A T A	G C C	G C C	C T C
Species 11	A T G	A T A	G C A	T A A	A A C	A C T	T A A	A C C	A G T	G G G	C A A	A T T	C C T
Species 12	A T G	T A C	G C A	T A A	A A C	T G C	T A A	A C C	A G T	A T A	G C C	A T T	C T C
Out Group	G G C	A T A	G C A	T A A	A A C	T G C	A T G	A C C	A T G	A T A	C A A	A T T	C T C

Worksheet 2a: Building the Pseudocot Phylogeny

Name: \_\_\_\_\_

Date: \_\_\_\_\_

Build a phylogenetic tree depicting the evolutionary relationships among the out group and species 1-15 (12 living Pseudocots plus three extinct species: 13, 14, & 15).

Step 1:

Step 2:

Step 3:

Step 4:

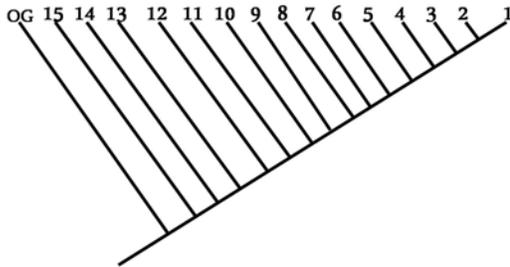
Step 5:

Worksheet 2b: Defending Your Pseudocot Phylogeny

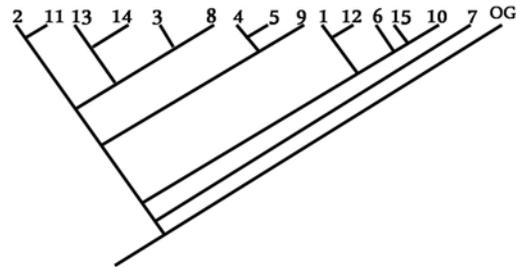
Name: \_\_\_\_\_

Date: \_\_\_\_\_

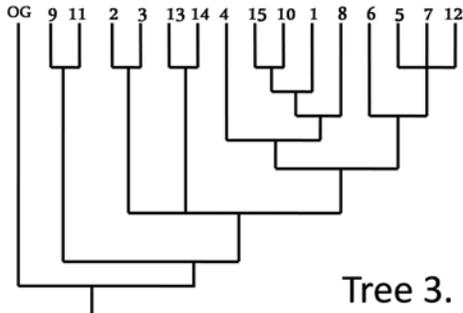
1. Compare the tree you developed with these six other models created. On each of these other models indicate by circling which nodes, if any, are supported by your tree?



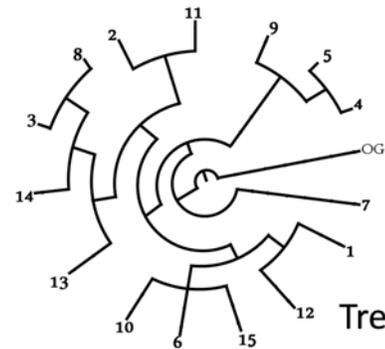
Tree 1.



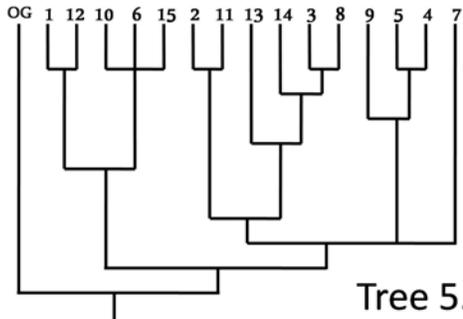
Tree 2.



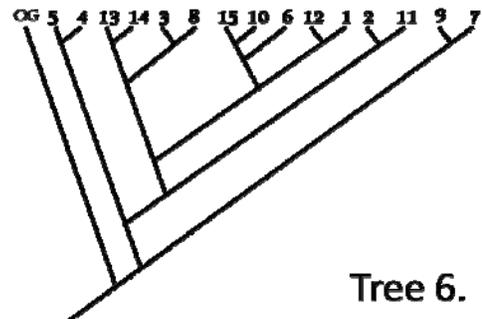
Tree 3.



Tree 4.



Tree 5.



Tree 6.

2. Which model is best supported by your tree? Describe how you are able to make this decision?

## VITA

Kristy Halverson was born in Fulton, Missouri where she completed her primary and secondary education. There, she also earned her Bachelor's degree in Biology from Westminster College. Kristy continued her education in biology at Iowa State University where she earned her Master's degree in Ecology and Evolutionary Biology and published two peer-reviewed articles on her biology research.

Kristy entered the doctoral program at the University of Missouri (MU) Science Education Center in 2005. During her four years at MU, she worked on five research grants in science education, published three peer reviewed articles from her research in science education, and received the Southwestern Bell Science Education Center "Graduate Research Assistant of the Year" award in 2009. During this time she was also the primary instructor for four biology courses: Evolution, Community Biology, Introduction to Environmental Science, and Biodiversity.

Kristy has accepted a tenure track position as Assistant Professor of Biological Sciences at the University of Southern Mississippi, beginning August, 2009. In her role as biology educator, she will teach undergraduate courses in biology and graduate courses in science education. Kristy will continue her research on college student learning with biological representations.