Learning to Understand the Tree of Life

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Abstract: Tree-thinking is increasingly recognized as a crucial skill in the biological sciences. However, for students, the task is wrought with challenges. Even as representations are meant to facilitate reasoning about difficult concepts such as macroevolution and the phylogenetic relationships among taxa, existing tree diagrams that are so crucial to the biologist's profession present many challenges that hinder students' understanding. The presenters in this symposium take multiple theoretical and methodological lenses to examine the many-faceted challenges of tree-thinking with representations – from the issues of representation and symbolization, to the cognitive and developmental issues of reasoning, to the implementation of a classroom intervention. Brought together in this symposium, the researchers initiate an ongoing agenda to understand and to design interventions that will support students' reasoning with this important representational tool.

Introduction

Natural historians have long created diagrams to represent their beliefs about the relations among species. With Darwin's famous 1837 sketch, the metaphor of a "tree of life" that illustrates the origin and divergence of species captured scientific thought. Thereafter, it became an icon of evolution, and firmly associated with biological understanding (Figure 1). In modern biology, tree diagrams such as cladograms have become invaluable tools for scientific reasoning. They have played roles in such diverse areas as the discovery of new biological compounds, the restoration of damaged ecosystems, and the understanding of the functional role of genes. Such representations are gateways to what biologists call tree thinking, which, contrary to much of evolutionary reasoning before the 20th century, recognizes the divergence of species, and the interconnected relationships between them (O'Hara, 1997).

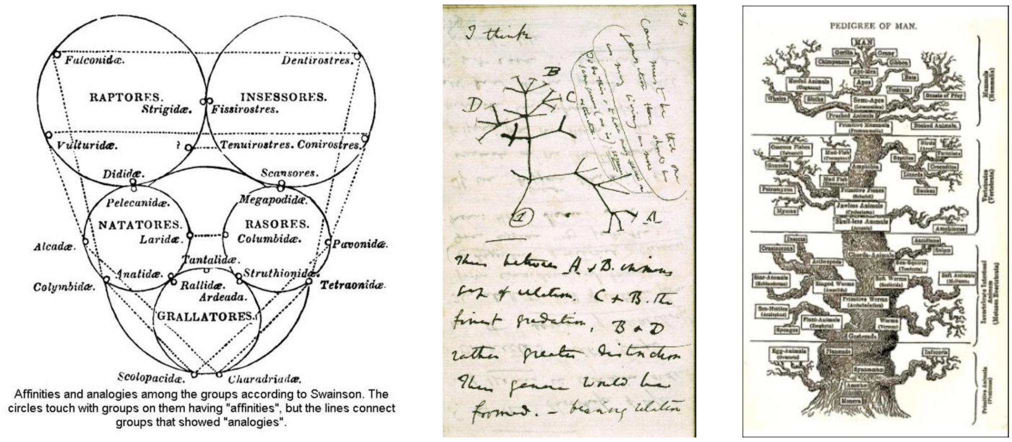

Figure 1. Early illustrations of species relationships by Swainson, 1836-1837 (left); Darwin, 1837 (center); and Ernst Haeckel, 1891 (right)

Cladograms come in many forms, but generally consist of interconnected lines, or branches, which represent the lineages of groups of organisms referred to as taxa. Taxa are named at their branch tips, and nodes, where two such branches intersect, represent the most recent ancestral traits shared by those taxa (see examples in Figures 2, 3, and 5). By identifying the relative recency of these ancestries, one can reason about the relatedness among the taxa depicted. Experienced biologists use cladograms to test evolutionary hypotheses, to learn about the characteristics of extinct and newly discovered species, and so to better understand the relationships among organisms on earth. The ability to read cladograms is thus crucial for understanding fundamental concepts of evolutionary biology (Baum, Smith, & Donovan, 2005; Catley , 2006) and is as well an important component of scientific literacy. Educators are moreover urged to teach these tools of professional practice (American Association for the Advancement of Science, 2001; National Research Council, 1996).

Yet, despite their simple forms, there is growing evidence that students find tree diagrams difficult and are prone to misinterpret them. Consequently, one strand of research has begun to document the types of mistakes that students make when make when reading cladograms. Common errors include reading increasing qualities in species from the bottom toward the top of the diagram, reading progress across the branch tips, and viewing the cladogram as a story of linear transformation rather than as one of divergence toward species diversity (e.g., Gregory, 2008; Halverson, Pires, & Abell, 2008; Meir, Perry, Herron, & Kingsolver, 2007; Novick & Catley, 2007). Other research has explored the factors that influence cladogram interpretation. For example, Novick & Catley (2007) point to the Gestalt principle of Good Continuation as a perceptual hindrance to interpreting a particular form of cladogram. Catley and Novick (2008) moreover find that this form of cladogram most prone to misinterpretation is also the one most prevalent in biology textbooks..

It is clear from existing research that meaning from a cladogram is constructed by the viewer, as it is in the case of other scientific representations. It is also clear that we cannot design more effective interventions to support that construction until we better understand the interaction of the multiple factors involved in interpretation. This symposium brings together researchers active in the budding area of tree-thinking. Together, the papers tackle the many dimensions of interpretation – be they representational, cognitive, educational, or developmental – and address the mechanism of diagrammatic reasoning through different methodological and theoretical lenses.

In the first paper, Phillips, Novick, and Catley examine the role of prior content knowledge in tree diagram interpretation. They compare high school and college students' performances on core tree reading skills, and show how reasoning strategies vary with students' biology background. Namely, they find that specific knowledge of taxa depicted in a tree diagram can interfere with students correctly reasoning based on the structure of the diagram. This carefully designed study contributes to untangling the influences of conceptual knowledge and perception in diagrammatic interpretation. In this manner, the authors provide us with valuable foundational components to consider in the design of an effective tree-thinking learning progression based in representations.

Meanwhile, Matuk and Uttal filter out specific content from the cladogram in order to more closely examine the perceptual and representational issues underlying the challenges with tree-thinking. In their study, they ask students to invent representations of *relatedness* and then observe how invention influences students' later interpretations of a standard cladogram. Most interestingly, they find differences in the kinds of representations students' invented to represent evolutionary relationships, vs. the kinds they invented to represent social relationships. However, they also observe that the common errors made reading cladograms persisted no matter whether the student was in the evolution or the non-evolution condition. Their work at once demonstrates the powerful influence of visual structure independent of content, as well as the influence of content beliefs on representational acts. It furthermore suggests more intuitive representational forms that may help support novice understanding of standard cladograms.

Next, Ainsworth and Saffer present a surprising finding. Given appropriate but only limited training (10 to 15 minutes), they find that children as young as seven years old can be successfully taught to read these complicated representations. On the one hand, their work reinforces the messages of the first two papers, that adults' reasoning errors are largely due to perceptual and conceptual biases acquired from prior knowledge in other domains; and on the other, it suggests promise for developmentally appropriate educational interventions. The authors encourage us to imagine possibilities beyond conventional educational standards, and challenge us to rethink when, and what we consider to be developmentally appropriate material for students to learn.

Finally, Halverson presents findings on the impact of novel instructional interventions among undergraduate students enrolled in a tree-thinking course. By documenting students' developing reasoning skills over three semesters, she demonstrates how certain specific challenges of representational competency can be addressed through scaffolded activities that involve students manipulating a three-dimensional cladogram fabricated with pipe cleaners. Halverson's study teaches us that sometimes, simple and elegant solutions exist, although these often only become clear through better understanding the problem.

An important component of scientific literacy is to understand the tools of scientific practice. Each of the papers in this symposium addresses issues of scientific literacy within the discipline of biology. Through the specific case of evolutionary trees, the authors consider important questions of representational competency: What are the conceptual and perceptual influences on diagrammatic interpretation? What is the role of content knowledge vs. perception? How does tree thinking develop from childhood through high school, through college? What interventions and scaffolds can educators provide to support tree-thinking? Together, the authors apply multiple methodological and theoretical perspectives to paint a more complete picture of the reasoning process and of diagrammatic interpretation and understanding. Each seeks to better understand when and how students imbue diagrammatic marks with evolutionary meaning; and each takes their findings a step further to suggest useful learning progressions, designs for more effective interventions, and scaffolds to help students develop reasoning skills in the domain of evolution. Led by our discussant, Karl Rosengren, this symposium promises lively interaction among presenters and members of the audience. It is an opportunity to discuss issues of interest to researchers concerned with how representations mediate our understanding of complex topics, as well as to those specifically interested in biological learning.

How high school students reason about the tree of life: A developmental perspective

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In 1996, the National Research Council put forth a set of guidelines for K-12 science education that state that students be introduced to the theory of evolution in primary and secondary schools. Tree thinking is an essential tool for understanding evolutionary hierarchies, based on the distribution of derived characters among a set of taxa; yet, there is little research devoted to the acquisition of tree thinking skills during development. The present study examines the cognitive processes that underlie high school students' abilities to engage in tree thinking. We compare students' responses to those recently obtained from a college sample of students with weaker and stronger backgrounds in biology (Novick & Catley, 2009). These results will provide critical information regarding the developmental trajectory of tree thinking skills during adolescence and early adulthood.

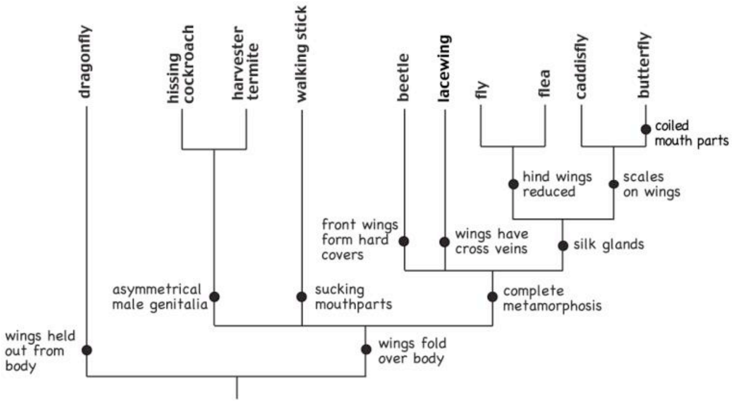

Figure 2. An insect cladogram

Methods

60 students (31 males, 29 females) who were enrolled in a 10th grade high school biology class at a public high school in a rural area of western North Carolina (*M*=15.65, range of 15-17 years) completed a 4-page booklet, which included a cladogram and three questions on each page. Students were instructed to utilize each cladogram to answer questions regarding the evolutionary relations among several taxa, including insects (Figure 2), dinosaurs (Figure 3), placental mammals, and marsupial mammals. Students' tree-thinking skills were assessed in five domains including identifying a character shared by a most recent common ancestor (MRCA) and a set of taxa based on a given derived character. Students were also asked to identify clades (i.e., monophyletic groups) and evaluate the relative evolutionary distance (degree of relatedness) between taxa. A fifth skill required students to make inferences about what taxa are likely to share a derived character (the focus of the analysis presented in this symposium). Students were told that birds are warm-blooded (dinosaurs cladogram) or that termites digest cellulose (insects cladogram) and were asked which taxon is most likely to share this character. The answers (*T-Rex* and hissing cockroach) can be seen in Figure 3 and 2, respectively.

Results

College students with a stronger background in biology had the highest number of correct responses overall. However, all students were more likely to make correct inferences when asked about insects as opposed to dinosaurs (Table 1).

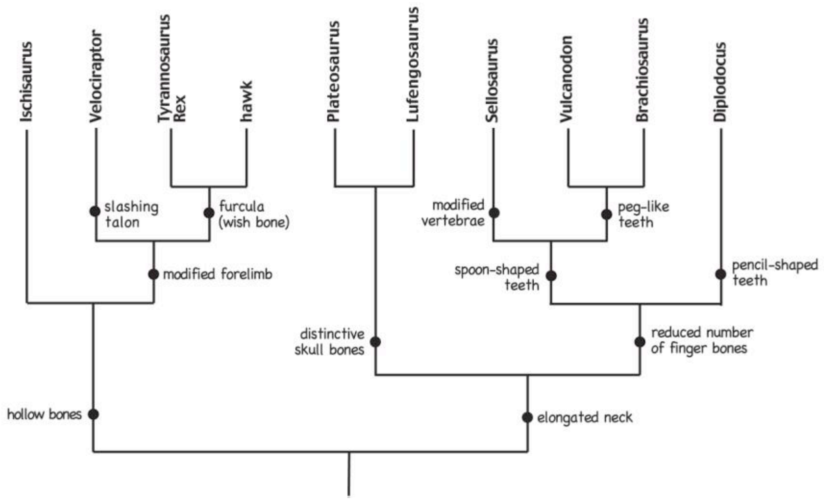

Figure 3. A dinosaur cladogram

Table 1. Mean accuracy scores for inference questions

Sample	Insect Cladogram	Dinosaur Cladogram
College Students (stronger biology background)	.77	.47
College Students (weaker biology background)	.58	.25
High School Students	.67	.27

Students' justifications provide further information regarding their tree-thinking abilities. Across samples, students appealed to the best evidence – most recent common ancestry or evolutionary relatedness – only to support correct inferences. In comparison, students who made incorrect inferences frequently provided categorical justifications (e.g., hawks share warm-bloodedness with birds because they are birds; see Table 2). High school students and college students with weaker backgrounds in biology were significantly more likely to provide this justification when asked about dinosaurs than insects.

Table 2. Mean proportion of categorical responses

Sample	Insect Cladogram	Dinosaur Cladogram
College Students (stronger biology background)	.29	.21
College Students (weaker biology background)	.22	.43
High School Students	.32	.52

These results indicate that prior knowledge of the specific taxa can interfere with successful tree thinking. Students' justifications underscore the conflict they had with reasoning with the information that birds are dinosaurs. Our results suggest that for younger students, as well as those with less biological knowledge, the combination of shaky biological knowledge and evidence presented in an unfamiliar diagram leads to poor understanding of macroevolution. The present baseline results will be used to help guide the development of empirically-based curricula and instructional practices at the high school and undergraduate levels that will lead eventually to a more widespread appreciation for and understanding of tree thinking.

Inventing a representation of relatedness

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Prior research has shown that reasoning with cladograms is a skill that must be taught. Novice students, who do not understand the peculiarities of the representational system, can rely only upon prior content knowledge and perceptual resources (e.g., embodied and culturally-learned spatial metaphors (Tversky, Kugelmass, & Winter, 1991) and Gestalt perception (Novick & Catley, 2007) to make sense of them. The problem is that students' prior knowledge is sometimes incorrect or incomplete. They rely upon misconceived folk theories of evolution as a linear transformation through successive stages; and their intuitive perceptions often counter the obscure symbolic rules by which the cladogram operates. It is such that even with instruction, many students tend to make errors when interpreting cladograms (Meir et al., 2007), which keeps them from mastering an important component evolutionary reasoning.

In spite of the difficulties this diagram presents, it is nonetheless a standard representational tool within the field of biology. As such, designers are faced with a different task: How to design an effective learning sequence that addresses the issues students are known to encounter. Where previous work has both identified the common errors that students make when reasoning with cladograms (Gregory, 2008; Meir et al., 2007), and as well has examined the reasoning processes underlying those errors (Halverson et al., 2008) this research addresses more fundamental questions of the nature of representation and of intuitive symbolization in the domain of evolution. Specifically, we ask (1) What kinds of representations will students intuitively invent to represent the central concept of cladograms, "relatedness?" (2) How does the act of inventing a representation influence the interpretations students later make of the standard cladogram? and (3) How do students' inventions and interpretations differ when the content of the representation does or does not concern evolution?

Methods

To investigate our questions, we conducted individual interviews with 33 undergraduate students. Of these, 22 students were first asked to invent a diagram (on a tablet pc) to depict the relationships among either a group of species with shared traits (the *Evo* condition), or among a group of children with shared toys (the *Toy* condition), and to discuss why they invented what they did. Except for the content of the problem, the data sets given to students in the *Evo* and *Toy* conditions were equivalent. In the *control* condition, 11 students were asked to sketch and discuss any image they recalled of evolution. Afterwards, they were shown a solution to the problem in the form of a standard cladogram. In a series of open-ended and fixed choice questions, all 33 students were then asked to use this diagram to reason about the relative relatedness among the items depicted, and to interpret its various symbolic attributes. Interviews were video recorded and transcribed for later analysis and demographic data was collected on students' science coursework and belief systems.

Results

Students drew upon a rich array of representational resources to depict "relatedness," including familiar representational forms (e.g., Venn diagrams, networks, graphs, tables) and devices for organizing information (e.g., colour cues, systematic variation of graphic qualities). With one exception, only the *Evo* condition elicited temporal-based inventions, which depicted linear progressions from an ancestral to a more contemporary species (n = 7 vs. n = 1). Meanwhile, only the *Toy* condition appeared to elicit propositional-like statements (n = 2 vs. n = 0). These observations suggest particular manners in which students' beliefs about the content will influence the form of the representation they invent. Specifically, the concept *evolution* appeared to elicit the very kind of linear thinking that may be at the root of students' difficulties with interpreting tree diagrams.

However, our qualitative analysis of students' reasoning processes with the standard cladogram, showed that students that first invented a representation appeared to focus more attention on the relationships depicted. They tended to describe the symbolic functions of lines and nodes as indicating conceptual relations, rather than as timelines or as paths of change as did the students in the control condition. The latter rather tended to interpret the cladogram in terms of a misconceived folk theory of evolution. That is, despite the cladogram's branching structure, students in the control condition described the progressive transformation of a species through a series of states from left to right of the graphic space. Our findings extend prior work on inventing representations (e.g., Schwartz, 2006) by contributing a particularly challenging example from the domain of biology. They suggest that an opportunity to consider the problem of representing relatedness helps students better understand the standard diagram as a solution, no matter the kind of representation these students first invented (e.g., Cox & Brna, 1995). The fact that common errors made reasoning with the cladogram were still evident among all students, suggests the powerful influence of visual structure and of perceptual processes on interpretation. Our findings suggest intermediate representations and activities that might serve to bridge novice and expert understanding (Roschelle, 1996).

Figure 4. A sample of students' inventions

Can children read trees?

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The research reported in other papers in this symposium reveal difficulties in adult and teenage interpretation of cladograms. This paper explores if children in middle childhood could interpret cladograms given minimal training and if so what factors might influence their success. In particular, we explored if their reasoning was influenced by the species represented or the way that cladogram was presented (its rotation).

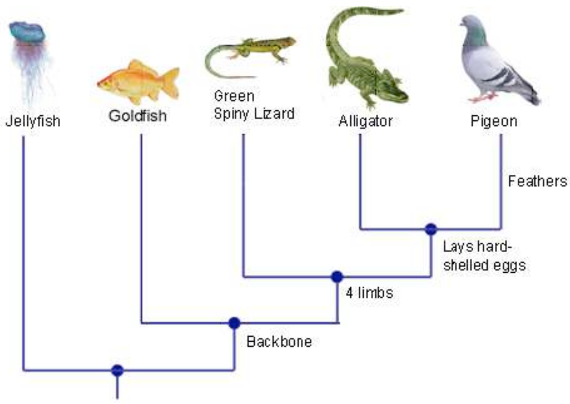

Figure 5. Pigeon cladogram in RRRR rotation

Methods

13 boys and 15 girls aged 7:1 to 11:11 years were trained for 15 minutes on 'fake' cladograms before answering 8 questions on each of 4 new cladograms. Children were introduced to key terms before proceeding to finding common ancestors, determining relatedness, how synapomorphies (features) are inherited and the arbitrary nature of branching. Training was designed to support four types of reasoning: finding the most common recent ancestor of two species; identifying a species' features based upon its ancestry; describing which animals have particular features; and determining which species are most closely related to a particular example. They then answered eight questions on each of four new trees (one each of the different contents and rotation counterbalanced by Graeco Latin square). After every second answer they were prompted to explain their reasoning. A [4 by 4 by 4 by 4] repeated measures study examined: species depicted in the cladogram; branch rotation, the depth of tree searched and type of question. Just those answers including only correct responses were considered correct (e.g. "Which animals are most closely related to the green spiny lizard?"; 'alligator and pigeon'). Analysis was by four (4 by 1) ANOVAS with post-hoc comparisons using the Bonferroni correction. Children's performance was surprisingly good with an average of 56% of answers completely correct. This is significantly above chance (Ancestor: 25%, Feature/Relation: 6.67%, Animal: 3.22%).

Results

Species represented influenced performance ($F(3,81)=9.63$, $p<0.001$). Children reasoned with flea (45%) more poorly than pigeon (63%) and human (64%) cladograms. Other researchers (e.g. Evans, 2006) have found poorer evolutionary reasoning by children about invertebrates that, in our case, cannot be explained simply by unfamiliarity (as piloting ensured these were known insects). However, Philips, Novick & Catley (this symposium) found insect cladograms were associated with better performance than dinosaur cladograms. There was no evidence of the human cladogram leading to different reasoning. Rotation had no impact ($F(3,81)=1.87$). It may be that children have yet to develop these biases or potentially they did not affect overall accuracy but did affect children's erroneous strategies. Children's performance worsened as the depth of tree that needed to be searched increased $F(3,81)=28.58$, $p<0.001$, $\eta2 = .51$): Level one questions (82%) were answered more accurately than any other level (level 2 (53%) level 3 (51%) and level 4 (45%). It seems wise to recommend that cladograms for children should be relatively shallow.

Children found some types of question easier than others ($F(3,81)=10.48$, $p<0.001$, $\eta2 = .28$). Questions about relations (39%) were answered worse than those concerning ancestors (69%) and animals (63%). Performance on the ancestor questions is particularly encouraging as it is a key skill that other tree-thinking practices build on. Children's explanations were examined to explore whether they were able to justify their responses using correct semantic explanations (e.g. *because that's* [pointing to the appropriate node] *the ancestor of the stick insect and the flea*"); correct syntactic explanations ("*because the lines link to it"; "that's the first dot they have in common')* incorrect syntactic reasoning (for example reasoning by tip proximity;

'*because they are next to each other*') or were not based on the tree at all ("*because I've seen a lizard before and I can see all the legs of the alligator*"). Unsurprisingly, age and number of correct answers correlated significantly (r=.64, p<0.001). The youngest quartile of children answered 39% of questions correctly and the oldest 68%.

This study suggests that after a short amount of training children can begin to reason with cladograms. This has important implications for biological education as tree-thinking could be used with younger children than has previously been considered appropriate (our results suggest from around nine year upwards). Naturally, much of the complexity of tree-thinking will remain hard for this age group (as it is for adults) but given demonstration of this basic competency researchers can now determine how best to teach children to tree-think and to further explore which cladogram designs help novice tree-thinkers.

Improving undergraduates' approaches to understanding tree thinking

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Evolutionary biologists see biology through the perspective of phylogeny, or evolutionary history. 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, Abell, Friedrichsen, & Pires, 2009; Halverson et al., 2008). The alternative types of reasoning students use can cause them to generate a variety of responses when interpreting and using phylogenetic trees (Halverson, 2008). Yet, few studies have focused on why students misinterpret trees or how students can overcome these misconceptions to develop internalized tree thinking skill. The purpose of this study was to examine how undergraduates developed and used phylogenetic trees during a plant systematics course as well as identify/design scaffolds to facilitate improvements in core skill development.

Research Design

This study took place in the lecture section of an upper-level, plant systematics course at a Midwestern research extensive university during the Spring 2007, 2008, and 2009 semesters. This course was organized primarily around phylogenetic tree thinking. Students were engaged in interpreting and building phylogenies in addition to learning about plant systematics. I used open-ended student responses from two-tiered pre/posttests, a two-part interview series, weekly reflective journal entries, field notes from course observations, and course assessments to learn how 87 upper-level undergraduate science majors enrolled in a plant systematics course interpreted phylogenetic trees and developed tree thinking skills. I utilized all transcripts, field notes, expanded observation notes, and documents in data analysis. I wrote profiles describing each student's reasoning when using phylogenetic trees. 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. I inductively coded the profiles to identify reasoning students used when reading trees and their reactions to instructional interventions. I compared the coded student profiles to identify themes. Once the themes were identified, I triangulated findings using secondary data sources to ensure the research findings represented accurate interpretations of the data. I wrote rich descriptions of students' tree thinking skills and documented themes that emerged from the data about effective instructional scaffolds.

Findings

I identified 13 major challenges students encounter when developing tree thinking skills: (1) Overcoming prior ideas about organisms and using a tree to draw conclusions; (2) Visualizing how branches can rotate; (3) Reading from the tips rather than nodes; (4) Mapping a species lineage from tip to root of a tree; (5) Comparing patterns of relationships among trees; (6) Lumping organisms on single characteristics rather than looking at them holistically; (7) Ignoring critical data and/or using uninformative evidence to construct a tree; (8) Difficulties transferring empirical data into a tree illustrating evolutionary relationships; (9) Creating consensus nodes to address discrepancies; (10) Altering the format or orientation of the tree alters the relationships depicted; (11) Generating accurate, branching, hierarchical representations; (12) Using trees to reconstructing ancestral states; (13) Comparing representations to identify the most supported tree.

Two instructional interventions were used in the course (e.g., a hypothetical plant exercise and a pipe cleaner phylogeny activity) Students perceived the pipe cleaner phylogeny activity as the most effective instructional intervention. 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. Students began manipulating the pipe cleaner trees by swiveling the branches, and came to see that nodes to determine relationships rather than the tips. For example, after the activity he suggested that "*That when studying trees, one should focus on nodes.*" and knew "*trees can be displayed in different formats while still showing the same information.*" Sally discussed 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.” In the presentation, I will elaborate on how this instructional intervention helped students overcome four main challenges: namely numbers 2, 3, 4 and 7 above

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). 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. 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. By investigating how undergraduates learn tree thinking during three semesters of a plant systematics course, this study adds to our understanding of critical elements necessary for continuing to improve instruction with phylogenetic trees and maximize the potential of evolution education.

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