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IN PRESS (EVOLUTION: EDUCATION AND OUTREACH)

Title: Communicating Phylogeny: Evolutionary tree diagrams in museums

Running Head: Communicating Phylogeny

First Author: Teresa MacDonald

Institution: University of Kansas Natural History Museum

Address: University of Kansas, Lawrence, KS 66045-7593, USA

Second Author: E. O. Wiley

Institution: Ecology & Evolutionary Biology and Biodiversity Institute

Address: University of Kansas, Lawrence, KS 66045-7593, USA

Corresponding Author:

Teresa E. MacDonald

University of Kansas Natural History Museum

University of Kansas, 1345 Jayhawk Blvd, Dyche Hall, Lawrence, KS, 66045-7593, USA

Phone: 785-864-2371

Fax: 785-864-5335

Email: tmacd@ku.edu

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Abstract

Tree of life diagrams are graphic representations of phylogeny—the evolutionary history and relationships of lineages—and as such these graphics have the potential to convey key evolutionary ideas and principles to a variety of audiences. Museums play a significant role in teaching about evolution to the public, and tree graphics form a common element in many exhibits even though little is known about their impact on visitor understanding. How phylogenies are depicted and used in informal science settings impacts their accessibility and effectiveness in communicating about evolution to visitors. In this paper, we summarize the analysis of 185 tree of life graphics collected from museum exhibits at 52 institutions and highlight some potential implications of how trees are presented which may support or hinder visitors' understanding about evolution. While further work is needed, existing learning research suggests that common elements among the diversity of museum trees such as the inclusion of anagenesis, and absence of time and shared characters might represent potential barriers to visitor understanding.

Key Words: Evolutionary Trees, Trees of Life, Phylogeny, Museums

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The idea of a 'tree of life' represents a core concept of evolutionary science—phylogeny—and is depicted graphically using an almost bewildering array of formats and terminology, in which even a particular geometry used can have multiple names associated with it.

Evolutionary trees of life are branching diagrams that depict hypothesized relationships—the historical pattern of divergence and descent between taxa—as a series of branches that merge at internal branches representing common ancestry, which in turn are connected with more distant relatives. As visual representations of the history of lineages or phylogeny, trees reflect the core concept of common ancestry. The importance of phylogeny in supporting understanding of evolution is highlighted in key education documents (American Association for the Advancement of Science, 2001; Baum, DeWitt-Smith, & Donovan, 2005; National Research Council, 1996). Tree diagrams, as a graphical representation of this principle, have the potential to play a valuable role in conveying evolutionary ideas.

How people interpret and understand evolutionary trees is a complex interaction between their prior knowledge and understanding of underlying evolutionary ideas such as similarity, ancestry and relatedness, and their ability to read the relationships depicted in a schematic tree diagram. Given the diversity of tree depictions, one might ask what people understand from these different graphic representations. Many of the common misconceptions about reading and interpreting tree diagrams are well established (Gregory, 2008; Meir, Perry, Herron, & Kingsolver, 2007), and work has been, and continues to be done on the use of trees with students in structured learning environments (Baum, et al., 2005; Halverson, 2010; Novick & Catley, 2007; Novick, Shade, & Catley, 2010). However, there is a gap in our knowledge about how trees are used and understood outside of a formal instructional framework. An understanding of how, and in what form, tree graphics are used in informal settings is an important part of supporting the development of evolutionary thinking in museum visitors.

Museums are an important part of how the public accesses science information, including evolution, and in teaching about these ideas to their visitors (Diamond & Evans, 2007; National Science Board, 2008). In fact, a recent study found that even a single visit to an evolution exhibit can influence children's thinking about evolutionary concepts (Diamond, Evans, & Spiegel, in press, 2010). Evaluation studies with natural history museum visitors shows that they are interested in the tree of life, but struggle with interpreting the content and relationships represented in trees (Giusti & Scott, 2006; Spiegel, Evans, Gram, & Diamond, 2006). While few museums use phylogeny as an organizing principle in their galleries, evolutionary diagrams form a major graphic element in many museums and other informal science settings (Diamond & Scotchmoor, 2006; MacDonald, 2010). Tree diagrams as a way of representing relatedness is a pervasive element in exhibits that extends beyond science institutions; for example, even the Creation Museum in Kentucky contrasts evolutionary trees with a series of trees depicting separately created kinds, including a solitary and independent line for humans.

In natural history museums, visitors can see a wide range of historical depictions of the tree of life depending on when an exhibit was developed and the research emphasis of the scientific curators. The graphic representation of the tree in each new exhibit usually reflects the current usage or discipline preferences, but since older depictions often are kept on display, a range of different presentations of tree diagrams are depicted even within a single institution (Diamond & Scotchmoor, 2006; MacDonald, 2010). Some galleries intentionally use more than one depiction of the tree of life to emphasize to visitors the validity of alternative approaches or

In addition to orientation, geometry has implication for tree understanding. While different geometries show equivalent relationships, and the selection of one versus another may be arbitrary, the particular form used may have implications for interpretation. Novick & Catley (2007) found that undergraduate students had greater difficulties extracting the hierarchical structure and relationships in angled cladograms than rectangular ones (what they refer to as ladders and trees, respectively) despite their being equivalent in terms of the information they contain. The authors suggest that the difficulty in seeing the nested relationships in the ladder results from the Gestalt principle of good continuation. Good continuation implies that the sloped line at the base of the ladder/angled diagram represents a single hierarchical level rather than the multiple levels it actually represents. The principle of good continuation then acts as a cognitive constraint resulting in the straight line being seen as a unit that continues without change, making it difficult for students to understand and interpret the relationships being depicted. Angled cladograms were also found to be more likely to elicit anagenic responses—speciation by transformation of one form into another—than rectangular ones (Novick, et al., 2010).

Humans in Evolutionary Trees

Museum visitors' reasoning about organisms and evolutionary explanations varies depending on the taxa included in the tree diagram, particularly humans (Diamond & Evans, 2007). How visitors perceive exhibits with humans and other living or extinct primates in them is complex and challenging, but they are often interpreted as being linear, directional and progressive (Scott, 2007, 2010; Scott & Giusti, 2006).

In addition to the common vertical orientation of trees, the location of *Homo sapiens* and other hominin species in relation to the other taxa in the tree has the potential to reflect and reinforce ideas of teleology and progression (Matuk, 2007; Tversky, 1995). A survey of textbook charts found most to be vertically organized with *H. sapiens* at the top (Tversky, 1995), and an analysis of anthropocentrism in phylogenetic textbooks found the position of humans on the top-right of the left–right axis of vertical cladograms to be significant (Sandvik, 2007). In museum trees, a bias for top-right placement of humans was not found; however, the sample size was small (n=9).

The common misreading of time across the top of a cladogram from left to right—coupled with reading the order of terminal taxa across the top as relatedness—may be interpreted as a progression from 'old, primitive or simple' to 'recent and complex', culminating in humans (Baum, et al., 2005; Catley & Novick, 2006; Giusti & Scott, 2006; Halverson, Pires, & Abell, 2008; Meir, et al., 2007). Furthermore, a recent study of the impact of taxa placement in cladograms found that students were more likely to provide teleological responses and explanations if humans occupied an end, rather than a central location (Phillips, et al., 2010).

In addition to the placement of *H. sapiens*, the portrayal of hominin evolution as primarily anagenic, by depicting one or more taxa placed on or within a single branch, is problematic for its potential to reinforce ideas of teleology, progression and anthropocentrism. While anagenesis is common in textbook trees with humans (Catley & Novick, 2008), fewer than a third of museum trees that include humans depict anagenesis. However, of those that do, all include *H. sapiens* and their most recent extinct relatives (e.g. *Homo*, *Australopithecus*, etc.) rather than humans in relation to other extant primates or other taxa.

Geological Time

Time is an important and difficult concept in understanding evolutionary trees, and the interpretation of time on trees is influenced by a range of factors including branch length, and naïve understanding of evolutionary processes (Dodick, 2010). It has been suggested that where temporal data is available, the inclusion of geological time on diagrams may help to support understanding (Catley & Novick, 2008), and help with the common misreading of time across the top rather than bottom-up in vertically oriented trees (Meir, et al., 2007).

Variation in branch length is thought to have the potential to promote understanding if the earlier ending points indicate extinct taxa (Catley & Novick, 2008), and the inclusion of extinct taxa could help to avoid ideas of species persistence and progress (Donovan & Hornack, 2004)—in part because a long branch is often incorrectly interpreted as a lineage in which no change has occurred (Crisp & Cook, 2005; Novick & Catley, 2007). However, the potential value of different branch length to identify extinct groups may be hampered by the fact that the significance of this diagrammatic feature is often not made explicit. Recent research indicates that there is a strong correlation between understanding the direction of time and the ability to explain evolutionary problems as represented in phylogenetic diagrams, and that explicitly including temporal information on diagrams may support understanding and avoid the common misreading of relatedness along the tips, a.k.a tip-reading (Dodick, 2010). The interpretation of time in phylogenetic trees, and advantages and disadvantages of explicitly doing so are subject to much discussion, and continuing research will help to clarify these issues (Catley & Novick, 2008; Dodick, 2010).

Tree Content and Labeling

Most of the museum trees do not label tree components such as the root or node(s) as representing common ancestors or shared derived characters (synapomorphies) between taxa.

Fewer than half refer to ancestors/common ancestors—with less than 15% included on the diagram itself—and only 20% labeling specific synapomorphies that support the relationships depicted on the tree. Donovan & Wilcox (2004) suggest that labeling the root or other internal node as 'common ancestor' can help to overcome the abstractness of tree representations and support the interpretation of nodes. Others argue that since the ancestor is unknown it is disingenuous to include it (Catley & Novick, 2008), and doing so has the potential to reinforce the view of nodes as precise moment of change (Meir, et al., 2007). Recent research has found that the inclusion of synapomorphies can help support understanding of tree diagrams and that evolutionary relationships are based on shared characteristics (Novick, Catley, & Funk, Published online: 22 June 2010), making their relatively uncommon use in museum tree diagrams problematic in terms of supporting visitor understanding.

Museum trees often include, in graphic form, other information beyond relatedness and common ancestry, such as diversity, by altering variables such as branch length, thickness or shape, using color-coding and symbols. These are often not made explicit on the tree itself or in an associated legend or key. Textbook trees often use branch thickness to indicate diversity, but the graphical significance of this is generally unclear and undefined (Catley & Novick, 2008). The absence of clear labeling means that the significance of these variables, if any, may be unclear, which makes it difficult to read and interpret the diagram. Being explicit about the intent of abstract diagrammatic elements is likely to aid in tree interpretation.

Tree Explanatory Information

For most museum trees, the exhibit text describes what can be seen in the tree—e.g. which taxa are most closely related—but the link to the graphic itself is usually not explicit. Evaluation studies suggest that it is important to directly tie labels to what visitors can experience at that point in the exhibition (McLean, 1993; Serrell, 1996), and presenting explicit information and concrete ideas in exhibit labels helps to instruct visitors about what they should look for (Bitgood, 2000; Falk, 1997; Falk & Dierking, 1992). However, the lack of explicit annotation in many museum trees is not surprising given its absence in most evolutionary diagrams used in textbooks (Catley & Novick, 2008); although its inclusion could support an understanding and interpretation of evolutionary processes (Donovan & Hornack, 2004). Overall, the absence of explicit explanations for many trees or information about trees as products of science is likely to add to the difficulty that visitors have in reading and understanding of these diagrams.

Tree Presentation

Overwhelmingly, tree diagrams used in museum exhibits are part of graphic panels with images or specimens/models of taxa at terminal taxa points. Incorporating visuals into trees may draw attention to the organisms, help users to recognize and identify taxa, and assist visitors in connecting labeled synapomorphies with visible morphological characteristics. Many novices emphasize morphological features and similarity-based reasoning in their thinking about biological relationships, and so caution should be used to avoid conflating overall similarly with relatedness (Gelman, 2004; Gelman & Markman, 1987; Halverson, et al., 2008; Sloutsky, Lo, & Fisher, 2001); however, explicitly labeling synapomorphies that are used to support the relationships shown in the tree—and perhaps that can be seen in accompanying visuals—may help highlight the evidence used in tree building, that of relatedness based on shared derived characters, and support ideas about scientific inference (Donovan & Wilcox, 2004).

Fewer than 10% are multimedia based, but some of these kiosks and online trees were interactive, where the user could step through the information or navigate to different parts of the tree. Summative evaluation of Yale's *Travels in the Great Tree of Life* exhibit found that the computer game exploring relationships was effective at communicating the idea that phylogenetic relationships may not always be what you might expect (Giusti, 2008), which suggests that interactivity and/or animation may help address some issues with reasoning using trees. Based on personal experience with museum visitors, exploring the tree of life using manipulatives such as using scale models of taxa and different graphic representations can be effective with museum visitors. Research on the potential role of animation in understanding cladograms has found that animations can influence the perception and interpretation of diagrams, but that interpretation is also impacted by a user' prior knowledge and common evolution narratives (Matuk, 2008a, 2008b, 2008c, 2010; Matuk & Uttal, under contract).

Conclusions and Further Work

Museums seek to share current scientific research with the public, and to teach visitors about evolution through their exhibits and programs. As this study and review of the literature shows, museums have a long history of using evolutionary graphics to communicate about relationships, and informal science institutions of all types are making efforts to incorporate evolutionary history or relatedness. Visitors are likely to be exposed to a variety tree of life diagrams during a single museum experience. This diversity and the long standing use of trees of life in museums makes them an ideal setting to explore visitor understanding of these diagrams and to investigate strategies that can increase their effectiveness as tools for communicating about evolution and the tree of life.

Pilot studies from the *Understanding the Tree of Life* project provide some important insights into visitor understanding of trees including the ability of young children to reason with tree diagrams, that trees can foster thinking about common ancestry and time—but may hinder an understanding of variation and selection, the impact of prior knowledge and existing narratives in interpreting trees, and the importance of time.

These studies, and this review, highlight the importance and educational potential of evolutionary trees in museums, and how much more work needs to be done. Further research is needed to explore how visitors interpret and understand these varied representations in a museum setting, and to understand what the visitors bring with them and how this can be used to support their understanding of phylogeny and the tree of life. However, the existing literature suggests three elements that might help to clarify visitor understanding of trees: (1) show time axis; (2) include shared characters; and (3) carefully consider the placement of taxa in trees, particularly humans.

The flexible and ubiquitous nature of informal learning provides a great opportunity to share current scientific knowledge and our understanding of the tree of life with the public—yet brings its own challenges as these experiences occur within the context of visitors' prior knowledge and conceptions. As we strive to support the understanding of evolution with museum visitors we need to think carefully about what we are trying to communicate, what role trees can play in supporting evolutionary thinking, and how this may be supplemented and supported by other exhibit components—in essence, how trees of life fit into the broader context of the visitor experience.

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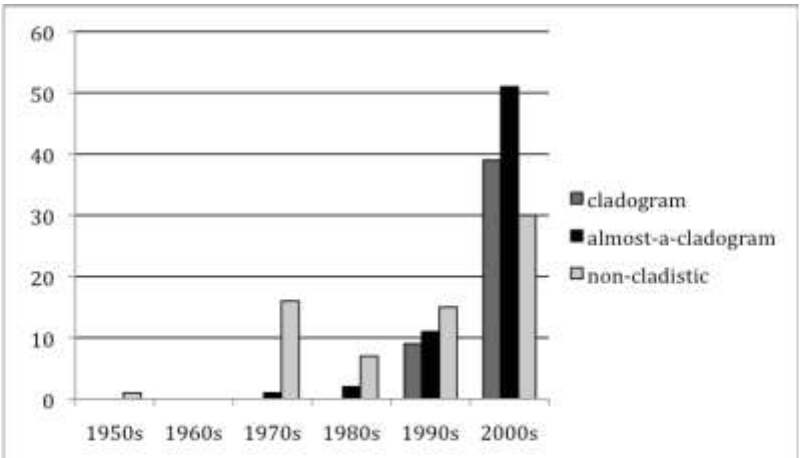

Figure 1. Distribution of study trees by decade and type.

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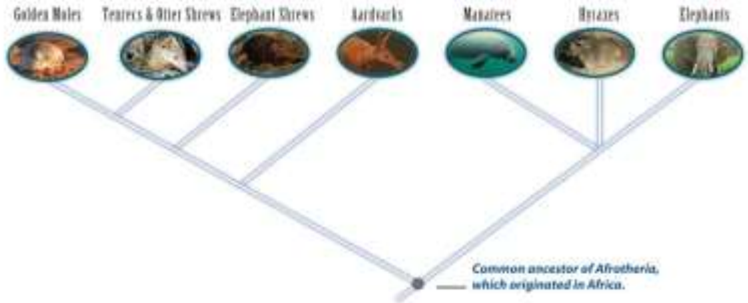
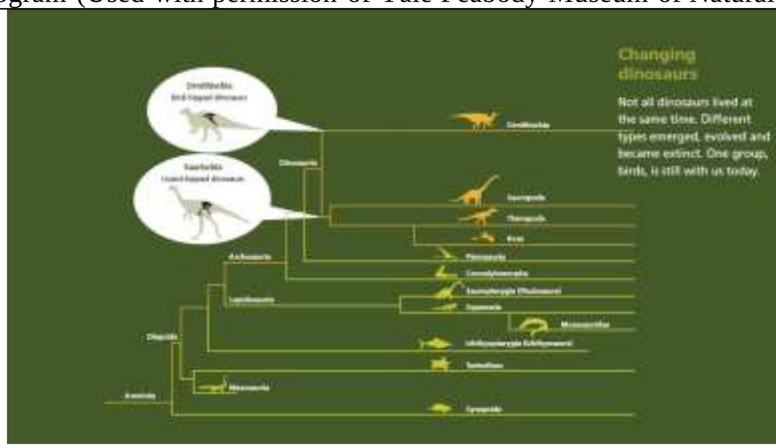
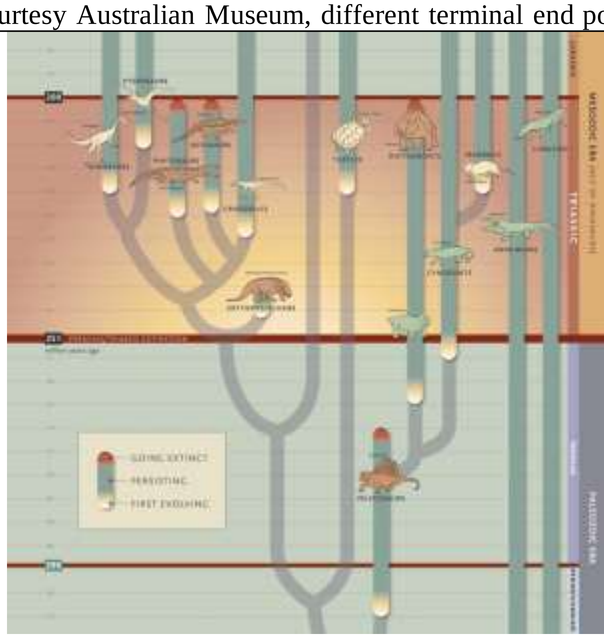


(a) Cladogram (Used with permission of Yale Peabody Museum of Natural History)



(b) Almost-a-cladogram
(Courtesy Australian Museum, different terminal end points)



(c) Non-cladistic/other evolutionary tree
(Courtesy New Mexico Museum of Natural History & Science, multiple taxa along branch)

Figure 2. Examples of museum tree types: (a) Cladogram, (b) Almost-a-cladogram, and (c) Non-cladistic/other evolutionary tree.

Teresa MacDonald & E. O. Wiley (2012) Communicating Phylogeny: Evolutionary Tree Diagrams in Museums. Evolution Education Outreach (2012) 5:14–28.
Publisher's Version: http//dx.doi.org/10.1007/s12052-012-0387-0. Open Access version: http://kuscholarworks.ku.edu/dspace/

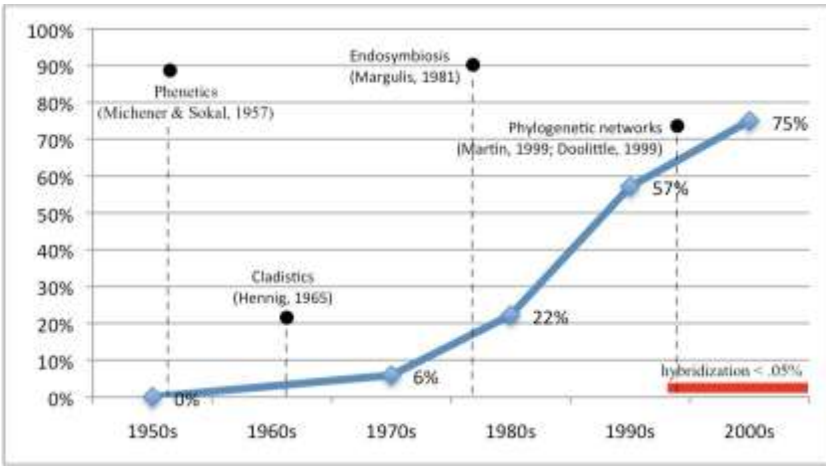


Figure 3. Percentage of museum trees that are cladograms (*sensu lato*) over time.

Teresa MacDonald & E. O. Wiley (2012) Communicating Phylogeny: Evolutionary Tree Diagrams in Museums. Evolution Education Outreach (2012) 5:14–28.
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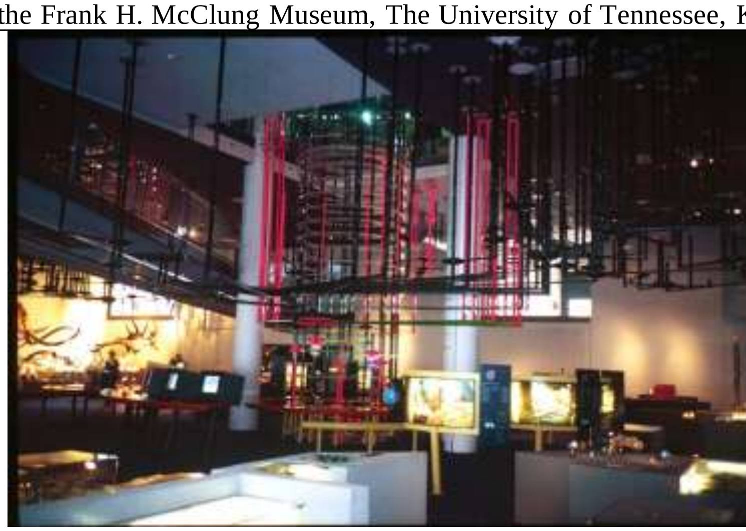
Courtesy of Dusquene University (Pittsburgh Zoo and PPG Aquariums), all life (2009). Credits: Art director/lead art—Joana Ricou; executive director—John Pollock; research—Brinley Kantorski, Allison Pogue; additional art—Robert Hoggard.

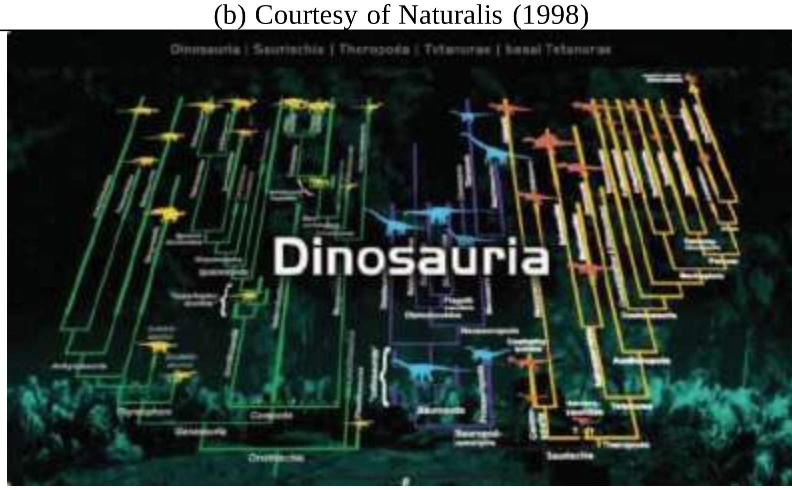
Figure 4. Example of a tree graphic that depicts hybridization.

Teresa MacDonald & E. O. Wiley (2012) Communicating Phylogeny: Evolutionary Tree Diagrams in Museums. Evolution Education Outreach (2012) 5:14–28.
Publisher's Version: http//dx.doi.org/10.1007/s12052-012-0387-0. Open Access version: http://kuscholarworks.ku.edu/dspace/

(a) Courtesy of the Frank H. McClung Museum, The University of Tennessee, Knoxville (2004)



(b) Courtesy of Naturalis (1998)



(c) Carnegie Museum of Natural History (2008). © Carnegie Museum of Natural History.

Figure 5. Examples of tree presentation formats: (a) 3D tree, (b) 3D tree, (c) media kiosk.

Courtesy Omaha's Henry Doorly Zoo (2004)

Courtesy Santa Barbara Zoo (1996)

Figure 6. Examples of primate trees with a central trunk and side branches.

Table 1. Categories, criteria and coding used for museum trees.

CATEGORY	DESCRIPTION AND CODING
Topological and Diagrammatic Elements	
Orientation	Overall orientation of tree, or the position of the root relative to branches. Those with no overall orientation (e.g. circular or radial geometries) were coded as N/A.
Direction	Overall direction of branches from the root; circular trees were coded by the direction of the initial spiral, and radial trees were coded N/A.
Geometry	Trees classified as a cladogram and 'almost-a-cladogram' were coded as angled, rectangular, curvogram/swoopogram, circular, radial, or eurogram. Non-cladistic/other evolutionary trees, were coded as N/A.
Terminal branch end points	Whether branches end at different levels.
Images of taxa	Taxa are represented visually (graphically through images, silhouettes, or with models/specimens).
'Tree of Life'	Diagrams has a central main trunk with taxa branching off of it with a clear linear progression from 'lower' to 'higher' forms (Haeckel, 1874).
Tree Content	
Anagenesis	Depicts ancestor-descendant relationships between named taxa (e.g. genus or species) with one or more named taxa in a sequence along a branch
Taxa	Invertebrates, vertebrates, broad taxonomic categories, or other (e.g. viruses).
Extinct taxa	Includes extinct taxa.
Humans and their most recent extinct relatives	Includes one or more members of this group.
Geological Time	Includes an indication of time.
Classification	Explicit links between parts of tree and more familiar classifications of organisms.
Common ancestor	Refers to one or more common ancestors.
Synapomorphies	Synapomorphies (shared characteristics) are indicated.
Hybridization	Includes lateral transfers of genetic material, i.e. it represents a phylogenetic network in which hybridization or similar events are believed to have been involved, rather than a tree that only depicts branching sequence.
Presentation and Explanation	
Exhibit component	Static flat graphic panel, graphic backdrop for specimens/models, 3D representation, media component (e.g. video or game in kiosk/online), or a supplemental document.
Instructional information/interpretation	Provides an explanation of what the tree shows (e.g. refers to relationships between taxa, describes changes or trends over time), instructs how to interpret evolutionary diagrams (e.g. describes trees as branching diagrams that show relatedness).
Nature of Science	Labels or legends include information about the data used to build the tree, refers trees as hypotheses or product of scientific reasoning.

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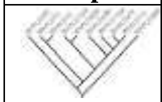
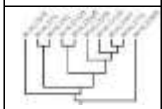
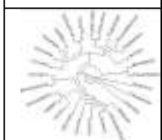
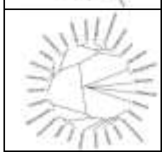
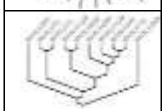
Table 2. Phylogenetic tree geometry (descriptions modified from tree software sites, e.g. Phylodendron, Drawgram, etc.).

Table 1.

Example	**Description**	**Names used & sources**
	Nodes connected to other nodes and to tips by straight lines directly from one to the other. This category includes diagrams with slightly wavy lines or curved lines, but have an overall pectinate layout.	• Angled (e.g. PhyloDraw, TreeView) • Slanted (e.g. PhyloDraw, TreeView) • Cladogram (e.g. Drawgram, Phylodendron) • Diagonal (e.g. Mesquite) • Ladder (Catley & Novick 2008)
	Nodes connected to other nodes and other tips by a horizontal and then vertical line. This category includes diagrams with slightly curved corners and/or wavy branches.	• Rectangular (e.g. PhyloDraw, TreeView) • Square (e.g. Drawgram, Mesquite) • Phenogram (e.g. Drawgram, Phylodendron) • Tree (Catley & Novick 2008)
	Nodes connected by curves that are 1/4 of an ellipse; curvogram starts horizontally then curves up to become vertical; first 1/3 of swoopogram starts out horizontal then vertical then follows curvogram.	• Curvogram/Swoopogram (e.g. Drawgram, Phylodendron) • Angular curvograms/Curved curvograms (e.g. TreeDom)
	Nodes connected outwards from a central point, with tips forming a circle. Radial lines run outward from the center with the arc segments centered on them.	• Circular (e.g. Phylodraw, TreeView, PAUP)
	Nodes connected outwards from a central point without horizontal lines.	• Radial (e.g. Phylodraw, TreeView)
	Nodes connected to other nodes and to tips by a diagonal line that goes outwards to at most 1/3 of the way up to the next node, then turns sharply straight upwards and is vertical.	• Eurogram (e.g. Drawgram, Phylodendron)