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PLACING BIRDS ON A DYNAMIC EVOLUTIONARY MAP:
USING DIGITAL TOOLS TO UPDATE THE EVOLUTIONARY METAPHOR OF THE
“TREE OF LIFE”

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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in the College of Arts and Humanities
at the University of Central Florida
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ABSTRACT

This dissertation describes and presents a new type of interactive visualization for communicating about evolutionary biology, the dynamic evolutionary map. This web-based tool utilizes a novel map-based metaphor to visualize evolution, rather than the traditional “tree of life.” The dissertation begins with an analysis of the conceptual affordances of the traditional tree of life as the dominant metaphor for evolution. Next, theories from digital media, visualization, and cognitive science research are synthesized to support the assertion that digital media tools can extend the types of visual metaphors we use in science communication in order to overcome conceptual limitations of traditional metaphors. These theories are then applied to a specific problem of science communication, resulting in the dynamic evolutionary map.

Metaphor is a crucial part of scientific communication, and metaphor-based scientific visualizations, models, and analogies play a profound role in shaping our ideas about the world around us. Users of the dynamic evolutionary map interact with evolution in two ways: by observing the diversification of bird orders over time and by examining the evidence for avian evolution at several places in evolutionary history. By combining these two types of interaction with a non-traditional map metaphor, evolution is framed in a novel way that supplements traditional metaphors for communicating about evolution. This reframing in turn suggests new conceptual affordances to users who are learning about evolution.

Empirical testing of the dynamic evolutionary map by biology novices suggests that this approach is successful in communicating evolution differently than in existing tree-based visualization methods. Results of evaluation of the map by biology experts suggest possibilities for future enhancement and testing of this visualization that would help refine these successes.

This dissertation represents an important step forward in the synthesis of scientific, design, and metaphor theory, as applied to a specific problem of science communication. The dynamic evolutionary map demonstrates that these theories can be used to guide the construction of a visualization for communicating a scientific concept in a way that is both novel and grounded in theory.

There are several potential applications in the fields of informal science education, formal education, and evolutionary biology for the visualization created in this dissertation. Moreover, the approach suggested in this dissertation can potentially be extended into other areas of science and science communication. By placing birds onto the dynamic evolutionary map, this dissertation points to a way forward for visualizing science communication in the future.

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LIST OF ABBREVIATIONS

CSS: cascading style sheets

DNA: deoxyribonucleic acid

HTML: hypertext markup language

MY: million years

MYA: million years ago

NASA: National Aeronautics and Space Administration

URL: uniform resource locator

CHAPTER ONE: INTRODUCTION

This dissertation describes and presents a new type of interactive visualization for communicating about evolutionary biology, the dynamic evolutionary map. This web-based tool utilizes a novel map-based metaphor to visualize evolution, rather than the traditional “tree of life.” Metaphor is a crucial part of scientific communication, and scientific visualizations, models, and analogies play a profound role in shaping our ideas about the world around us. In this dissertation, I analyze conceptual affordances of the traditional “tree of life” as the dominant metaphor for evolution. I then explore the ways that digital media tools can extend the types of visual metaphors we use in science communication, in order to overcome potential conceptual limitations of traditional metaphors. Next, the dynamic evolutionary map is described as an example of rethinking the tree of life metaphor. Users of the dynamic evolutionary map interact with evolution in two ways: by observing the diversification of bird orders over time and by examining the evidence for avian evolution at several places in evolutionary history. By combining these two types of interaction with a non-traditional map metaphor, we can frame evolution in a novel way that supplements traditional metaphors for communicating about evolution. This reframing in turn suggests new potential affordances to users who are learning about evolution.

Chapter One situates this project within the field of research on the public understanding of science, outlines the rest of this study, and describes the structure of this dissertation. Chapter Two treats the ways in which metaphor is used in science communication, sketches a history of its use within the field of evolutionary biology, and describes how tree-like representations are used to support our thinking about evolution. Chapter Three discusses the ways that material

technologies affect the range of metaphors that are available for science visualizations, synthesizes new media theory and theories of the learning sciences that help explain how interactive technologies support learning, and sketches the history of evolution visualization. Chapter Four explains how principles from several fields were used to guide theoretical choices in envisioning the visualization, describes how the dynamic evolutionary map was constructed, and illustrates key features of the resulting visualization. Chapter Five describes the results of empirical evaluation of the map by subject matter experts as well as feedback from biology novices who were directed to use the map to answer questions about evolution. Chapter Six evaluates the theoretical and technical implications of the dynamic evolutionary map and discusses broader implications of the research results for the public understanding of science. I describe the focus of each chapter in more detail later in this chapter, after discussing science communication and the public understanding of science.

Science communication and the public understanding of science

Before engaging with the question of how we can use digital tools to reshape traditional scientific metaphors, it is useful to look at the field of science communication to gain a sense of why such a question might be important. Why, for example, should we use metaphor in science communication, instead of teaching about the scientific process and scientific principles directly? There are several potential answers to this question. One possible reason is that scientific concepts are challenging to understand, and that a large segment of the population does not have the time or inclination to learn them. A second possibility is that most people are satisfied to regard science as a specialized field of study that impinges little on their everyday lives, and so are uninterested in a detailed understanding of science. Finally, some researchers (e.g., Lakoff

and Johnson; Brown) argue that metaphor is an intrinsic part of science, and that it is actually impossible to discuss science without relying upon metaphor. I will take up a discussion of the ways metaphor is used in science in Chapter Two of this dissertation, and concentrate on the first two possible reasons in this part of the introduction.

First, there is the possibility that science is difficult. In one definition, science is “the search for verifiable ‘truths’” (Shamos 47). By this definition, science is a process by which ideas are tested against external reality. One important aspect of this process is that the scientific approach to understanding relies upon repeated hypothesis generation and empirical testing rather than producing commonsense explanations of phenomena. The discovery process can therefore lead to conclusions that appear counterintuitive from the perspective of everyday experience (Shamos 63). Scientific concepts themselves exist as highly formalized logical models or mathematical constructs (Shamos 63). If scientific conclusions run counter to common sense, and also rely on the occasionally esoteric language of mathematics, then it is possible to see why science is challenging.

Another ramification of the non-common sense nature of science is that it seems separate from everyday life. Science is frequently seen as a specialized endeavor of society, undertaken by specialists. While most people regularly interact with the technological products of science, it is a much less frequent occurrence for individuals to engage in a process of, for example, hypothesis generation, testing, and refining ideas about ways to improve those technologies. Both science and scientists are, to some extent, seen as separate from ordinary society.

Researchers from socially oriented traditions of studies of science suggest that the view of science as a separate endeavor from society is inaccurate (e.g., Fujimura; Roth and Lee;

Schiele, "On and About"). Scientific institutions, after all, are made up of individuals, who converse, argue, and negotiate with one another in the course of conducting research. However, the idea of science as a specialized practice remains common, both among scientists and the broader public (e.g., Bauer; Bucchi, "Of Deficits").

If we argue that science is at least somewhat separate from the daily activities of the general public, we can speak of the "public understanding of science." This is a concept with contested meanings. For example, "understanding" could encompass understanding about scientific facts (or even whether "facts" exist in science), the scientific process, how scientific institutions operate, or how to evaluate the authority of scientists making statements in public. The "public understanding of science" also has a specific meaning as a framework and methodology for social research (Bauer 111).

Communication between science and non-scientist members of society has been theorized in multiple ways since science has become professionalized and institutionalized. For example, science popularization was once, but is no longer, a key part of the scientist's job description (Dunwoody 16). Today, scientific institutions often rely upon professional science communicators to disseminate their findings to non-scientists. The growth of science communication as a field has been fostered by the spread of mass media and the concomitant creation of predictive models of mass communication (Bucchi, "Of Deficits" 57). Science communication at present is largely, though not exclusively, viewed as a problem of exchanging information between two fundamentally separate spheres of society: the scientific community and the lay public.

Concern about the public's understanding of science in the United States has its roots in

the period of rapid technological changes around World War II (Shamos 76). Beginning in this era, and periodically since that time, several frameworks for public understanding of science have been iteratively proposed, tested, modified, and sometimes discarded (Shamos 84). For example, “science literacy” focuses on a public factual scientific knowledge deficit, appreciation of the role of science in civic life, and rejection of “superstition” in decision-making (Bauer 115); “public understanding of science” focuses on the public’s attitude toward scientific research and ability to apply scientific knowledge in specific settings (Bauer 118-119); and “science in society” focuses on the public’s lack of trust in scientific experts, and assumes that an attitude deficit (i.e., elitism) on the part of scientists has fostered this mistrust (Bauer 122).

In this dissertation, I will use “public understanding of science” in a non-specific sense as a basic understanding of how the scientific process works, along with a certain level of factual knowledge. Under this admittedly general definition, individuals can be said to have a range of understandings of science, from no understanding to expertise in a particular field, rather than a binary “literate/illiterate” understanding. If understanding exists on a continuum, then metaphor can be highly useful in communicating science for many ranges of understanding. It is primarily at the expert levels of understanding that individuals must conceptualize science in formal mathematical language rather than metaphorically.

Avenues for science communication

Science communication takes place across a wide range of different media. In this part of the introduction, I will briefly sketch two major avenues of communication between science and the public: mass-media based communication, and experiential learning. A third major avenue

for understanding science is formal education, which I will touch on only briefly in this dissertation.

One of the characteristics of early science in the late Seventeenth Century that distinguished it from such activities as alchemy and astrology that preceded it was its openness: rather than couching their texts in mystical trappings and recording their thoughts in obscure codes, early scientists communicated with one another and shared knowledge in non-esoteric language. These early scientists communicated with one another in what would be called a “Republic of Letters,” sharing information in vernacular languages across national and religious boundaries (Schiele, “On and About” 94). Scientists also shared their speculations and results of their research with the wider public. Eventually mass-media genres such as popular science books (Turney 7) and newspaper- or magazine-based science journalism (Dunwoody 16) arose to disseminate scientific ideas to the wider public. Today, most people’s exposure to science news comes through television and the Internet (Groffman *et al.* 286).

There are major differences in the structure and content of book-length and journalistic formats for science communication. The format of the popular science book lends itself to narrative development, making this medium ideal for storytelling about scientific discoveries and people (Turney 10). However, the process of writing and editing books is time-consuming, making this a poor medium for disseminating scientific information rapidly. News media are by their nature episodic and timely, making them ideal for discussing new, pressing discoveries, but challenging to use to discuss the incremental and complex day-to-day processes of science (Dunwoody 21). Journalistic science operates under journalistic norms, rather than an *ethos* of science education. For example, news is tied to “pegs” (e.g., violence and drama), and the ideas

that are presented are generally those “filtered” by the editorial establishment (Dunwoody 20). According to Hans Peters and colleagues, “the meanings of scientific messages change when they are reconstructed by journalism for the public sphere” (269). Another key problem is the journalistic norms of objectivity and balance: when reporters are unable to judge competing science claims, the default position is to offer more than one viewpoint. This practice gives both viewpoints validity, and has been challenged both by scientists and members of the public, for example in reporting on global climate change (Dunwoody 21; Groffman *et al.* 287). Finally, exposure to science on the news or in popular media has little effect on public understanding of scientific facts or concepts, though it does lead to greater awareness about scientific issues (Groffman *et al.* 287).

Experiential venues for the public understanding of science also have a wide range of different characteristics. The classic model for public engagement with science is probably the science museum, which began as a “cabinet of curiosity” in the Sixteenth Century (Schiele, “Science Museums” 28). While museums’ purpose today remains that of preservation and education (Schiele, “Science Museums” 27), they have a new level of interactivity in displays and active participation by visitors in the museum experience (Schiele, “Science Museums” 33). Museums are often the sites of informal science lectures, which are another venue for interaction among scientists and the public. Even more informal interactions take place in semi-structured “science cafes” and other events, including science fairs (Riise 305). These more informal formats are generally designed to increase public interest in science, rather than provide factual or procedural science education.

While science cafes and other forums for discussion engage the public in one way, other more organized venues solicit public participation in the scientific process. Public participation with science is designed to offer the public the opportunity for a more meaningful level of engagement than that found in primarily educational settings such as museums. Participation generally occurs either in the context of public policy discussions and decision-making, or as participation in the research process. Public participation in science research has a twofold purpose: to use public involvement to gather large amounts of data for scientific analysis, and to educate the public about the underlying science of the project in which they are participating (Trumbull *et al.* 265). These projects can be either face-to-face (e.g., for community watershed monitoring; Roth and Lee) or have the majority of their interaction via mail (e.g., the Cornell Lab of Ornithology's "Neighborhood Nestwatch;" Trumbull *et al.*), or via more complex digital tools (e.g., *eBird*).

Digital media and the public understanding of science

Digital media, particularly the Internet, are clearly becoming catalysts for widespread changes in science communication: in science journalism, in interactions among individual scientists and the public, and in large projects for public engagement with science. For example, the Internet provides the public with a certain level of access "backstage" into scientific institutions and into previously "hidden" professional processes, such as communications within professional organizations or among scientists, and pre-publications of research papers (Trench 187). Many Internet-based tools combine the wide reach of mass-media communication with participatory elements of experiential learning.

It has been said that the Internet refashions all other forms of media (Bolter 203). For example, online journalism increases the need for timeliness in news, fosters a frame of competing narratives in reporting (because readers can easily click from one story to another and compare information), and incorporates visual and audio-based media (Dunwoody 23). Websites are becoming ever more interactive, providing animations, podcasts, and multiply-linked navigation features that enable a user to find information easily and in multimedia formats (Minol *et al.* 1130), as well as communication and social networking tools like blogs, Facebook, and Twitter.

Interactive digital media hold great promise for increasing public understanding of science and providing new opportunities for public participation in scientific research and evaluation (e.g., Bonney *et al.* 37; Friedman *et al.* 24). These technologies can give audiences access to sophisticated tools for science understanding: interactive, exploratory tools that encourage both intellectual understanding and excitement. It is, however, important to note that, while digital media enhance access to information, they do not in themselves lead to depth of understanding. For example, without a baseline level of scientific understanding, it is difficult to decide between competing claims to judge the veracity of online information. Internet technologies may facilitate the public's search for multiple narratives about science concerns, but the vast majority of technologies favor flashy multimedia "signaling" styles of communication, rather than in-depth narrative structures (Dunwoody 22-23). Another complication for the public understanding of science relates to the nature of scientific "facts." The static nature of print media lends itself to the interpretation of facts as fixed and authoritative. However, ever-changeable online tools suggest that scientific facts are fluid and negotiable. While scientists

themselves regard “facts” as provisional and subject to further testing (Shamos 48), the recognition of uncertainty in science by the public often results in distrust and confusion (Trench 195).

A pressing question for researchers is how we can develop and mobilize new digital tools in ways that increase public understanding of and excitement about science, while providing ways to interpret scientific claims and uncertainty. The complexity of this task suggests that such tools should be developed in a situation-specific context. This dissertation focuses on one such example of a scientific communication issue: public understanding of evolution.

Public understanding of evolution

One specific challenge for contemporary science communication in the United States is the public understanding of evolution. There are a number of reasons that communication about evolution is challenging, some psychological, some religious or philosophical, some based upon factual misunderstanding, and some political. For example, psychological research suggests that essentialism, teleology, and intentionality constrain children’s ability to understand evolution (Sinatra *et al.* 190-191). In many cases, these factors intersect, such as in the perception that the evils of Nazi eugenics and theories of racial superiority were based upon the evolutionary metaphor of the “survival of the fittest.” In fact, “fittest” in this metaphor refers to the best-adapted organisms in a specific environmental context, and it is a misunderstanding of the metaphor that implies that one race (in the Nazi example) can be more “fit” in a larger sense (Scott 93). Individuals can also understand some components of evolution (e.g., natural selection, shared descent, adaptation, mutation) while misunderstanding others (MacFadden *et al.* 880).

Prior experience can often lead to factual misunderstandings about evolutionary processes (e.g., Alters and Nelson; MacFadden *et al.*). For example, individuals may conceptualize the nature of evolution as an event, rather than a process, based upon their event-based perceptions of everyday life (Sinatra *et al.* 192). As this example illustrates, evolution is a clear example of the counterintuitive nature of science. Evolutionary processes are generally microscopic, incremental, and slow: difficult to relate to everyday scales of time and space.

As with other complex scientific concepts, metaphor has been one of the traditional vehicles for communicating our understanding about evolution. The “tree of life” is Charles Darwin’s key visual metaphor illustrating the grand sweep of evolutionary history over time: speciation, extinction, and the relatedness of every living thing. The tree of life was, however, first conceptualized in an era before interactive computer animation, databases, or even an understanding of the role of DNA as the genetic material. Might a refashioning of this image help promote understanding of evolution, at least for individuals for whom inaccurate understanding of evolution is not based in religious or political premises?

This project investigates how the availability of interactive digital tools can help change the metaphors we construct for scientific concepts, focusing on the tree of life. It describes the importance of metaphor for science communication and discusses the ways that digital tools extend our capabilities for constructing new metaphors. The centerpiece of this project is the creation of a computer-based visualization as a concrete example of how digital media can be used to create a new visual metaphor for evolution. Analysis of the conceptual connections this metaphor facilitates for users suggests broader implications of this approach for science

communication. In the remaining pages of this introductory chapter, I outline each of the remaining chapters in more detail, and discuss how each one contributes to this overall project.

Chapter Two: Metaphor in science and the Tree of Life

Metaphors help people make associations between new concepts and familiar ones, providing them new insights and suggesting that certain interpretations of information are more likely to be correct than others. Chapter Two situates the traditional metaphorical representation of the evolutionary “tree of life” in the field of research on metaphor and science. The first part of this chapter discusses several theoretical perspectives on the ways in which metaphor is used in science. For example, metaphoric representations of complex concepts or ideas afford “epistemic access to features of the object that are otherwise difficult or impossible to discern” in representations that strive for simple mimicry (Elgin 5). Metaphor thus plays a key role in facilitating science cognition. Large-scale metaphoric thinking may also support scientists’ emotional investment in the creative aspects of science (Gruber, “Darwin’s ‘Tree’” 255).

Metaphor also plays a key role in science communication. As in other specialized fields of human endeavor, science communicators mobilize metaphor to persuade or to enhance their audience’s understanding of a topic. Formal scientific concepts take the form of mathematical constructs or highly formalized models for understanding (Shamos 63). The translation of these formal constructs into metaphoric vernacular language and imagery facilitates the diffusion of scientific ideas into broader society (Bucchi, “Of Deficits” 58). Metaphor facilitates communication among specialized scientific discourses as well as among scientific-and non-scientific communities; it is what creates the common ground for discussion among or across disciplines (Hellsten and Nerlich 95). Metaphor is also used for issue framing in mass

communication, a tool that increases public engagement with scientific issues, rather than increasing factual understanding (Nisbet 515).

In the second part of Chapter Two, I build upon the theoretical framework of metaphor studies and focus on metaphors for evolution. The evolutionary “tree of life” is one particularly well-known metaphor that combines visual and verbal components to illustrate the broad scope and branching pattern of evolution over time. The tree of life metaphor was extensively developed by Charles Darwin in *On the Origin of Species*, and with other metaphors played a central role in shaping Darwin’s ideas about evolution by natural selection (Gruber, “Ensembles” 266). The tree motif presents his central organizing vision of “shared descent,” the idea that all species are related and have evolved from a common ancestor in the distant past (Gruber, “Darwin’s ‘Tree’” 255). In this section, I will sketch the historical and cultural context in which this metaphor was constructed, and provide a historical grounding for a discussion of its connotations. For example, Darwin’s choice of a tree to represent the pattern of life drew upon other culturally symbolic “trees,” such as religious tree imagery and family trees representing human lines of descent, and may have been an attempt to create an aesthetic argument for his theory (Roberts 521).

The tree of life metaphor has certain limitations, as does any other metaphor. Darwin recognized some of these, such as the comparative thickness of a tree trunk and branch, which maps poorly to the relative number of historical and recent species within an evolutionary lineage. Today, the tree metaphor has important theoretical links to the quantitative study of relationships among organisms, phylogenetics. The science of phylogenetics has brought to light additional incomplete mappings between the tree of life and our understanding of the pattern of

life. One key example is the recent recognition of frequent instances of horizontal gene transfer among groups of organisms early in the history of life (Doolittle 94), which makes the trunk of the “tree” look nothing like a typical temperate tree trunk. Chapter Two will conclude by discussing the affordances and associations suggested by the tree of life metaphor, and highlighting areas of tension in using it for science communication.

Chapter Three: Visualization technologies and changing scientific metaphors

Chapter Three describes the ways by which changes in visualization technologies are being used to expand the range of metaphors that are available for science communication. This chapter situates the practice of creating science visualizations within the changing field of digital technologies, and describes the ways by which changing technologies are being used to expand the range of metaphors that are available for science communication. I begin the chapter by discussing the relationship between metaphor and material technologies for science visualization. Next, I briefly sketch a history of the material technologies of visual representation, and describe how visual conventions can be constrained by representational tools. The range of digital tools available today to help build scientific visualizations includes automated gene sequencing and genetic analysis tools, programming environments that facilitate interactive animations, and tools for communication and dissemination of the visualization. Representational technologies can affect our interpretations of traditional metaphors, make us aware of aspects of an issue of which we had been unaware previously, help us derive new metaphors for a traditional problem, and help spur the formation of new metaphors.

In the second part of this chapter, I describe two key components of visualization research that can be used to theorize the visual and interactive design choices that shape science

visualizations: interactivity and visual design. Interactivity is most obvious mechanism by which digital texts differ from non-digital texts (Bolter 122). Digital media can enhance the viewer's ability to take meaningful action through direct participation with interactive features (Murray 74), thus creating a sense of shared agency. However, interaction with digital media may also guide and constrain the viewer's interpretations of the objects being depicted in subtle yet wide-reaching ways (Manovich 61). The theory of distributed cognition suggests that visual design can create affordances that suggest appropriate actions, as well as constraints that limit inappropriate actions (Zhang and Norman 117). The human mind uses these visible cues to help it make decisions. In effect, visualizations become part of our thinking process (Zhang and Norman 116). This theory provides a useful framework for examining the affordances and constraints of existing metaphors for evolution, identifying areas of metaphoric limitation, and generating a new metaphor to address these limitations.

New media theory describes two important properties of interactive media, transparency and hypermediacy, which describe how a visualization can either hide or foreground the theoretical and subjective assumptions that go into visualizations. Scientific visualizations, like other types of texts, can be designed to either efface their medium of production and serve as "transparent" transmitters of information, or to call attention to their medium and create an environment of "hypermediacy," in which the user is continually reminded of the interface between herself and the information (Bolter 25). Scientific visualizations are typically designed for transparency (Headrick 98). For example, design conventions urge subordinating artistic considerations to communicating information clearly (Tufte, *Visual Display* 181). Such conventions, however, obscure the underlying assumptions and processes that go into creating

visualizations (Kenney 101). Digital media can provide a useful space to explore the ways in which scientific representations are not transparent. The visualization presented in this dissertation embodies this property: on one level, viewers will be able to look *at* patterns of evolutionary relationships over time; on another level, they will be able to look *through* the visual display of this information by learning about the data and decisions that drive the visualization. Such an experience might help a viewer critique the notion that scientific visualization is a non-mediated, transparent view of reality by affording them access to some of the assumptions and evidence behind the dynamic evolutionary map.

Chapter Three concludes by describing how material technologies have influenced visual representations of evolution through time. I first describe several major ways that the relationships between species were visualized in pre-Darwinian times, and then describe how these representations have changed as new representational tools have been developed. I also discuss contemporary digital media research projects that visualize evolutionary biology. The described projects largely share a rationale of improved information access (e.g., more efficient linking of information about species in databases with phylogenetic trees), and do not explicitly attempt to modify the tree of life metaphor (e.g., Maddison *et al.* 21). These contemporary trends in visualization research will be used to build support for the design of the dynamic evolutionary map visualization for this dissertation project.

Chapter Four: The dynamic evolutionary map

The fourth chapter of this dissertation describes the theoretical methodology and technical methods used to construct the dynamic evolutionary map and presents the finished visualization. This chapter synthesizes the theoretical concepts introduced in the preceding

chapters, and applies these concepts to the creation of a new visual metaphor. To evaluate the issues raised in this project, this dissertation draws upon several research traditions. These include new media theory, theories of metaphor and creativity, cognitive science, information design, visualization research, and evolutionary theory. Chapter Four begins by describing how principles from these traditions were used to guide theoretical choices in creating the visualization. These choices include the selection of the map metaphor, navigation method, elements of the visual style, and details presented about the visualization process presented within the visualization itself.

The second part of Chapter Four describes the technical methods used to construct the dynamic evolutionary map, including the data sources and programming methods that were used. This visualization maps the relationships among bird orders onto a dynamic two-dimensional space and allows both synchronic and diachronic exploration of the relationships between orders. The diachronic aspects of the visualization are based upon animation backward or forward through time; beginning at the point when birds originated, the animation shows new bird orders budding off of the initial bird lineage and spreading across the evolutionary map as they diverge genetically over time. Synchronic exploration occurs at several stopping points during the animation sequence. At these points, the viewer can click on a dot to find information about that order at a point in time, such as fossil evidence of that order. Viewers can also see the relative genetic distinctiveness of orders by looking at how far away they are from other orders.

In the concluding section of this chapter, I describe how users interact with the map and present screenshots showing the key map functions for diachronic and synchronic exploration, thus illustrating how the concepts theorized in the preceding chapters were instantiated. The

metaphoric affordances and constraints of the map are discussed in relation to the technical map functions. The map itself is archived online, and a link to it is provided in the final part of this chapter.

Chapter Five: User interaction with the dynamic evolutionary map

Chapter Five synthesizes reactions of users, both biology experts and biology novices, to the visualization. In the first section, I describe the methods used to evaluate the dynamic evolutionary map. In this evaluation, biology experts and biology novices were asked to interact with the visualization and answer questions about bird evolution, as depicted in the map. Participants who assisted in evaluating the map include professionals in the fields of science education and biology (experts), as well as undergraduate students (novices).

The purpose of the expert evaluation was to solicit input from individuals with expertise in teaching evolution using visual communication tools. Experts were directed to interact with the map with an eye toward identifying the conceptual affordances it may suggest to viewers. They were also asked questions about specific conceptual affordances. The novice evaluation was designed to gather information about how well the map functioned in an inquiry setting and suggest potential affordances that the map communicated. Novices were directed to answer a series of questions about avian evolution designed to evoke this information while using the map. Some novices received a paper-based questionnaire that they could complete at their own pace, and others were directed through the evaluation verbally.

The second section of Chapter Five presents the results of responses of the evaluation participants. I summarize and discuss the responses of expert and novice users separately. In this section, I also discuss areas of confusion for the novice users of the visualization. The participant

evaluations provide additional support for the argument that digital tools can be used to extend metaphors for science communication in intellectually and affectively appealing ways, as well as suggesting areas for future refinement of the visualization.

Chapter Six: Conclusion

The theoretical implications of the dynamic evolutionary map are evaluated in Chapter Six. In this final chapter, I first review the theoretical synthesis that contributes to the structure of the dynamic evolutionary map. I then briefly discuss how the map is situated within the history of evolution visualizations. Next, I discuss the metaphoric similarities and differences between the map and the tree of life metaphor for evolution, contrast the affordances and constraints of each visual metaphor, and discuss areas of alignment and disagreement. Participant feedback results are used to suggest future uses of the evolutionary map metaphor as either a supplement to the tree of life or a stand-alone communication tool for communicating about evolution.

In the second part of this chapter, I examine the technical operation of the visualization. I describe technical challenges that arose while creating the map, and discuss their implications for future iterations of this type of visualization. I briefly sketch possible ways to improve the technical construction of the visualization and thereby extend the range of communication situations in which it can be used. The dissertation concludes by examining the broader implications of the research results for science communication and the public understanding of science, as well as the fields of education and evolutionary biology.

CHAPTER TWO: METAPHOR IN SCIENCE AND THE TREE OF LIFE

This chapter situates the traditional metaphorical representation of the evolutionary “tree of life” in the field of research on metaphor and science. I begin the chapter by discussing metaphor as a tool for scientific understanding. First, I discuss theories of how metaphor operates and outline different theoretical perspectives of its role in science. Then I outline the major ways metaphor comes into play when communicating scientific ideas and describe both cognitive and affective effects of metaphor.

In the second part of this chapter, I describe the ways metaphor is used specifically for communicating biological evolution. I begin this part of the chapter with an overview of the main concepts of our current understanding of evolution. Next, I outline Darwin’s metaphors for natural selection and evolution in *On the Origin of Species*, discuss the historical and cultural context in which Charles Darwin developed the tree of life metaphor, and finally describe the structure of the tree of life metaphor in detail.

Finally, I focus on the connotations of the tree of life metaphor for evolution. I distinguish between two different, though related, uses of the tree of life: as an informal or qualitative image of the scope of evolution, and as a formal hypothesis that underpins quantitative phylogenetic biology. Together, these two uses of the tree of life contribute a diverse set of metaphoric affordances and associations about evolution. This chapter concludes by discussing how these affordances and associations help shape our understanding of evolution.

Metaphor as a tool for scientific understanding

One key part of the communication of science, as with other specialized fields of human endeavor, is mobilizing metaphors to persuade or to enhance an audience’s understanding of a

topic. Moreover, metaphor plays an important role in structuring individual scientists' understanding of their fields of study. Darwin's tree of life fits into this broad tradition of using metaphor in both the discourse of science communication and as part of the conceptual framework of science itself. Iina Hellsten and Brigitte Nehrlich define metaphor as "interaction between a source and a target domain, or a mapping between these two domains" (94). Metaphors help people make associations between new concepts and familiar ones, providing them new insights and suggesting that certain interpretations of information are more likely to be correct than others.

According to this "interaction" theory of metaphor, metaphors work by linking a concrete or familiar "secondary domain" of knowledge with a "primary domain," which is typically more abstract (Hesse 158). Ideas or implications from the familiar secondary domain are transferred to our nascent conception of the primary domain, and help us structure our developing understanding of the latter (Hesse 163). For example, the process by which DNA directs cells to synthesize specific proteins occurs in two steps: "transcription" (the process whereby a RNA molecule is generated from the DNA molecule) and "translation" (the process by which a protein is generated from the RNA molecule). The overall metaphor in this instance links written communication (the secondary domain) to a set of complex biochemical pathways (the primary domain). The transcription-translation metaphor highlights the modular or letter-like structure of these three types of molecules (i.e., DNA and RNA are composed of nucleotide subunits, while proteins are composed of amino acid subunits), while hiding the more complex aspects of protein synthesis (e.g., interaction between proteins, RNA, and DNA to regulate the rate and timing of synthesis).

Metaphor is used to represent scientific concepts and phenomena using visual, linguistic, and mathematical means. Scientific representations are often designed to be or are interpreted as either purely mimetic or as transparent “windows” onto the natural world (Pauwels vii). Rather than simply mimicking or reproducing the subject exactly, however, scientific representations are more useful when they exemplify important aspects of the subject being represented by emphasizing certain properties and omitting others (Elgin 1). Such non-mimetic representations afford “epistemic access to features of the object that are otherwise difficult or impossible to discern” in representations that strive for simple mimicry (Elgin 5). Metaphor is an important tool for constructing non-mimetic representations that highlight or shade certain aspects of a scientific concept.

Scientific metaphors are often compared to literary metaphors in that they are open to interpretation. A scientist and a non-scientist certainly might interpret a given scientific metaphor differently, for example. Within a scientific community, interpretations are generally highly constrained by the intersubjective nature of the community, whereas readers of literary metaphors are freer to build individual associations between the primary and secondary domains of the metaphor (Aubusson, Harrison and Ritchie 4; Hesse 164-165). Intersubjective interpretation is particularly important for more formalized types of scientific metaphors, such as model systems and experimental analogies, which are based on complex theoretical structures and empirical observation (Black 239).

The distinction between *metaphor* and *analogy* within the field of scientific education is somewhat fluid, and the two terms are often used interchangeably. The primary difference is that scientific metaphors are used to make covert comparisons between two domains, whereas in

scientific analogies the explicit similarities and differences between the two domains are highlighted (Aubusson, Harrison and Ritchie 3). To put it another way, “all analogies are metaphors but not all metaphors are extended into analogies” (Aubusson, Harrison and Ritchie 3). While metaphor can facilitate scientific understanding, it can also present a picture of a scientific concept that is oversimplified or one that suggests a complex topic is well-understood when it is not. For example, educational research has shown that the process of natural selection is very simple to explain to students, but that the very simplicity of the metaphors used to explain it can lead to misconceptions (Pramling 544). Some researchers suggest that direct observation and experimentation can help students move from a metaphor-based understanding of a concept to an analogical mode in which they examine the similarities and differences between domains (Wilbers and Duit 40). In this dissertation, I will focus on metaphor as a general communication tool, and primarily use the term in the more general sense to encompass both scientific metaphor and analogy.

How metaphor operates within science

Before I discuss specific cases of scientific metaphor in detail, it will be helpful to look at the way metaphor operates within science in general. Different schools of philosophy of science have different interpretations of the role of metaphor in science. Additionally, the question of how metaphor actually functions is an active area of research. While the details of these research areas are outside the scope of this dissertation, I will briefly summarize two contrasting views of the role of metaphor in science here.

For many scientific philosophers, science is “the search for verifiable ‘truths’” (Shamos 47), a process by which ideas are tested against the outside world. In the “strong inference”

scientific approach, scientific concepts begin as mathematical constructs (Shamos 63), or perhaps highly formalized models for understanding. The models and equations themselves are exact, though highly reductive, descriptions of the natural world. Within the strong inference tradition, intuition, individual motivation, and social conventions do not play a large role in the scientific process (Brown 7). While this position has been effectively critiqued by many sociologists of science, it serves here as an example of one philosophical perspective on the role of metaphor in science. From the strong realist perspective, metaphor might be used to communicate between disciplines, but scientific concepts all ultimately refer to mathematical or formalized logical models; metaphor plays a very minor role in research.

Other researchers argue that metaphor is used in science in a more fundamental way than for deliberate communication efforts. Philosophers who take a social constructionist view of science differ from those who prefer a strong inference approach in their views about the use of metaphor, intuition, and tacit observation in the creation of scientific ideas. In fact, one school related to constructionist philosophy, conceptual metaphor theory, holds that all human thought is “fundamentally metaphorical in nature” (Lakoff and Johnson 3). Scientific thought is no exception. In this view, conceptual mental frameworks underlie and shape human reasoning. The same conceptual frameworks structure both everyday and scientific cognition. Charles Darwin’s theory of natural selection, with all the metaphors incorporated into *Origin*, is one such conceptual framework (Al-Zahrani 52). Scientific “truth” is a kind of metaphorical representation based upon scientists’ embodied experiences of the world, and scientific reasoning is not fundamentally different from other logical reasoning (Brown 50-52). Reality is knowable only to an extent; our understanding of it will always be shaped by our embodied experience.

Based upon conceptual metaphor theory, all scientific reasoning is metaphoric in some way. According to Brown:

. . . metaphor plays an extensive role in the way we interpret individual experiences and relate one kind of experience to another. The metaphorical underpinnings of our conceptual systems are evidenced in our use of language, but according to conceptual metaphor theory, metaphor is much more than a matter of just language. Our experientially grounded metaphorical understanding of abstract concepts influences our thought patterns and actions as well as the ways in which we express ourselves. (49)

For Brown, scientific metaphors include linguistic metaphors (e.g., “light is both a wave and a particle”) and scientific models incorporating both an underlying structure and metaphorical entailments (e.g., Bohr’s “solar system” model of the atom, with electrons moving in fixed orbits like planets) (25). Theories themselves can be metaphoric: while Newton’s laws of motion describe the forces we encounter in everyday life, special relativity is a more complete (i.e., less metaphorical) explanation of reality. Scientific experiments themselves can also be thought of as a type of formalized metaphor for a natural process, in which certain aspects of the process are included and others omitted (Elgin 6).

Several criticisms of conceptual metaphor theory exist, particularly as it applies to the practice of science. First, some cognitive psychologists argue that the theory that our minds are organized according to metaphorical frameworks has not been demonstrated in empirical research (Brown 186). For example, one of the central claims of conceptual metaphor theory is that idiomatic expressions always create metaphoric mappings; empirical research suggests that

metaphoric mappings are only created for unfamiliar idioms (Keysar *et al.* 591). Another criticism from the strong realist tradition states that the external truth of reality is ultimately knowable, regardless of the human embodied condition (Brown 187). Conceptual metaphor theory states that our interpretation of reality is dependent upon our physical experience and internal mental frameworks, so this is a major point of disagreement between these two views.

Importantly, both the strong realist and the conceptual metaphor theory philosophies can be interpreted to agree that metaphor is useful as a first stage in introducing people to scientific ideas. Metaphor can also be useful within science when new concepts and results are being incorporated into frameworks of understanding (Brooks 446). While strong realists might argue that one cannot understand a scientific concept without understanding the mathematical model underpinning it, a pragmatic approach to science communication suggests that a more metaphoric non-mathematical understanding of a concept can be a good and workable approximation. If empirical research suggests that not all cognition is actually based on a metaphoric cognitive structure, as conceptual metaphor theory indicates, nevertheless we may very well contextualize novel concepts more readily when we can refer to familiar objects and situations.

Scientific uses of metaphor

Metaphor is used extensively in both formal science education and for informal science communication. We can make distinctions between these two communication settings; for example, the relative authority dynamic of the instructor-student relationship differs from that of the communicator-audience relationship. Rather than viewing these two settings as completely disparate, it is useful to look at them as existing on a continuum of scientific discourse.

Massimiano Bucchi's diffusion model for science communication suggests that scientific ideas are generated within disciplines, and normally diffuse first within a given discipline, then among disciplines, then to students in formal settings, and finally enter the popular discourse ("Of Deficits" 62). This model of science communication emphasizes the scientific discipline as the predominant site for generation of science concepts. Metaphor, however, is sometimes used to "shortcut" the usual pathway for diffusion; a specialist may introduce a new metaphor at the popular level via the mass media, whereupon other specialists then take up the idea as they consume the news (Bucchi, "Of Deficits" 63). The mere appearance of a scientific idea in the popular press confers a degree of legitimacy upon it (Bucchi, "Of Deficits" 64), so communicators might deliberately craft a metaphor that appeals to the popular imagination in order to facilitate its acceptance among the science community. Historically, *On the Origin of Species* has been one of only a few primary science research works written by its author for a popular audience (Turney 7). It is likely that Darwin pursued a strategy of popularization in order to overcome substantial resistance from both his scientific peers and the larger public to his ideas about evolution.

Metaphor is also used to help solidify scientific ideas. Bucchi's diffusion model predicts that, at each level of discourse (from specialist to popular culture), the uncertainty surrounding a scientific concept idea is removed and "ideas" become "facts" ("Of Deficits" 62). One way to see this process in action is by comparing the presence of qualifying language in scientific papers and press releases, as compared to the presentation of the same ideas in the popular media. For example, journalistic coverage of cancer research frequently omits qualifying language and details of scientific studies (Brechman *et al.* 463). Communication in this model becomes

dialogue between specialist and popular discourses, in which metaphors serve as “boundary objects” among communities. Boundary objects can be either concepts (e.g., cell theory, “big bang” theory) or physical objects (e.g., textbooks, DNA sequencers) that facilitate agreement about facts by providing a stable meeting point for interaction between disciplines (Fujimura 172).

Metaphors can affect their audiences via affective or emotional, as well as cognitive or factual, pathways (Gruber, “Ensembles” 261). Within the broader field of communication, metaphor is used extensively in framing, a process of setting up “interpretive storylines” whose aims are to increase public engagement with specific issues, rather than for education of the public itself (Nisbet 515). Frames are used to increase personal salience and the emotional affect of issues, rather than being used to increase factual comprehension. They are often used in mass communication efforts, where public engagement with a scientific issue requires the formation of a connection with a previous frame or concept (Hellsten and Nehrlich 95).

One final important way that metaphor is used in science is for personal motivation. Howard Gruber describes a class of personal, central metaphors he calls “images of wide scope.” Images of wide scope are often constructed by one individual over a long period of time (“Darwin’s ‘Tree’” 256), and provide structural support for both emotional and intellectual investment in creative endeavors (“Darwin’s ‘Tree’” 255). These large-scale metaphors are not only found within the sciences; for example, the experience-based mental map of a city created by its individual inhabitants (“Darwin’s ‘Tree’” 254). As an image of wide scope, Darwin’s tree of life helped him structure his cognitive and emotional frameworks when thinking about evolution. Gruber suggests that images of wide scope are intensely personal, though they can

also serve as “figures of thought” that help scientists track important concepts in different disciplines (“Diverse Relations” 178).

Metaphor supports both cognitive and affective ways of thinking about science, both within the sciences and by the broader public. In the remainder of this chapter, I will examine how metaphor is used to conceptualize and communicate evolution. I will focus upon the work of Charles Darwin, particularly *On the Origin of Species*, and on the “tree of life” as a central metaphor for evolution.

Evolution, natural selection, and the pattern of life

Before discussing Darwin’s work and the tree of life metaphor, I will summarize the main ideas of how the process of evolution is understood today. For Kevin de Queiroz, *evolution* is defined by two components: change (of biological characteristics within populations) and common ancestry or common descent (245). Of the two, de Queiroz suggests that common descent is the more crucial component. While people have observed biological differences between taxa (biological groups) and changes in characteristics of those taxa over time for thousands of years, it is the idea of descent with inheritance from common ancestors that both provides a mechanism for this pattern and explains the patterns of difference and similarity we see among species. For de Queiroz, “Because of the implications that each has for the other, the concepts of change and common ancestry are closely tied. In this light, perhaps the best general definition of evolution is Darwin’s ‘descent with modification’” (245).

The concept of common descent with modification was first consistently applied to evolution in Darwin’s *Origin of Species* (Mayr 23), and has continually been refined until the present day. For Darwin, and the co-developer of this theory, Alfred Russel Wallace, the primary

mechanism driving evolution was natural selection. A simple explanation of this concept has two parts: 1) in nature, harsh environmental conditions and competition for resources mean that not all organisms survive to reproduce, therefore 2) organisms with traits that give them a survival advantage are more likely to have offspring than organisms lacking those traits. Offspring will inherit those survival traits, and the proportion of those traits will increase in the population as a whole. Over successive generations, the population will evolve. An important point is that the evolutionary process does not perfect a population; instead, it facilitates temporary adaptations to local environmental conditions that are always in a state of flux. Besides natural selection, two other factors were also important to Darwin: “divergence of character” (i.e., the presence of different traits among organisms) and extinction; together, variation, natural selection, and extinction create descent with modification (Costa 116).

Since Darwin’s time, the discovery of the genetic material (DNA) and the units of inheritance (genes) has refined our understanding of evolution. For example, we now know that mutation, gene transfer, and genetic recombination are the primary sources of trait variation. While natural selection remains a key mechanism of evolution, we now know that the evolutionary process as a whole is stochastic. Random factors such as genetic drift, gene flow, and mutation, play major roles in determining the prevalence of traits in populations, and then natural selection acts upon these traits. Nevertheless, many of the concepts introduced by Darwin in 1859 are still used to communicate about evolution today.

Metaphor and evolution in *Origin of Species*

When Charles Darwin wrote *Origin of Species*, metaphor played a central role in shaping his ideas about evolution by natural selection. Darwin also was explicit about using metaphor to

describe his theory (Gruber, “Ensembles” 266). He used a number of different metaphors in *Origin* to exemplify different aspects of his theory. Some of these metaphors took years to develop, and became central organizing schemas for his work beyond *Origin*, or “images of wide scope.” One example of this type of metaphor is the tree of life. Darwin seems to have used other metaphors more to translate his theoretical concepts for public understanding than as personal organizing schemas, and he re-worked several of these metaphors in succeeding editions of his book in response to their reception. For example, the now-popular phrase ‘survival of the fittest’ appears only in later editions of the *Origin*, apparently in response to its increasing use and acceptance among philosophers and the general public (Costa 61, 345).

Howard Gruber describes five main metaphors in *Origin*: artificial selection, wedges, war, a tangled bank, and a tree. He interprets three of these images (artificial selection, wedges, and warfare) as describing the “simplifying” aspects of natural selection and extinction, while the tangled bank and tree “dramatize the principle of vitality, the explosive, irregular living material on which selection works” (“Darwin’s ‘Tree’” 251). A brief look at these images illustrates how they each emphasize different aspects of his theory.

First, Darwin used *artificial selection*—plant and animal breeding—to draw connections between natural selection and a process that was familiar to many of his contemporary readers. In both natural and artificial selection, a population of organisms begins with some level of genetic variation. Different selection pressures in each situation will result in only a few organisms reproducing and passing on their traits: in natural selection, pressure comes from limited resources and competition; in artificial selection, humans deliberately breed organisms with desired traits. While this metaphor suggests that natural selection can result in large changes

in a population over time (Costa 109), one problem with it is that “selection” implies a “selector,” and natural selection happens largely via stochastic processes.

The *wedge* metaphor made it into the first edition of *Origin*, but Darwin removed it from the second: “The face of Nature may be compared to a yielding surface, with ten thousand sharp wedges packed close together and driven inwards with incessant blows, sometimes one wedge being struck, and then another with greater force.” (67) Wedges that remain in the surface are species that survive, but to remain there they presumably must force other wedges out and render those species extinct. Gruber suggests that this image was primarily used by Darwin to develop his thinking on the cumulative action of many small evolutionary forces, but that he ultimately decided it was too mechanistic and “ruptur[ed]... the seeming harmony of nature” (“Darwin’s ‘Tree’” 250).

While the wedge metaphor implies that competition is necessary for survival, the *warfare* metaphor makes this more explicit. This metaphor is present in several places throughout *Origin*. In one example, seedlings must overcome “enemy” seedlings in a competition for space; in another (63), males compete for females in sexual selection (88). Today, the warfare metaphor is largely known by the phrase ‘survival of the fittest,’ which was added to *Origin* beginning in the fifth edition (Costa 61).

The *tangled bank* illustrates the present-day diversity of life:

It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on

each other in so complex a manner, have all been produced by laws acting around us. (*Origin* 489)

Darwin uses the diverse “tangled bank” to illustrate how the complexity of life we see around us can arise from the interaction of a few simple rules for natural selection (Costa 489). This image is the final grand metaphor presented in *Origin*, and in it he tries to provide readers with a vision of life’s diversity, ultimately resulting from evolution acting upon the common relationships of species.

While the tangled bank illustrates the diversity of life that we see in the present day, the *tree of life* represents the grand scope of evolution over time. From a population at a single ultimate starting point, the mechanisms of “divergence of character,” natural selection, and extinction act upon succeeding generations of descendant populations (Costa 116). Genetic changes (divergent characters) in different populations send species down different evolutionary paths. Some of these “branches” are selected and survive, splitting in turn to end off new branches. Other branches wither, and species become extinct. Over time, the single starting species gives rise to a multitude of different species, some persisting and some passing away. The metaphor of the “tree of life” is one that Darwin worked on for years and was never entirely satisfied with (Gruber; “Darwin’s ‘Tree’” 248), but still holds a great deal of resonance today.

As biologists have built upon the scientific understanding of Darwin’s time, other metaphors for evolution been developed. Many of these metaphors build upon the discovery that DNA is the genetic material (e.g., evolution “rewriting” the “language of life”), and attempt to articulate the desire of biologists to “read” DNA in order to understand more about the evolutionary process (e.g., Fujimura; Hellsten and Nehrlich). The richness and visual

associations of Darwin's tree of life, however, have remained relevant for over a century and a half. In the remainder of this chapter, I will focus on the tree of life and its central importance for articulating a vision of evolution, both in Darwin's time and until the present day.

The historical and cultural context of the tree of life metaphor

In this section, I will briefly discuss two major spheres of influence on Darwin's thinking as he was developing his metaphors about evolution, with emphasis on the tree of life metaphor. First, Darwin did his research and writing within a particular cultural context, and this affected his work. For example, Richard Roberts argues that Darwin's central metaphors, as well as his prose style, borrowed much from Romantic traditions. As he puts it, Darwin's prose was designed to "deliver to the reader an aesthetic assessment that lay beyond the scientifically articulable" (521). The question of how humans could have evolved an appreciation of aesthetics and beauty through natural selection was, in fact, one primary argument against natural selection; Darwin took pains to address the evolution of human aesthetics in later editions of *Origin* (Prodger 51).

Darwin's invocation of tree iconography in *Origin* drew upon several sources. Tree imagery is widespread in mythological and religious traditions (Hellstrom 11), for example, Biblical trees of life and knowledge, and the Norse World Tree, Yggdrasil. Trees are frequently found in the stained glass of British churches, and the Christmas tree and British oak were also important symbols in Darwin's time. More prosaically, Darwin's tree metaphor relates common descent to tree-like diagrams that were used for human genealogies, livestock pedigrees, and language classification (Darwin, *Origin* 422; Gontier 526).

Interestingly, popular reception of Darwin's theory emphasized the tree motif. Janet Browne finds trees in many contemporary cartoons and caricatures of ideas about evolution and Darwin himself. Browne suggests that the tree became a recognizable symbol because of public interest in the newly articulated relationship between humans and other apes (31-32); apes and monkeys, after all, do frequently live in trees. Browne argues that popular cartoons played a large role in publicly disseminating at least some of the concepts and implications from *Origin* (31).

The second major sphere of influence on Darwin is that of science and natural history. It is not hyperbole to suggest that Darwin's vision of shared descent, as exemplified in the tree of life, caused a revolution in the way scientists conceptualized the relationships among species and even the organization of the natural order of the world. Darwin's work revolutionized the Natural System, or the representation of the concept that there is an underlying order in the diversity of life (O'Hara, "Representations" 255). The earliest Aristotelian description of the Natural System was a linear, progressive hierarchy of species from most imperfect and simplest (sometimes including non-living minerals) to most perfect, with humans at the apex (Gontier 521). This system, called the Great Chain of Being or *scala naturae*, was ultimately based on Platonic Forms, and had largely fallen out of favor before Darwin's time (Ragan 44).

By the late Eighteenth Century, biologists began to organize their depictions of Natural System based upon "affinities" among species, rather than by reference to Platonic Forms (Ragan 46-47). Depictions of the Natural System were map-like, relied upon symmetrical "circles of affinity" (O'Hara, "Representations" 256), or showed dichotomously branching tree-like organization (Ragan 47). Importantly, these affinity-based depictions did not imply any

biological relationships among species (Stevens, “Pattern and Process” 157). Instead, each taxon was thought to have been created in its present form, or perhaps have changed slightly from that specially created form over time. Ernst Mayer, for example, suggests that *Origin of Species* was, in Darwin’s own words, “one long argument” against special creation (94). Although Maddison and colleagues state that “Darwin merely needed to breathe evolutionary life into the static hierarchy as a means to convey perhaps the most profound metaphor in biology” (20), the idea that all species are related through common descent from a single ancestor is quite a profound difference between Darwin’s metaphor and previous systems. It is also probably the aspect of Darwin’s work that has generated the most controversy in the general public.

The concept of shared descent has had profound implications for our philosophical ideas about the organization of living things:

The ramifying and grand revolution in understanding that Darwin foresees stems from one seemingly trivial change in the way we view organisms: when species are seen to have a *history*, he says— when we see that they are genealogically related— only then will we see them comprehendingly. (Costa 485)

The *Origin of Species* contradicts three main components of traditional metaphors for the Natural System: special creation, teleology, and order. As we shall see, however, Darwin’s tree metaphor can be interpreted ambiguously with regard to these components, ideas about which persist in scientific metaphors today (O’Hara, “Representations” 272).

One final way that the scientific sphere influenced *Origin of Species* is in the way that it is constructed according to the scientific conventions of its time. While the stylistic presentation of Darwin’s text is not the focus of this dissertation, it is pertinent to mention that Darwin likely

enlisted contemporary conventions in order to marshal support for his revolutionary ideas. For example, Darwin referenced the work of several dozen geologists, biologists, mathematicians, and other scientists in *Origin*, and updated later editions of the book in response to new research findings and criticism of his work. In another example, the tree figure published in *Origin* conformed to visual scientific conventions, particularly those of geology and stratigraphy.

Darwin's tree of life as a metaphor for evolution

Darwin's tree metaphor is his central organizing vision of shared descent, the idea that all species are related and have evolved from a common ancestor in the distant past (Gruber, "Darwin's 'Tree'" 255). As discussed previously, the concept of shared descent has led to large changes in philosophical ideas about the organization of the Natural System. This concept was so central to his theory that the only illustration included in *Origin of Species* was a schematic of the tree of life, albeit a highly-stylized version (figure 1).

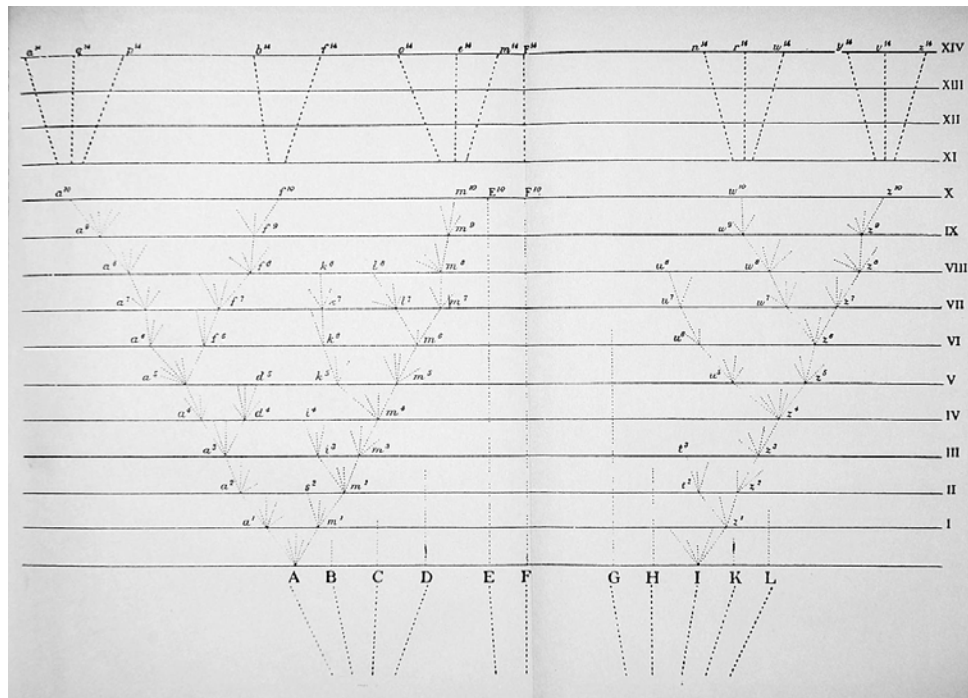


Figure 1: Darwin's tree diagram from *Origin of Species*, 1859

Darwin's tree metaphor and his diagram of common descent describe evolution as a process that begins with a single clade, or group of related organisms. From this original population, genetic changes in descendant groups send species down different evolutionary paths. Genetic change within a population (i.e., changes in gene frequency) is sometimes called microevolution, and genetic change at the species level and above is called macroevolution. Darwin's tree diagram, and tree diagrams in general, largely describe macroevolution, or large-scale changes in the relationships among taxa.

Macroevolution can occur either within a single lineage (anagenesis) or as a result of a lineage splitting into different descendant lineages (cladogenesis); Darwin included both types of evolution in his diagram (Costa 120). Extinction also plays a key role in this image; some

branches wither, as species “overtop” and outcompete one another (Darwin, *Origin* 119). The species we see today are represented on the tree by new budding twigs, and those species that have become extinct are represented by the woody branches; Darwin draws attention to the woody branches as an answer to criticism that evolution must not occur because of the lack of modern day “missing links” between species (Gruber, “Diverse Relations” 182).

Although the language Darwin uses in *Origin* is very visual, the only diagram he links to the tree of life metaphor is highly stylized, and not very evocative of a tree at all (Oppenheimer 126). It is important, however, to note that this is the single diagram to appear in *Origin*, which is a measure of its centrality to his thinking. While the concept of the family tree probably influenced his choice of metaphor, the language Darwin uses to describe the tree of life suggests that he was emphasizing the “tree as biological object” instead. While material trees are acted upon by natural selection, the tree of life appears not to be intended to exemplify all these processes in exact detail (e.g., there are not multiple trees of life competing with one another for space or water), but instead to evoke an organic image of spreading growth on a grand scale.

Darwin created his tree diagram before his theory of natural selection, and he constantly re-worked the metaphor to express his developing thinking about evolution. For example, he toyed with the idea of exchanging the tree for a “Coral of Life,” which was better at incorporating dead or hidden basal branches to suggest extinction and the imperfect fossil record than a trunked tree (Gruber, “Darwin’s ‘Tree’” 248). David Archibald suggests that Darwin used the tree despite the better fit of the coral image because tree iconography was already widespread in popular culture and natural philosophy (570). Darwin’s choice of a tree to represent the pattern

of life also drew upon other culturally symbolic “trees,” such as religious tree imagery and family trees representing human lines of descent.

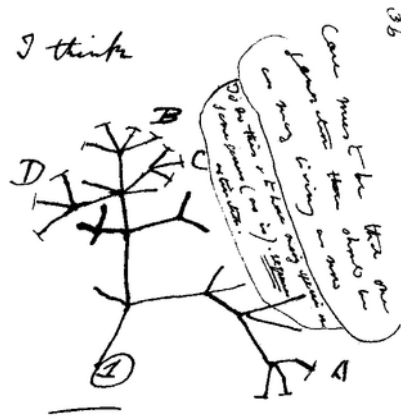


Figure 2: Early sketch of an evolutionary tree from Darwin's 1837 “B’ notebook”

Another example of how Darwin developed the tree of life lies in how he adapted it in response to his changing ideas about the directionality of evolution. Sketches of trees appear in his early notes, most commonly in his 1837 “B’ notebook” (e.g., figure 2). Julia Voss describes Darwin’s earlier sketches as teleological, but over time, “teleology, regularity, and orderliness gave way to accident, variation, and extinction” (101). To Voss, both Darwin’s imagery and his theory flouted both teleology, which was thought to be a necessary part of the Natural System among contemporary natural historians, and order, thought to be necessary among physical scientists (124).

The tree diagram in *Origin* does an excellent job of exemplifying the major features of Darwin’s theory: divergence of character, descent, lineages either splitting or evolving without splitting, long periods of time, and extinction. However, it can be argued that this is not an image

that evokes a powerful emotional response in the viewer. Darwin's prose description of the tree of life is much more compelling:

As buds give rise by growth to fresh buds, and these, if vigorous, branch out and overtop on all sides many a feebler branch, so by generation I believe it has been with the great Tree of Life, which fills with its dead and broken branches the crust of the earth, and covers the surface with its ever branching and beautiful ramifications. (*Origin* 130)

Subsequent authors and illustrators would attempt to present this metaphor in a more evocative pictorial form, notably the German anatomist Ernst Haeckel.

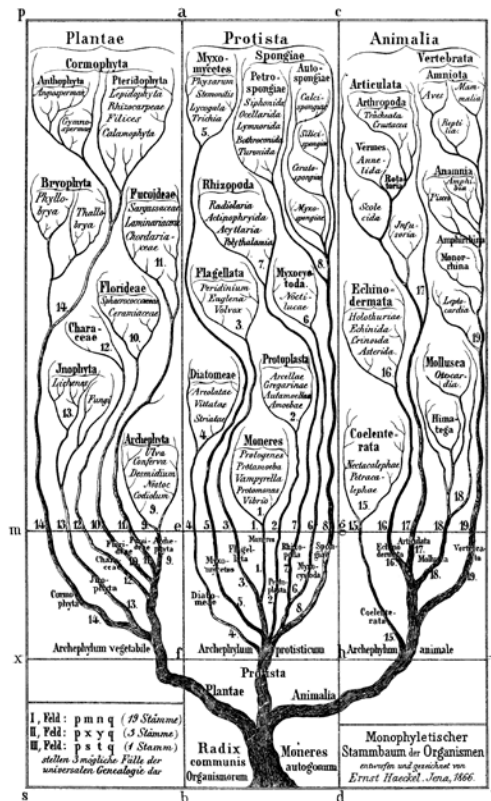


Figure 3: Tree of life diagram by Ernst Haeckel, *Generelle Morphologie*, 1866

Haeckel developed several tree illustrations as a much more literal interpretation of Darwin’s metaphor, complete with thick trunks, and in some cases, even textured bark (figures 3 and 4). These additions embellished the tree metaphor without exemplifying specific parts of the theory. For example, figure 3 seems to show a number of branches being terminated before the present day, such as the Bryophyta (mosses and relatives) and “Archephyta” (green algae). In fact, this was a space-saving measure, rather than a statement that these lineages had gone extinct.

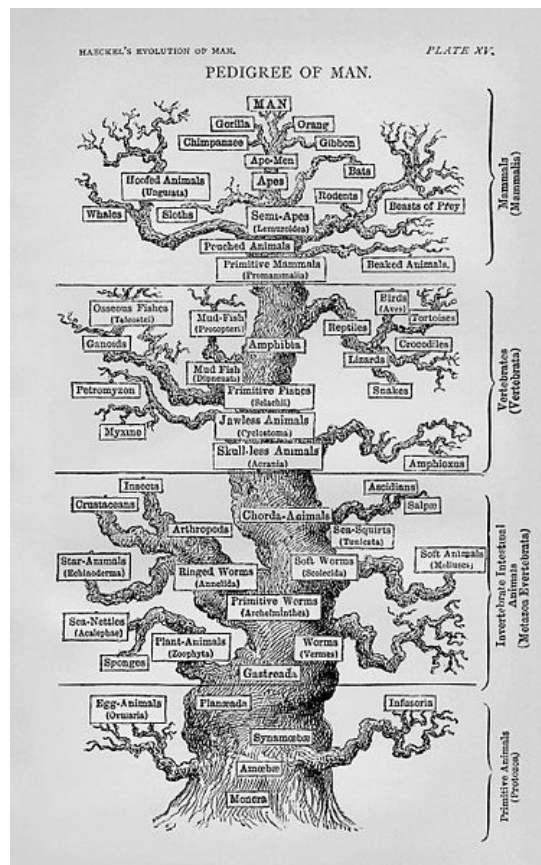


Figure 4: Tree of life diagram by Ernst Haeckel, *Anthropogenie*, 1874

Jane Oppenheimer suggests that Haeckel was “attempting to improve on himself, or on nature” (134) by more clearly illustrating the underlying pattern of life, rather than consciously attempting to make the metaphor more vivid (a tendency which would ultimately prove problematic with his embryology illustrations). She suggests that, though metaphorically blurred, Haeckel’s illustrations did help further popular acceptance of the tree metaphor (134). Others have argued that the symbolic changes Haeckel made to the tree made his illustrations problematic metaphors for Darwin’s theory. Julia Voss suggests that Haeckel “brought evolution to a halt after it reached mankind... the principles of branching and continuation disappeared almost completely in this tree, whose powerful trunk concealed a self- enclosed stepladder at its heart” (123). Robert Brain links Haeckel’s illustrations to “protoplasm theory:” the idea that an all-encompassing protoplasmic medium linked all life and directed development, and whose vibrations were the vehicle for heredity (92-93). Brain argues that Haeckel’s tree illustrations depict lines of descent based on protoplasmic lines or waveform movements (99-101). Other art historians argue that Haeckel’s illustrations emphasized harmony, order, and progressive evolution (Morton 62), and suggested that the characteristics acquired during the life of an organism could be passed on to its descendants (Simpson 229-230). None of these themes are found in Darwin’s theory, and in fact contradict important elements of it.

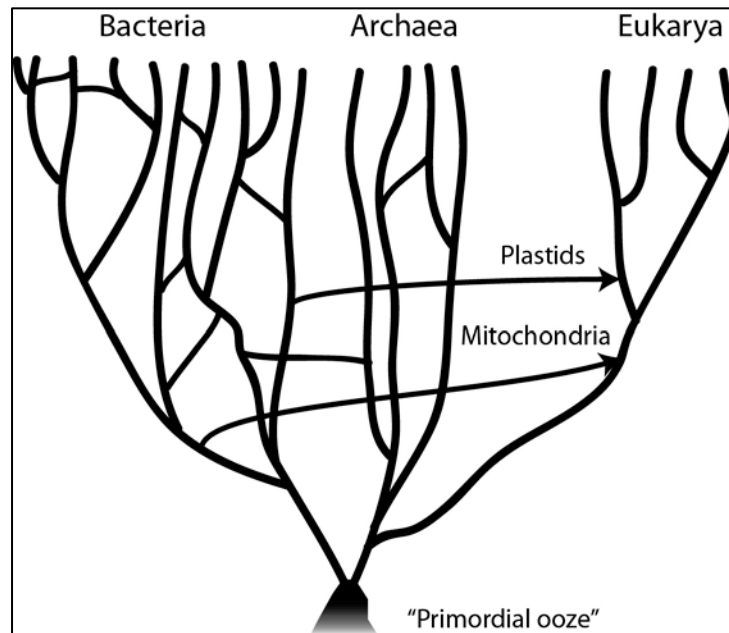


Figure 5: Horizontal gene transfer's effects on the tree of life

Like any metaphor, the tree of life has certain limitations or can suggest incorrect associations to its viewers; Haeckel's illustrations provide several examples of this problem. Darwin recognized some potential problems with his metaphor, like the trunk, typically depicted in pictures as a temperate deciduous tree such as an oak. Today, we are aware of additional limitations of the tree metaphor. One key example is the recent recognition of frequent examples of horizontal gene transfer among groups of organisms (Doolittle 94), which makes the "trunk" of the tree look nothing like a typical temperate tree trunk (figure 5). Horizontal gene transfer occurs when one organism obtains DNA from another, rather than acquiring DNA via inheritance from its parent(s). Examples of this include the transfer of genes affording antibiotic resistance among species of bacteria and the historical incorporation of entire bacterial genomes into eukaryote cells via organelles (mitochondria and plastids). In the concluding section of this

chapter, I will discuss several associations attached to the tree of life, and suggest areas of tension for using this metaphor in science communication.

Two distinct uses of the tree of life metaphor

Before discussing the metaphoric associations of the tree of life, I will distinguish between two distinct, though related, uses of this metaphor. The primary purpose of the tree of life is to visualize the branching pattern of evolution via shared descent. The first use of the metaphor is qualitative and impressionistic, as a representation of the overall pattern of evolution, or as a representation of the Natural System. The visual metaphor of shared descent is also used as a scientific hypothesis in quantitative studies of the relationships among organisms, called phylogenetics (Doolittle and Baptiste 2043). In this dissertation, I examine the ways that digital technologies let us rethink the metaphor of the tree of life in general terms, and do not propose to rethink the assumptions behind phylogenetic analysis. Nevertheless, the formal implications of the phylogenetic perspective add an additional layer of connotations to the less formal elements of the tree of life metaphor.

As one of the key contributions of modern biology to our understanding of the world, phylogenetics provides us with a way to explain the relatedness of species through a historical perspective based upon Darwin's idea of shared descent (Maddison *et al.* 20). The phylogenetic approach to classifying organisms lets us both explore relationships among living species and make inferences about the history of life. Prior to Darwin's publication of *Origin*, classification of species was based upon the recognition of "natural" groups, which were defined by having a suite of features in common (Stevens, "Metaphors and Typology" 171), rather than by inferred genealogical relationships. Phylogenetic tree diagrams, in contrast, present information about the

relationships between species. They also illustrate the history of evolution and carry specific formal implications about the represented relationships. The pattern of relationships in a phylogeny “reflects an underlying natural reality with a natural cause,” the cause is descent with modification, and natural selection drives this process (Doolittle and Baptiste 2044). These properties of phylogenetic trees are inherent in a less formal way in the tree of life as a general communication tool.

Affordances and associations of the tree of life

In one common explanation, metaphor works by facilitating the linkage of different concepts, either directly or through an associational link (Hellsten and Nehrlich 94). Associations between familiar and novel concepts help people memorize and contextualize new factual material. They also help link new ideas into emotional or affective frameworks.

In cognitive science, the theory of distributed cognition describes how objects and external representations, including verbal or visual metaphors, help structure internal mental models. In Chapter Three of this dissertation, I will discuss the theory of distributed cognition in detail. This theory distinguishes between three types of associations that are useful when describing the tree of life metaphor: affordances, constraints, and mappings (Norman 12). Affordances are “the perceived and actual properties of [a] thing, primarily those fundamental properties that determine just how the thing could possibly be used” (Norman 9). Affordances *suggest*; they are cues that help us make new associations. In contrast, constraints *limit*; they restrict the range of associations that we make when incorporating new concepts into our mental models. Finally, mappings are *sets of possible operations*; they help us determine how to manipulate our mental models of objects, as well as the objects themselves.

Several researchers have suggested a wide range of affordances and constraints of the tree of life metaphor (I will discuss associational mappings in Chapter Three, in the context of cognitive research on evolutionary education). While the following list is not exhaustive, it touches upon some of the implications of this metaphor for public understanding of evolution, and highlights several areas of tension when using the tree of life in science communication:

- **Common descent:** The overall pattern of growth of the tree illustrates shared descent: the idea that species arise over time as they become differentiated from a common ancestor, and that species today are therefore related by those bonds of descent. Some specific tree illustrations, however, imply that branching (and by extension, evolution) occurred long ago, and does not continue to occur today. One example of this type of tree, by Darwin's contemporary, Edward Hitchcock, suggests "special creation" as the mechanism for branching, rather than natural selection (Archibald 582; figure 6). The latter example suggests that, while a tree motif illustrates the *pattern* of life we see today, it is not necessarily tied to the accepted *mechanism* that explains this pattern. Additionally, if branches arose from special creation, it is more difficult to use this metaphor to support common descent.

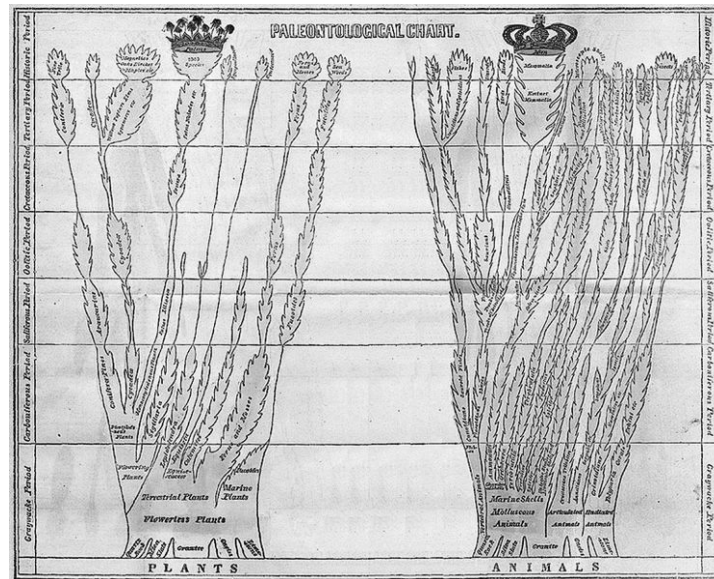


Figure 6: Hitchcock's paleontological chart of the Natural System, from *Elementary Geology*, 1840

- **Cladogenesis and anagenesis:** Branching in the tree illustrates cladogenesis (evolution by lineage splitting), which is an important component of evolutionary theory (Archibald 571-2). Darwin's original diagram published in *Origin* illustrates both cladogenesis and anagenesis (evolution within a single lineage; Costa 120). Anagenesis is more difficult to convey in a more representational tree diagram. For example, figure 6 could be interpreted as showing either anagenesis or simply the persistence of lineages that arose long ago without further evolution (i.e., "living fossils").
- **Time:** Darwin's *Origin* tree incorporates both spatial and temporal diversification of species (figure 1). His diagram more obviously uses the conventions of scientific figures, such as having meaning attached to differences in both vertical and horizontal dimensions, than later, more qualitative tree illustrations do. Perhaps the most obvious

example of this is the horizontal divisions through which the tree ramifies upward.

Darwin intended these divisions to represent either generations or epochs of geologic time (Darwin, *Origin* 124), depending on the context in which the reader was studying the image. In more qualitative diagrams that are untethered from this temporal dimension, the sense of time passing may become blurred.

- **Teleology:** A tree growing upward implies progress, improvement, and directionality. While the teleological explanation of the Natural System found in the *scala naturae* was replaced by the undirected tree metaphor, elements of teleological thought persist (O'Hara, "Representations" 262), even though contemporary evolutionary theory states that evolution does not perfect species or proceed in a specific direction. Robert O'Hara describes four narrative devices in trees that suggest teleology: directionality (e.g., in descriptions of existing taxa as "primitive" or "advanced"); "pruning" of the side branches to suggest a trunk or "main line" of evolution (e.g., leaving modern chimps off of a hominid tree that culminates in *Homo sapiens*); naming of certain derived groups within a lineage suggests that the larger group is more primitive (and implies stages in a narrative sequence, e.g., reptiles and birds); and differential resolution of different parts of a tree (e.g., incorporating more detail for mammals, vertebrates, or flowering plants than for other groups; "Telling the Tree" 144). Steven J. Gould points out a constraining feature in evolutionary trees that he calls the "cone of increasing diversity;" this results from depicting an overall pattern of diversification of lineages from an ancestral lineage (63). Gould argues that it is easy to conflate the vertical time axis with an axis of progress, and infer that one of the properties of evolution is a drive toward diversity (65).

He argues that this bias in interpretation can partly be avoided by depicting extinctions of lineages, but that even this fails to take into account the working of random chance in “determining” which taxa become extinct (67).

- **Nature of evolution:** The metaphor of the tree growing and branching as time goes by can provide a narrative of evolutionary history. Robert O’Hara suggests that evolutionary trees serve as chronicles (descriptions of a series of events without causal explanations), upon which we can base evolutionary histories (which do include causation; “Homage to Clio” 144). Evolution incorporates two components, descriptions of change and the mechanism of descent with modification (de Queiroz 245); these components are often differentiated in biology education as the fact of evolution and the theory of natural selection (e.g., Campbell and Reece 438). O’Hara differentiates between two types of explanations these components provide, respectively: “explanations of state” and “causal explanations” (“Homage to Clio” 147). He argues that, as evolution gains public acceptance, explanations of state (i.e., the idea that evolution *has* occurred) will become less necessary, and that causal explanations (i.e., descent with modification and natural selection) will become more prominent (“Homage to Clio” 150). Until that time, the tree-as-chronicle attesting to the historical fact of evolution is an important metaphor.
- **Tree trunk:** As discussed previously, the trunk of the tree of life is typically depicted as a single, thick woody stem. This depiction both hides the complex historical pattern of evolution (Costa 130) and suggests a “main line” of evolutionary progress (O’Hara, “Telling the Tree” 144). Extinct, fossil species are not accounted for in the tree; “at all levels, from the roots to the tip, the tree is alive” (Maderspacher R476).

- **Continuity:** Tree iconography can conflict with historical elements found in other types of depictions of the Natural System, but ones that remain culturally relevant today. For example, the *scala naturae* incorporated strong elements of continuity and symmetry (O’Hara, “Representations” 261, 265). In a preliminary exploratory study, I found that individuals were puzzled at the exclusion of these elements from an evolutionary tree, such as common ancestors for branching taxa. Tree-shaped diagrams represent a hypothesis of relationships, and the “branch points” are only very rarely identifiable entities. Where the *scala naturae* showed a continuous, though discrete, series of relationships, tree diagrams effectively show viewers a set of taxa connected by “missing links.”
- **Cultural associations:** In part, Darwin selected the tree of life metaphor because associations of the tree with culturally significant tree iconography helped promote acceptance of his ideas among natural historians and the public (Archibald 570). Pedigrees and family trees, for example, were an accepted form used to depict shared genetic inheritance, and this association helped Darwin illustrate the ties among taxa in his trees. Cultural associations of tree iconography, however, might overshadow the scientific aspects of evolution that the metaphor is intended to exemplify. For example, Nils Hellstrom suggests that *TREE*— an artistic illustration in the British Museum— is iconic because it relies on non-Darwinian cultural influences (e.g., Haeckel’s drawings, the symbolism of oak in Britain, trees in religious stained glass, and Christmas trees). While these cultural associations may have affective impact and “remind us of our humble place in this world and... inspire reverence,” (13) they do not necessarily lead to

an accurate picture of evolution. Robert O'Hara points out that the comparison of evolutionary trees with family trees can be problematic, because of the lack of a sense of closure. In evolutionary trees, subjects are clades (ancestor-descendant lineages), rather than individuals. At any given point along the evolutionary tree, the subject is different from the one we started with ("Homage to Clio" 152); O'Hara suggests that this lack of closure can lead to teleological thinking and the construction of narratives of progress ("Homage to Clio" 152).

- **Pattern pluralism:** Recent research in molecular biology, particularly biology of prokaryotes (bacteria and archaeobacteria), shows that gene transfer between species (for example, during bacterial conjugation) is an important mechanism for evolution. This horizontal gene transfer creates different phylogenetic patterns of descent than the hierarchical pattern of "vertical" gene transfer that results from descent from parent to child (e.g., figure 5). In many cases, phylogenies based on different genes result in different evolutionary trees, even among the same species (Doolittle and Baptiste 2046). Plants provide another example of a complex pattern of evolution, involving hybridization, self-fertilization, and polyploidy (formation of a new species by internal doubling of chromosomes). After *Origin of Species* was published, botanists struggled over fitting traditional methods of plant classification into a hierarchical structure of relationships (Stevens, "Metaphors and Typology" 188-190). Some researchers suggest that the metaphor of tree-like relationships might be appropriate for some taxa (e.g., animals), but other should be reticulate (e.g., plants) or web-like (e.g., prokaryotes; Doolittle and Baptiste 2048); such an assortment would be called "pattern pluralism".

As the preceding examples illustrate, the tree of life metaphor highlights certain aspects of evolution while shadowing others. In the next chapter of this dissertation, I will examine the ways that technologies of representation and visual conventions help determine how the pattern of evolution has been historically presented, and therefore co-determine the affordances and associations that visual metaphors facilitate. Representational technologies can affect our interpretations of traditional metaphors, help us derive new metaphors for a traditional problem, and help spur the formation of new metaphors. Chapter Three describes the ways that two key aspects of digital technology— interactivity and visual design— can affect the ways we relate to computer-based visualizations. This chapter also uses the theory of distributed cognition to provide a framework to analyze the ways visual metaphors help us think.

CHAPTER THREE: VISUALIZATION TECHNOLOGIES AND CHANGING SCIENTIFIC METAPHORS

This chapter situates the practice of creating science visualizations within the changing field of digital technologies, and describes the ways by which changing technologies are being used to expand the range of metaphors that are available for science communication. I begin the chapter by discussing the relationship between metaphor and material technologies for science visualization. Next, I briefly sketch a history of the material technologies of visual representation, and describe how visual conventions can be constrained by representational tools.

In the second part of this chapter, I describe two key components of visualization research: interactivity and visual design. These components work together to facilitate meaningful action in the viewer's experience. Next, I discuss the theory of distributed cognition, which provides a framework to support research on how interactive visualizations can help users learn. New media theory describes two important properties of interactive media, transparency and hypermediacy, which describe how a visualization can either hide or foreground the theoretical and subjective assumptions that go into visualizations. Both distributed cognition and new media theory can be used to theorize the visual and interactive design choices that shape science visualizations.

The third part of this chapter focuses on representations of evolution in the context of the material technologies used to produce them. I first describe several major ways that the relationships between species were visualized in pre-Darwinian times, and then describe how these representations have changed as new representational tools have been developed. I then discuss contemporary digital media research on the visualization of evolutionary biology.

Finally, I summarize the theoretical concerns introduced in this chapter for development of evolution visualizations.

Scientific visualizations, metaphor, and technology

Visual representations are important aids to thinking about science, and are therefore important tools in science communication. Many well-known scientists, including Leonardo da Vinci, Albert Einstein, and Niels Bohr, extensively used imagery to support their scientific thinking (Trumbo 272). As discussed previously, Charles Darwin is another scientist who used imagery to support his scientific thinking. Various types of visualizations are important science communication devices in different circumstances. For example, graphs and charts assert relationships between the variables being represented, while photographs can serve as visual evidence of conditions at a field site. Learning how both to interpret and to create visual representations is an important element in formal science education (e.g., Pea, “Augmenting;” Roth and McGinn).

Many scientific visualizations suggest metaphoric affordances or mappings, at least on some level. In one anecdote, during the mid-Nineteenth-Century Friedrich Kekule was struggling to picture the chemical arrangement of carbon and hydrogen atoms in the chemical benzene. One night, Kekule dreamed of an Ouroboros, and awoke with the inspiration that this molecule was shaped like a ring (Trumbo 272). While the benzene ring as Ouroboros is a largely metaphorical image, other scientific visualizations are more analogical in nature. Analogical images allow us to make explicit, predictive connections between the image and the object or system being represented (Genter *et al.* 5). A common image of the analogical type is the model of atomic structure that depicts electrons orbiting the nucleus of an atom as planets orbiting a star. In both

of these models, one set of objects is constrained by some force to orbit another object, though both the objects and the forces are different. Finally, one specific group of scientific images includes primarily spatial metaphors in which proximity is used to represent non-spatial concepts. One example of a spatial visualization of non-spatial information is the Hertzsprung-Russell diagram, in which stars are arranged according to similarities in brightness and temperature (figure 7). I will discuss non-spatial mappings in more detail in Chapter Four.

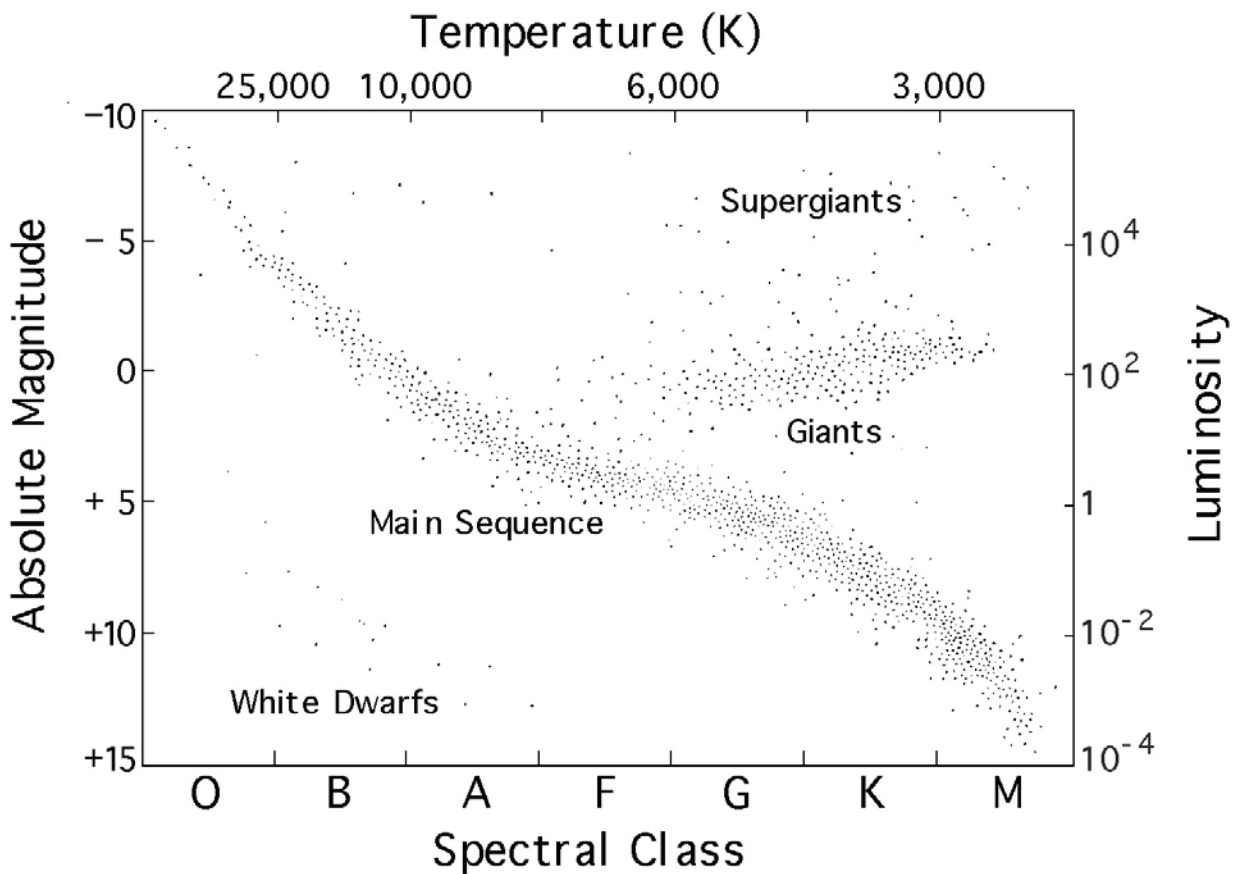


Figure 7: Hertzsprung-Russell diagram. From NASA, "Stars"

The material technologies available for creating visualizations place constraints on both how concepts are visualized to begin with and how they are ultimately depicted. Several examples of the interaction between technology, metaphor, and visualization can be shown from the development of digital tools for computation and visualization. Digital technologies allow us to interact with science visualizations, and any metaphors the images depict, in several ways.

First, digital technologies can enable the spread of images to new audiences in new settings, and proponents of informal science education recognize that digital media increase the geographic and social reach of these projects (Bonney *et al.* 37; Friedman *et al.* 24). For example, an image posted on a science-oriented blog might be seen by viewers with an active interest in science. If a viewer then shares the image on a social networking site, as is a current trend on Facebook and Google+, its potential audience expands to include a wide range of individuals who might not normally be interested in the topic. This type of sharing via social circles contrasts with traditional contemplation of scientific images as a solitary individual reads a book or a group of students is taught in a formal educational setting.

Another way that digital technologies interact with metaphor is by influencing our interpretations of traditional metaphors, or even helping us derive new metaphors for a traditional problem. For example, our familiarity with computers as programmable “thinking machines” has led to the creation of a metaphor for human consciousness as a machine, arising from a set of executable programs. Sherry Turkle makes a distinction between two types of programming as metaphors for human consciousness: “top-down” rules-based programming that operates in a hierarchical environment, and “bottom-up” flexible programming that emerges as a result of the combined effects of many small programs (20). This latter approach to

programming is currently favored as a model for human consciousness (Hayles 53). In this model, intelligence emerges from a set of semi-autonomous, flexible algorithms, rather than a rigid, rule-based structure.

Finally, digital technologies can help make us aware of aspects of an object or concept that we had been unaware of previously, and so help spur the formation of new metaphors. One such technology is digital gene-sequencing tools, which are used to help identify molecular markers in forensic investigations. Such “genetic fingerprinting” is frequently referenced in the news media and on popular television shows, and may help explain why students in one study referred to DNA as an identifying marker for individuals rather than as the carrier of heritable information (Venville, Gribble, and Donovan 90).

Material technologies of representation

Visualizations are inherently social objects, in that they are designed to communicate ideas about science with others (Pauwels 12). In the tradition of visual rhetoric, social and community conventions guide both the creation and interpretation of visuals (Kostelnick and Hassett 25). In the statistical information design tradition, researchers suggest that information design is universal like mathematics, rather than culturally specific like language (Tufte, *Visual Display* 10). The latter position does not imply that *no* interpretation is necessary to understand visual representation, but that once learned, visual conventions are stable across community boundaries. Regardless of the magnitude of the social nature of visual language, visual conventions can be constrained by the material tools with which we produce, disseminate, and store visual representations (Kostelnick and Hassett 106).

Technology can stabilize existing visual conventions by constraining design choices or destabilize conventions by affording opportunities for innovation (Kostelnick and Hassett 109). The effects of this process can occur at several levels of scale. For example, the transition from manuscript- to print-based writing in Europe stabilized conventions such as consistent length of lines of text, while destabilizing the practice of marginal commentary by scribes (Ong 120). At the level of individual expression, Elizabeth Eisenstein argues that the concept of style in forms as diverse as handwriting and architecture underwent a profound shift when standardized printed examples against which to compare personal efforts became available (53).

Works created using new technologies frequently employ existing conventions for a time as the technologies themselves gain acceptance within a community. Once a critical level of acceptance is achieved, designers can be more creative in their uses of the technology (Kostelnick and Hassett 109). For example, scientific wall charts for German classrooms illustrating various biological objects arose, in part, because of advances in printing technology (Bucchi, "Images of Science" 105). As these charts gained widespread use, their iconography expanded to include depictions of scientific classification, ecological and physiological processes, and appropriate behavior for students when interacting with nature (Bucchi, "Images of Science" 98).

**IDE'E D'UNE ECHELLE
DES ETRES NATURELS.**

L'HOMME.
Orang-Outang.
Singe.
QUADRUPEDES.
Ecureuil volant.
Chauvefouris.
Autruche.
OISEAUX.
Oiseaux aquatiques.
Oiseaux amphibies.
Poissens volans.
POISSONS.
Poissens rampans.
Anguilles.
Serpens d'eau.
SERPENS.
Limaces.
Limaçons.
COQUILLAGES.

Figure 8: Portion of the Great Chain of Being, by Charles Bonnett, *Traité d'insectologie*, 1745

Within disciplines, new conventions arise via adaptation of existing conventions, borrowing conventions from other disciplines, and codification of conventional practices (Kostelnick and Hassett 127). For example, the philosophical tradition in early Eighteenth-Century natural history was to arrange species in a linear and hierarchical Natural System called the Great Chain of Being or *scala naturae* (figure 8). By the mid-Eighteenth Century, the explosion of knowledge in the field of botany led scientists such as Linnaeus to begin to classify

communication has influenced the design conventions and distribution of science-related visuals. Interactivity and visual design, also important aspects of computer-based visualizations, will be discussed in the next section of this chapter.

Computer-based analysis provides the computing power that enables various types of large-scale statistical calculations that underpin scientific visualizations. The effects of fast and relatively error-free computing power, however, reach beyond statistical calculation and improved methods of data display, and influence scientific frameworks. For example, the discovery of horizontal gene transfer early in the history of life (see figure 5) has been facilitated because of computer-related advances in genetics, such as computer-controlled methods for large-scale gene sequencing and the development of massive interactive databases for storing gene sequence data.

Similar developments in computing allowed biologists to include genetic distance, as well as physical or chemical characteristics, in phylogenetic analyses. For example, figure 10 is a phylogram, a taxonomic tree in which each horizontal “branch” corresponds to one group of birds, and in which the length of branches corresponds to the amount of genetic change that has occurred in that group since it split off from its closest related “sister” group. More pertinent to this project, digital visualization tools provide the computational flexibility that, along with modern statistical methods, allows us to move beyond traditional hierarchical phylogenies as the basis for exploring relationships among biological groups.

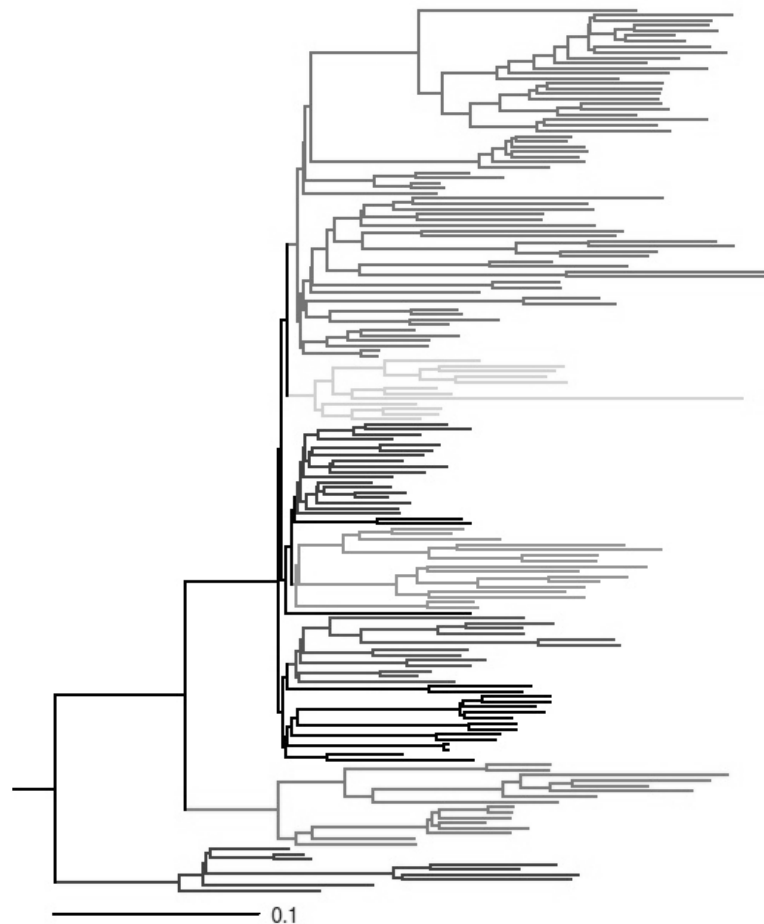


Figure 10: Phylogram showing the relationships among avian groups and genetic changes within groups. From Hackett *et al.* “A Phylogenomic Study of Birds Reveals Their Evolutionary History.” *Science* 320.5884 (2008): 1763-1768. Reprinted with permission from AAAS

Unlike the fields of study that preceded it, alchemy and astrology, early science in the late Seventeenth Century was distinguished by its openness. Early scientists communicated with one another and shared knowledge, rather than couching their texts in mystical trappings and recording their thoughts in obscure codes. These early scientists communicated with one another in what would be called a “Republic of Letters,” sharing information in vernacular languages across national and religious boundaries (Schiele, “On and About” 94).

Today, digital media are clearly becoming catalysts for widespread changes in science communication that are opening up scientific culture and discoveries beyond the science community. The Internet is as a crucial a medium for communication within science as it is in the broader public sphere; Brian Trench calls it the “engine of science” (“Internet” 185). Networked media allow individuals and institutions to share and comment on science visualizations across barriers of space, time, and community. The Internet offers affordances that promote communication and dialogue among scientists and the general public, while eliminating some traditional constraints for dialogue like distance and temporal coordination. Examples of open communication methods include (but are certainly not limited to) science blogs, podcasts, “Ask a scientist” websites, and digital archives for raw scientific data and published papers.

Contemporary information visualization research

In this section, I will focus on two key elements of research in interactive media: visual design and methods of interactivity. These elements interact to form the dynamic structure of visualizations, and both have important places in the design of digital media (Yi *et al.* 1224). For example, new media theorist Lev Manovich focuses on the computer interface as the site of human interaction with the databases that drive the functions of digital tools. Interfaces are important because they mediate human interactions with the database through a virtual navigable space (214). Other researchers, such as Katherine Hayles, highlight the ability of the interface to create an emergent space of shared agency. In this representational space, the actions of the human user and machine programming interact to create a hybrid experience of electronic literature (136). It can be challenging to tease apart the visual and interactive elements of interfaces because of the many tight linkages between them.

Two primary areas of inquiry contribute to our understanding of these elements, information visualization research and critical studies of new media. While these fields have large areas of overlap, I wish to point out here that they have somewhat different foci of study and methodology. While there are certainly many exceptions, information visualization research tends to be experimental and focuses upon data displays in both traditional and digital media. Critical studies of new media tend to be theoretical and centered upon digital media. I will draw from research in both of these fields in this part of the dissertation.

While the immediate content of pictures is more quickly grasped than that of words, many images convey information that less precisely than words do (Headrick 98), though both words and images span a range of usage from precise realism to abstract expression. The contemporary field of information visualization research focuses upon creating images that convey information efficiently, precisely, and accurately. This field draws strongly upon traditions of data display developed to present social and natural science information. Many types of visual displays, including a wide variety of tables, charts, and maps, have been developed expressly in order to increase the efficiency and accuracy of handling information (Headrick 6). Historically, this process dates to the Eighteenth Century, during which there was movement from “a descriptive or narrative visual language...to a scientific system of showing data visually” (Headrick 133). While the following discussion primarily includes examples from the field of technical and scientific illustration, visual design is also a prominent area in the field of digital visualization research (Yi *et al.* 1224).

Contemporary visual design theorists such as Edward Tufte emphasize both cognitive science and aesthetics (Grady 232). In his approach, Tufte offers several general principles for

visual design, which he then applies to specific situations (Grady 225). Three of his principles are using the “smallest effective difference” (making visual distinctions clear yet subtle), visual parallelism (*Visual Explanation* 73, 82), and layering of information (*Envisioning Information* 61). Tufte’s visual design rests upon the contextual interplay of visual elements that create visualizations with a high density of data. One of his axioms is “graphical excellence is that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space.” (*Visual Display* 51) Contemporary visual design is supported by research in human perception, which suggests that such features as color, relative quantities and sizes, proximity and direction of motion are processed pre-consciously in the mind, and thus are very efficient for encoding information (Card, Mackinlay, and Shneiderman 30).

Other researchers caution that the predominant trend in visual design toward efficiency, precision, and accuracy hides the socially constructed subjective decisions taken to produce images in a seemingly objective message (Dragga and Voss 266). Truth claims in scientific images such as maps and charts largely rest upon non-visible factors such as sampling and classification methods, as well as statistical analysis. These systematic procedures are frequently inferred to lead to “true” results (Rose 154). The use of formalized grids and charts in visual design is also a rhetorical appeal to scientific authority (Drucker and McVarish 254). Dragga and Voss suggest that the primary ethical focus for data visualization practitioners and theorists is the avoidance of misrepresentation and deception. They argue that this emphasis on factual accuracy omits the human element of data visualizations, creating “inhumane” graphs that, for example, bury the personal effects of disasters in emotionally neutral statistics (266). While their primary emphasis is on illustrations depicting harm to humans, they point out that adding quotes,

drawings or risk factors to a chart is “*statistically* redundant...but not *emotionally* redundant” (271; emphasis in original).

It is important to note that Tufte’s approach to visual design, while emphasizing efficiency, accuracy, and precision, also emphasizes that graphics can shape arguments. Indeed, graphics can form complex narratives, in which visual parallelism allows the viewer to draw analogies between components of an image (*Visual Explanation* 103). Tufte describes a class of images he calls “confections,” which “place selected diverse images into the narrative context of a coherent argument” (*Visual Explanation* 151). Confections are assemblages of “a multiplicity of image-events” assembled on “the still flatland of paper” (*Visual Explanation* 121). By using parallelism, layered meaning, and clear yet subtle visual distinctions, these visualizations construct rich narratives that go beyond the simpler arguments of graphs and charts. One example of a confection that Tufte discusses is the frontispiece of Thomas Hobbes’ *Leviathan*, by Abraham Bosse (figure 11). This image combines fantastical and allegorical images with a biblical quote that links the central figure, representing the monarch or state, to the biblical Leviathan. While Tufte largely, though not entirely, focuses on traditional media in his discussion of confections, there are some connections between his ideas and those of new media scholars; for example, in studies of hypertext and image juxtaposition (e.g., Bolter; O’Gorman).

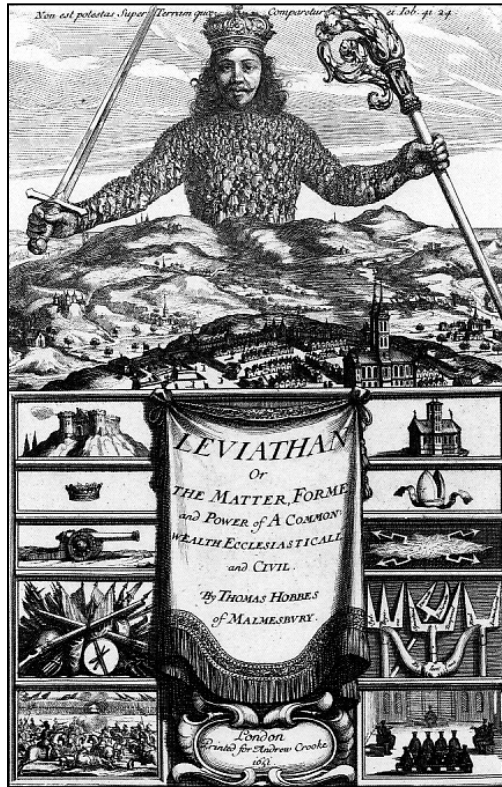


Figure 11: A visual “confection:” the frontispiece to Hobbes’ *Leviathan*, by Abraham Bosse, 1651

A different area of particular interest for contemporary new media scholars is interactivity. Literary theory suggests that all texts, whether composed in traditional media or new media, have at least some level of interactivity. In traditional media, for example, a text becomes interactive as readers bring their own expectations and mental associations into their interpretation of it. This level of interactivity is usually increased in digital media, which offer the reader a wider array of options for navigation and information retrieval (Bolter 122). More important than simple interactivity through navigation, however, is the ability of the viewer to take meaningful action through direct participation (Murray 74).

Meaningful action is important in an experiential sense because it can create a sense of shared agency between viewer and text, leading to a strong sense of engagement. It is important, however, to note that this shared agency implies that both the viewer and the text are being guided by each other. For example, interaction with digital media may guide and constrain the viewer's interpretations of the objects and concepts being depicted in subtle yet wide-reaching ways (Manovich 61). In the learning sciences, such constraints on interpretation are being harnessed to create interactive tools for learning. In the field of scientific "cyberlearning," defined as the use of "networked computing and communication technology to support learning" (Borgman *et al.* 5), the overarching goal is to facilitate lifelong science learning by using digital tools to redistribute learning over space and time (Borgman *et al.* 10). Cyberlearning tools can be used for both formal and informal learning, though the emphasis is on learning in informal settings. Borgman and colleagues suggest that one way to overcome current public lack of interest in science education, as well as to innovate away from an outdated science curriculum, is to take advantage of public interest in digital tools for informal science learning (12).

Meaningful action is not necessarily enabled by interactivity *per se*, but by specific types of interactivity. Yi and colleagues classify types of interaction by how they facilitate user intent, thus providing a user-centered taxonomy by which to understand interactivity (1226). In order to facilitate meaningful action, their taxonomy suggests that the type of interactivity should be appropriate to the task that the user is trying to accomplish. For example, if a viewer is interested in the specific details about one point in a data display, it would be more appropriate for her to select and elaborate on that one data point, rather than generate a web of associations between that data point and others.

One final aspect of contemporary visualization research that blends design and interactivity is the study of narrative structure in visualizations. Many complex visualizations have narrative structure, whether this arises from eye movement across a single scene, from more structured scene transitions as in comic books, or from temporal transitions in animated media (Segel and Heer 1140). The elements in visualization narratives can be characterized along a continuum of author-driven (linear ordering, heavy messaging, and no interactivity) to reader-driven emphasis (no prescribed ordering, no messaging, and free interactivity; Segel and Heer 1146). Segel and Heer suggest that visualizations are most effective when a mixture of these elements is used, such as by providing a brief linear introduction before opening up the interaction to allow more reader-driven interactivity (1146), or by providing a more exploratory space for interaction that is constrained at key points in the narrative (1147).

The theory of distributed cognition and representations of science

Visual and interactive design can make visualizations engaging and create a space of guided interaction through a narrative. Cognitive learning theory suggests that, in addition to being empowering or intriguing for the viewer, interactive texts help people learn. In this view of learning, our sensory perceptions are given meanings by our minds, and then these meanings are used to construct mental models of memory. Within cognitive science, the actual structures of mental model frameworks are debated. One constant in this discussion is that mental representations are organized into some sort of units (e.g., concepts or “nodes” of meanings) with a relational structure linking them (Nersessian 394). Learning takes place when people add new concepts to their mental models or create new connections linking different concepts.

The theory of distributed cognition suggests that external representations (e.g., diagrams or tools) let us extend our cognitive capacities (Nersessian 405). This approach builds on research that suggests that people complete tasks more quickly and accurately when assisted by external representations than when relying on abstract mental models alone (Liu *et al.*; Zhang and Norman). According to this theory, both tools and visual representations incorporate affordances that suggest appropriate actions to the user or viewer, as well as constraints that limit inappropriate actions (Zhang and Norman 117). Our tools effectively become knowledge-storage devices, which we then access as we learn how to use them. In other words, our tools become external adjuncts to our mental models.

Distributed cognition assumes that tools and visualizations become external memory supports (Nersessian 405) and reorganize our mental functions (Pea, “Practices” 57). It is easier for the mind to use visible cues to help it make situation-specific decisions than to first incorporate those cues into a mental model, and then make a decision (Zhang and Norman 116). In effect, external visualizations become part of our thinking process in a coupled cognitive system (Zhang and Norman 116). This theory provides a useful framework for visualization research, because it suggests that interaction with visualizations helps people learn (Liu *et al.* 1178). Such interaction can amplify cognition by enhancing calculating power, simplifying searching, facilitating pattern recognition, and providing a medium that allows manipulation of data (Card, Mackinlay, and Shneiderman 16).

The theory of distributed cognition also provides a framework for examining the affordances and constraints of visual metaphors for communicating about evolution. It distinguishes between three types of cognitive associations: affordances, constraints, and

mappings (Norman 12). Affordances are cues that help us make new associations, constraints restrict the range of associations that we make, and mappings help us determine how to manipulate both physical objects and our mental models of objects.

Different types of science visualizations can have different cognitive effects, based upon the affordances and constraints built into diagrams and symbol systems. For example, Arabic numerals are much easier to use for math than Roman numerals, even though the same concepts are being represented (Zhang and Norman 89). Interactive visual modeling tools are highly useful for mapping causal relationships onto mental models of science. For example, Roy Pea suggests that visual modeling tools be incorporated into classroom “learning conversations” about science (“Augmenting,” 316). Such tools can facilitate students’ production and interpretation of visualizations, as well as help them create “sense-making” (causal) narratives of the processes being depicted (326).

Visual transparency, scientific objectivity, and interactive media

One important aspect of science visualizations that is of concern for the cognitive learning framework is the widely varying nature of visualization referents. The nature of scientific referents falls on a continuum from material, physical, and directly observable to purely mental or conceptual (Pauwels 4). As referents become more esoteric and conceptual, the challenges for visualization increase. The ability to “convert” images between forms of representation, for example, from a chemical equation to an active molecular structure, is a difficult skill for science students to learn (Gilbert 6). Even when depicting directly observable referents, the artist makes a host of methodological, artistic, and theoretical choices. As Catherine Elgin describes this issue:

Science, we are told, is (or at least aspires to be) a mirror of nature, while art imitates life. If so, both disciplines produce, or hope to produce, representations that reflect the way the mind-independent world is. Scientific representations are supposed to be complete, accurate, precise and distortion-free. Although artistic representations are granted more leeway, they too are supposed to resemble their subjects. Underlying these clichés is the widespread conviction that representations are intentional surrogates for, or replicas of, their objects. If so, a representation should resemble its referent. This stereotype is false and misleading. (1)

Scientific representations tend to oversimplify the nature of the concepts they represent, subsuming methodology and theory into precise visual statements. This effect is particularly problematic when a non-specialist audience interprets them. Early scientific thinkers believed that it should be possible for the scientist to clear his mind of all subjective impressions that cloud his vision and thereby come to understand the truth of the world (e.g., Bacon 745). The “stereotype” Elgin describes is in keeping with this traditional philosophy of scientific objectivity, which regards science as a process of seeing the world more clearly, as though through an unclouded window. It is important to note that the view of scientific objectivity itself as based upon minimal mediation between the world and the observer is regarded as naïve among modern scientists, although this naïve conception of “science” is held by most non-scientists (Kuhn 126; Popper 8).

The modern understanding of scientific objectivity rests upon the intersubjective interpretation of a given concept among the scientific community, using standard methods of testing and validation (Elgin 14). The visualizations that result from this process are subject to

testing and revision, though this process is not apparent in the images themselves. Elgin goes on to say:

Since the same representation might be deployed by communities governed by different norms, a single representation may be objective when functioning in one context and subjective when functioning in another... When an illustration of a machine functions as a scientific representation, as it does in a science museum, features such as gear ratios are exemplified. When it functions as a work of art, as it does in an art museum, features like shading and delicacy of line are exemplified. The representation has all of the features each interpretation focuses on. But when interpreted against a background where different interests and values predominate, different features stand out. (15)

An image interpreted in one way in one scientific context can be interpreted in a very different way in another context. If the scientific and artistic decisions underlying the image are not available to the viewer, misinterpretation can result.

Many new media researchers describe the issue of media and representational practice as a relationship between transparency and hypermediacy. There is a tension within representation between the desire to minimize the reader's consciousness of the medium and to foreground the information being communicated, and the desire to emphasize the medium itself (Bolter 25).

Transparent representations deemphasize the medium of representation and highlight the information being represented. Some texts are designed for transparency, such as technical prose, graphs, charts, and contour maps. These textual forms are traditionally linked to scientific representations (Headrick 98), and design guidelines for them urge subordinating artistic considerations to communicating information clearly (Tufte, *Visual Display* 181). Such

conventions, however, obscure the underlying assumptions and processes that go into creating visualizations (Kenney 101).

In hypermediated representations, the reader's experience and awareness of the medium should be paramount. Hypermediate textual forms call attention to their own means of production, and include experimental typography (O`Gorman 36), "playful" graphs like those found in the *USA Today* newspaper (Bolter 53), and electronic literature (Hayles 43). The tension between transparency and hypermediacy can be brought to the fore in digital media, which allow the creation of works that oscillate between these two conditions (Bolter 185). For example, hypermediacy can be achieved by making the mathematical terms of an educational simulation visible and manipulable to users, and transparency can be achieved by simply rendering the results of the simulation in an animation. Bolter describes this shift in attention as the difference between looking *at* and looking *through* the representational medium (137). Within the context of science communication, the use of such a simulation might help a viewer critique the naïve notion that the visualization is a non-mediated, transparent view of reality.

Digital media can provide a useful space to explore the ways in which scientific representations are not transparent. For example, the scientific elements of a representation can be linked to information describing the phenomenon being depicted in more detail, such as research results supporting a data point, or a detailed explanation of the algorithm that links the underlying database with the user interface. The interface might also be designed to enable exploration of the metaphoric aspects of the visualization, for example, by comparison of the differences between the concepts that the metaphor is comparing. The artistic elements of the visualization could be explored in a similar fashion.

Material technologies and representations of evolution and the Natural System

Before discussing contemporary digital media research on evolution visualizations, I will briefly summarize historical visualizations of evolution and the Natural System in the context of the material technologies used to create them, and discuss the effects of digital technologies on visualizations of evolution. I will focus upon two primary types of tools that affect visual design: tools for representation and tools for calculation. Together, these tools interact with developments in visual design theory and facilitate innovative visualization approaches.

By the Eighteenth Century, the available media for natural historians interested in depicting the Natural System included pen and ink, as well as a variety of printing technologies. Pre-Darwinian depictions of evolution took a wide variety of forms. Older depictions were largely hierarchical, like the *scala naturae* (figure 8). During the early Eighteenth Century, geometrical depictions of the natural system, called “quinarian” because their creators believed that all biological groups could be placed into five-member circles of affinity (figure 12), reflected a growing awareness that life was too complex to be placed into a single hierarchy (O’Hara, “Diagrammatic” 2747). These maps provided a regular ordering system for living things, and even predicted groups that had not yet been discovered (see question marks in figure 12).

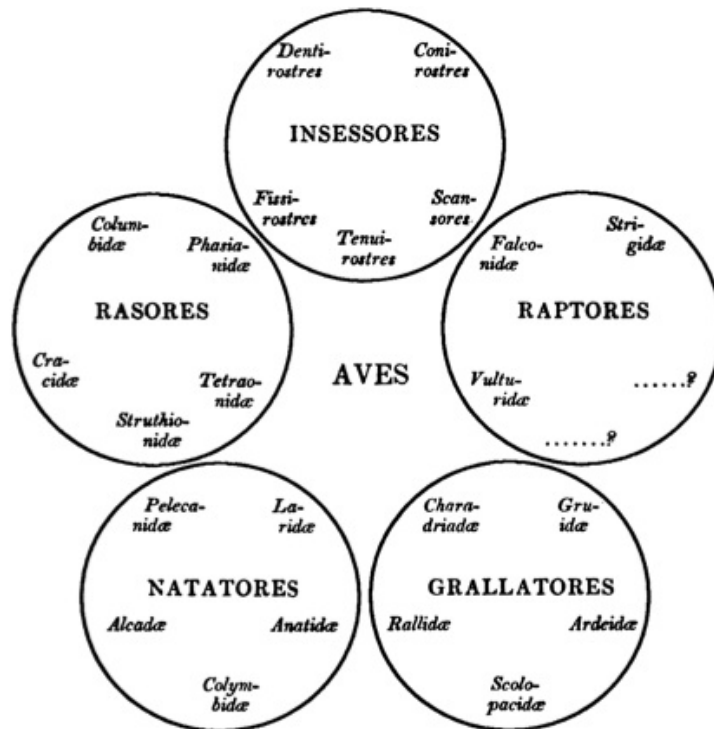


Figure 12: “Quinarian” circles of affinity connecting groups of birds, by Vigors, “Observations on the Natural Affinities that Connect the Orders and Families of Birds,” 1824

By the mid-Eighteenth Century, the conceptual constraints of quinarian visualizations began to prove too limiting for the variety of biological groups that were being classified (O’Hara, “Diagrammatic” 2749). Relationships among groups were proving to be neither symmetrical nor easily fit into strictly hierarchical space, and map-like depictions of the Natural System came to be favored (e.g., figure 9). In these early map-like visualizations, the distance between biological groups on the map became representative of the degree of “affinity” of the groups in the biological sense. Robert O’Hara argues that these map-like representations helped Alfred Russel Wallace, Darwin’s contemporary and co-proposer of natural selection, develop his

evolutionary view of nature at a macroscopic scale, while his work on species-level biology influenced his evolutionary views on a smaller scale (O'Hara, "Diagrammatic" 2751).

After Darwin and Wallace published their works on natural selection, shared descent became the crucial mechanism underlying the pattern of the Natural System; visualizations of the Natural System now also depicted evolutionary theory. As discussed in Chapter Two of this dissertation, tree-like visualizations became the dominant visualization types for evolution, particularly for trees depicting animal relationships. Within the field of botany, however, visualizations often had more complex reticulate (rather than branching) structure because of the ease with which plants hybridize with one another, as well as because of difficulties in determining shared ancestry among plant groups (Stevens, "Metaphors and Typology" 187-189). Figure 13 depicts the evolution of one lineage of plants in three dimensions: a genealogical tree shows plant relationships, while the position of lineages where they intersect a plane shows how closely extant plants are related and dotted lines show where hybrids between groups exist.

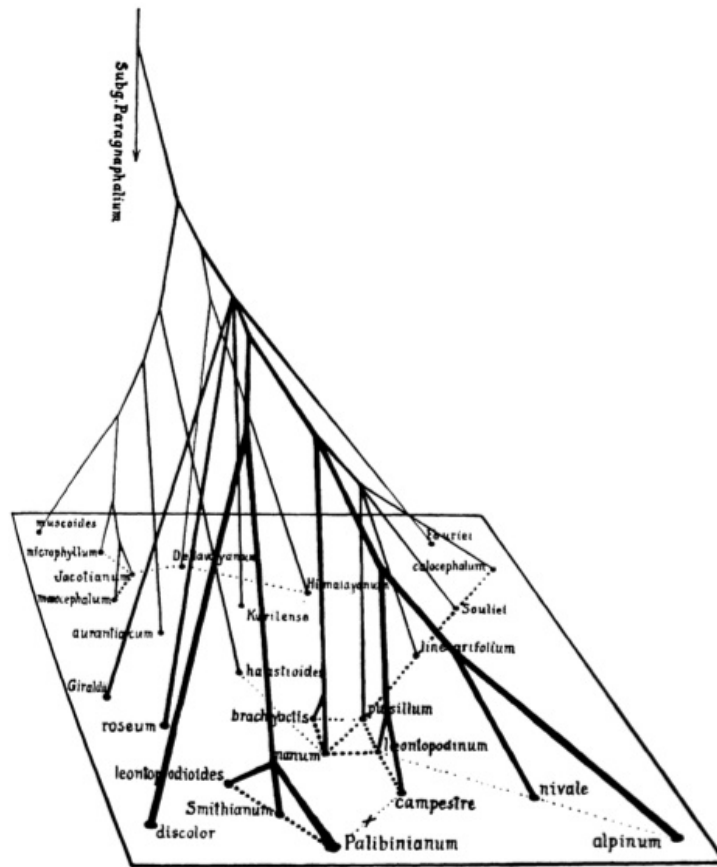


Figure 13: Evolutionary tree and similarities between plants in the genus *Leontopodium*. From Handel-Mazzetti, *Systematische Monographie der Gattung Leontopodium*, 1927

In addition to visualizing the crucial concept of shared descent among the twigs of the metaphorical tree of life, the tree metaphor allowed early illustrators to evoke the concept of change through their static images. The growth of a tree from seedling to sapling to mature adult allows a metaphorical mapping of growth and change of biological lineages over time onto the image of a tree. Growth and change over time were important components of Darwin's early tree-like visualizations of evolution (see figures 1 and 2), in contrast to the unchanging hierarchies and geometric visualizations of created biological groups.

Early quinary, map-like, and tree-like visualizations of evolution differed in theoretical assumptions, but all shared common technologies of representation. Changes in technologies of representation, such as film, have allowed artists to incorporate techniques like animation into their visualizations. While animation is, perhaps obviously, a powerful technique for showing change over time, sequential genres of visualization like comics stretch the capacities of traditional still media to show the passing of time while still using traditional media (McCloud). More recently, digital technologies have greatly expanded the range of graphical tools available for artists depicting evolution. The aspect of digital technology that has most likely made the greatest impact upon visualizations of evolution is the ability to make such depictions interactive for their viewers. I will discuss examples of contemporary interactive evolution visualizations in the next section of this chapter.

The second area in which technological developments have driven large changes in representational practices in biology is computation. Computation underlies all digital processes, and so is an essential part of visual display, interactivity, and communication. In this section, I focus on material tools to assist in mathematical calculation, so am using this term in a narrower sense.

In the Eighteenth Century, calculation aids such as Napier's bones, slide rules, and logarithmic tables were widely available to biologists. For example, Alfred Russel Wallace describes using a slide rule as a boy (Wallace 136). More complex analog calculators were available beginning in the Nineteenth Century ("Arithmometer"), but these were probably not as widespread. It is likely that such tools played a minor role in visualizing the Natural System. Natural historians of this period used mathematics for calculating ecological carrying capacities

and sizes of populations, but the bases of representations of the Natural System were more philosophical or narrative than mathematical.

Mathematics plays a much larger role in modern phylogenetic trees. Today's representations of evolution are largely based upon statistical inference, and require calculations of similarity of multiple different traits per biological group. In a standard "cladistic" analysis, each trait is weighted based upon whether the trait is derived (unique to that group) or ancestral (shared within a cluster of related groups). Phylogenetic trees are constructed by parsimony analysis, which compares many possible tree-shaped patterns of relationships to find the tree that requires the least number of changes in the state of traits among groups in order to arrive at the final pattern. When constructing trees based on large datasets, such as the analysis of avian orders by Hackett and colleagues that this dissertation utilizes (see figure 10), calculations are complex enough to require access to a supercomputer.

This method of phylogeny construction is quite different from those used prior to the publication of *Origin* in three ways. First, it is based upon the assumption of shared descent (Stevens, "Metaphors and Typology" 171). While early visualizations displayed affinities and differences among species, there was no theoretical framework of inferred genealogical relationships among groups. Second, cladistics differs in the material requirement of mechanical aid for calculation. This type of analysis was introduced in the mid-Twentieth Century, but did not become the predominant mode of phylogenetic analysis until the 1980s, largely because of the new availability of powerful desktop computers (Baron and Hoeg 7). A final important note is that while many post-*Origin* visualizations of relationships among organisms did share a theoretical framework of shared descent with cladistics, the resulting visualizations were based

more upon the subjective expert opinion of individual biologists, rather than on computation-heavy statistical analysis. Third, modern phylogenetic trees draw inferences from genetic sequence data, as well as other biological characteristics (e.g., Dyke and Gardiner; Kaiser and Dyke). Gene sequencing technology itself depends upon powerful calculating tools, so the range of evidence that informs modern visualizations of evolution is much wider than that which informed earlier visualizations of the Natural System.

Today, evolution through shared descent provides the theoretical framework that underpins biological science. The conceptual significance of this framework is the primary driver of preference for trees or tree-like structures as the conventional way to visualize evolution, regardless of medium of representation. Nevertheless, contemporary researchers have pointed out difficulties in using phylogenetic trees for teaching evolution, and are experimenting with different ways to visualize evolutionary patterns.

Contemporary digital media research on the visualization of evolutionary biology

In this section, I will briefly discuss contemporary research on learning using phylogenetic trees and current digital media research on alternative methods of visualizing evolution. Most cladistic phylogenetic “trees” developed today have little in common with early depictions of the tree of life, and are tree-like only in general outline. Many other tree-inspired representations of evolution, however, have stronger metaphorical ties to early tree representations like Ernst Haeckel’s (see figures 3 and 4). Such representations can be found in popular media, as well as in educational materials and museums (MacDonald 26).

Research in the learning sciences suggests that both static and animated phylogenetic tree and tree of life diagrams can foster misconceptions about evolution by readers (e.g., Catley,

Novick, and Shade; Matuk). For example, readers can infer cognitive mappings of cause and effect from diagrams, when no cause and effect relationship is intended. While tree-like diagrams of various types are useful for depicting common descent (e.g., Gould), their users can become confused about evolutionary mechanisms (Catley, Novick, and Shade 878). Design elements such as continuous straight lines may afford viewers the impression of continuity between ancestral and descendant species, when such a line actually represents a hypothesized relationship via many generations of reproduction (Novick and Catley 221). Finally, bottom-to-top and left-to-right orientation in trees can suggest teleological associations to viewers, although this effect can be countered to some extent if viewers are shown a tree that is animated “backwards,” from descendant species to a common ancestor (Matuk 397).

Contemporary digital media research that focuses on interactive representations of evolution is varied. It includes projects designed to improve information access, for example, providing users with an efficient means of linking information about species in databases with visual displays using phylogenetic trees (Maddison and Schulz) or hierarchically organized arrangements of groups (*Encyclopedia of Life*). Other projects focus upon making tree diagrams interactive in ways that might facilitate learning (Cranfill and Moe; Maroo and Halverson; Matuk and Uttal). None of these projects explicitly explores alternative visual metaphors to the tree of life, because they largely share an explicit focus of understanding phylogenetic uses of tree imagery (e.g., Maddison *et al.* 21).

Two large-scale online projects, the *Tree of Life* and *Encyclopedia of Life*, are currently being developed to let users explore life in various ways. Both of these sites are primarily text-based, though they do incorporate images in various ways. The *Tree of Life* primarily focuses on

evolutionary biology, and consists of a series of webpages that discuss the classification of organisms. On each page of the site, a small interactive phylogenetic tree is a linking mechanism that lets users explore textual and photographic information about biological groups (Maddison and Schulz). Users can click on branches to learn about the groups nested within higher-order branches, and work their way toward branch tips to learn about individual species. The *Encyclopedia of Life* differs in that its focus is exploring biodiversity, the geographical distribution and richness of organisms (*Encyclopedia of Life*). Users interact with its database primarily through species descriptions and location-based lists of species. The *Encyclopedia of Life* does not incorporate phylogenetic trees as the *Tree of Life* does. The *Encyclopedia* does, however, allow users to explore the hierarchical classification of individual species through a nested set of links. For example, users could explore each of the nested groups in which humans are classified by clicking on the links in the following list: Animalia > Chordata > Mammalia > Primates > Hominidae > Homo > *Homo sapiens*.

Several smaller-scale learning research projects have been described that focus upon evaluating the affordances of various types of interactive phylogenetic tree-based visualizations, and are being conducted as this dissertation is being written. In one project, visualization users rotate tree branches around their common attachment points while viewing the tree. This approach is designed to encourage users to read trees as branches connected by nodes with common ancestors, rather than reading trees by branch tips (Maroo and Halverson). Another current research project will explore ways to let users construct their own phylogenetic trees to represent evolution (Matuk and Uttal). The design of this second project is described as a three-dimensional space that lets users assemble personally meaningful narratives of evolution in the

form of interactive phylogenetic trees, with the intent of overcoming perceptual constraints of static representations of evolution. Both of these projects take different approaches than the research described in this dissertation: they primarily focus on tree visualizations and do not base their visualization designs on an analysis of metaphoric affordances.

Finally, a variety of methods have been explored for visualization of phylogenetic information using variations on tree structures. Many of these methods have been developed for use within the field of evolutionary biology, rather than for public communication of evolution. For example, trees can take the form of phylograms (figure 10) or have a radial structure (Carrizo 316). Interactive trees have been developed that allow the user to reorient the tree around a selected node or branch tip (Carrizo; Cranfill and Moe), highlight organisms related to a selected biological group, and make side-by-side comparisons of hypothesized tree arrangements (Carrizo). Savrina Carrizo outlines five categories of tree visualization problems: layout, labeling and annotation, navigation, tree comparison, and manipulation and editing (316). While some of these categories, such as annotation, comparison, and editing, are more of a concern for professional users of tree visualizations, the other categories are of broader concern within the field of visualization research in general (e.g., Yi *et al.*).

Theoretical concerns for the design of visualizations of evolution

As described in this chapter, digital technologies can be used to change the ways evolution is visualized by affecting several aspects of production: representational conventions, material capabilities for visual design, and interactive elements that contribute to meaningful action and narrative structure. Representational conventions include “holdovers” from historical practices of visualizing the Natural System, as well as more recent conventions that incorporate

crucial aspects of evolutionary theory. For example, one key theoretical concern for communication of evolution is the central importance of shared descent in any depiction of evolutionary pattern.

The field of new media research contributes to the design of evolution visualizations in two ways. First, new media theory suggests that interactive media can create a sense of shared agency through the meaningful interaction of the user with the visualization. This ability to take meaningful action can lead to a sense of engagement and interest in the user, both qualities that encourage meaningful science communication. Second, interactive media provide a useful space to explore the ways in which scientific representations are not simply transparent depictions of reality. Exploration of this space may help users construct a more nuanced understanding of the scientific decision process underpinning the pattern of evolution being depicted. Both scientific hypotheses and data displays have tentative characters, in that they are subject to revision when new evidence (or a new visualization method) is established. In their manipulability, interactive media provide a way for users to explore these characteristics.

The field of information visualization adds several empirical elements to the theoretical framework of new media studies. First, research on data display and usability informs aesthetic and structural aspects of visual design. Second, research on interactive elements suggests approaches for designing specific types of interactivity to support the overall narrative structure of more complex visualizations. Interdisciplinary information visualization research incorporates cognitive learning theory and aesthetics, and provides a framework for assessing the effectiveness of visualizations of evolution in an empirical setting.

The fourth chapter of this dissertation integrates these theoretical concepts with the discussion of metaphor in Chapter Two. The resulting synthesis is then used to guide theoretical choices in envisioning a new visualization for evolution, including the creation of the underlying metaphor, interaction method, and specific elements of the visual design. The second part of Chapter Four describes the technical methods used to construct the dynamic evolutionary map, including data sources and programming methods. In the final part of the chapter, I briefly describe the methods used to evaluate the resulting visualization.

CHAPTER FOUR: THE DYNAMIC EVOLUTIONARY MAP

In Chapter Three, I described several key concepts from the fields of new media theory, cognitive science, information design, and visualization research that inform the design of interactive visualizations. The fourth chapter of this dissertation integrates these theoretical concepts with the discussion of metaphor in Chapter Two. The resulting synthesis is applied to a specific empirical issue in science communication: the communication of the pattern of evolution. This chapter describes the choices that underpin different steps in the process of developing a new visualization for evolution, including the creation of an underlying metaphor and the visual and interactive design of the final construct. This process has resulted in the dynamic evolutionary map.

Chapter Four begins by describing how principles from several fields were used to guide theoretical choices in envisioning the visualization. First, the field of metaphor theory suggests ways that the conceptual affordances of evolutionary trees can be modified to create a map metaphor for the pattern of evolution. Second, the fields of new media theory and visualization research suggest design possibilities for elements of the visual style and the navigation method. Finally, evolutionary theory and learning research also inform the design of the map, such as the relative importance of various mechanisms that contribute to the theory of evolution and the current understanding of how visuals contribute to scientific understanding.

The second part of Chapter Four describes the technical methods used to construct the dynamic evolutionary map and presents the resulting visualization. This section first describes the sources of data for the evolutionary relationships that are depicted in the visualization and how these data were used to create the visual aspects of the map. Next, it describes the

programming methods used to create the interactive aspects of the visualization. The chapter concludes with a description and screenshots of the dynamic evolutionary map. The map itself is archived online and a link provided in this section of the chapter.

How can we change the “tree of life”?

The metaphors we use to communicate help us link different domains of understanding. They also suggest both affordances that help us make new connections between concepts and constraints that limit the range of connections we make. The tree of life has been a powerful central visual metaphor for the pattern of evolution and a communication tool for over a century and a half. Like any metaphor, however, it may suggest connections to its viewers that are invalid, based upon the current understanding of evolution. From the perspective of one art historian, “only in a very limited way do such important biological metaphors as natural selection or the struggle for existence give rise to pictures, and these are usually misleading.” (Ruse 76) The central purpose of this dissertation is to propose a method of visualizing evolution that uses a different underlying visual metaphor, a dynamic evolutionary map. This metaphor may provide a novel way of communicating about evolution that helps its viewers avoid some of the misconceptions suggested by the tree of life.

The first part of the theoretical basis for this new visualization consists of an analysis of the metaphorical affordances and constraints of evolutionary trees. The affordances of several graphical elements of tree-based visualizations were evaluated for possible inclusion in a map-like method of visualizing evolution. These elements were evaluated based upon how well they communicate the current understanding of evolutionary theory. Some of these elements were identified as important aspects of the theory of evolution that should be retained in the new

visualization. Another set of elements was identified as providing possible conceptual constraints that suggest misconceptions about evolution. These elements were altered in the visualization. Finally, a third group of concepts were identified as important components of the pattern of evolution, but were outside the scope of this project to address. As these affordances are discussed in the second chapter of this dissertation, I treat them briefly here.

The first group of visual elements from evolutionary trees that I will discuss suggests important evolutionary concepts. These elements were retained in the dynamic evolutionary map as much as possible. In trees, common descent is depicted by the branching pattern of tree limbs coming from a central trunk. In the dynamic evolutionary map, common descent will be represented by dots that split from a central origin, and then move across the map space in a radial pattern. Two evolutionary patterns, cladogenesis (evolution by splitting events) and anagenesis (evolution within a group), are suggested in trees by the pattern of branching and length of limbs. In the map, these patterns are depicted by movement: the splitting of dots represents cladogenesis and the movement of dots across the space represents anagenesis. Text elements accompanying the visualization also address these concepts.

Two important evolutionary concepts are present in evolutionary trees, but can be challenging to interpret. First, continuity from ancestral to descendant species is represented on trees by branch points, which can be interpreted as “missing links.” The dynamic evolutionary map attempts to preserve continuity more strongly by showing the motion of continuous dots across the map space. The text also addresses the concept of the most recent common ancestor between groups directly. Second, it is difficult to visualize the temporal aspect of evolution in a static diagram of a tree; one exception is Darwin’s tree from *Origin of Species* (figure 1), which

explicitly includes a temporal dimension. In the map, time is explicitly tied to the visualization through the animation, as well as through the text description.

The second group of visual elements suggests problematic concepts that can contribute to misunderstandings about evolution. The trunk of a tree can hide the ongoing branching pattern of evolution, and may suggest that evolution in the distant past proceeded through a set of different mechanisms than in the present day; alternatively, “pruning” of side branches can suggest a directional evolutionary trend. Several other aspects of trees can suggest teleology: descriptions of existing groups as “primitive” or “advanced,” labeling certain derived groups within a lineage while not labeling larger groups, differential resolution of different parts of the tree, and arranging the tree so that certain groups are on top of others. These directional aspects of trees are avoided in the map by animating the visualization in a radial pattern, as well as by the choice of language in text elements.

The third group of concepts includes several important aspects of evolutionary theory that are either difficult to address with this type of visualization, or are outside the scope of this project. First, the identity of the units that evolution operates on is the clade, rather than the individual. Since this visualization focused on the large-scale pattern of evolution, or macroevolution, the changing composition of groups of organisms was not addressed visually in the dynamic evolutionary map, though some text elements mention groups. A related limitation of this visualization method is the focus on evolutionary pattern itself, rather than the causal forces shaping the pattern. While the text addresses causal forces, these are not well represented by the visual elements of the map. Two additional issues relate to the pattern being depicted in the map: the evolution of one group of organisms through splitting and diversification from a

single origin to the present day. While this pattern is appropriate for the group being depicted, it perpetuates the depiction of evolution as a “cone of increasing diversity” (Gould 63). For example, it does not capture the complexity of the evolutionary pattern that includes extinctions that prune the tree over time. Extinction is largely addressed in the map within the descriptions of individual present-day orders, rather than by adding orders that are now extinct. Additionally, it does not include a depiction of horizontal gene transfer, which largely does not occur in birds.

A new evolutionary metaphor: the dynamic evolutionary map

After the desired affordances of the dynamic evolutionary map were identified, the visual style and navigational elements of the map itself, as well as the framework in which it is presented, were designed. There are three primary ways in which the overall visualization is designed to differ from traditional visual representations of evolution: the use of a map metaphor, animation, and semi-structured interactivity. The visualization also incorporates several visual design conventions that help users orient themselves to its operation quickly, so they can focus upon the message that is being communicated.

The map itself incorporates certain representational conventions of other evolutionary diagrams; for example, it evokes Sharpe’s affinity map of kingfishers (figure 9) and Handel-Mazetti’s diagram of similarities between plant species (figure 13). One important convention of the map from a scientific perspective is that the movement of the dots across the map space suggests shared descent, the key concept in evolutionary theory (Handel-Mazetti’s map is based upon shared descent, while Sharpe’s is not). Since shared descent occurs via branching events, it is difficult to depict it in a static diagram without evoking tree-like characteristics. In order to

illustrate this feature in the map, animation is used. This visualization option has been technically impractical until the development of modern computers.

The use of a map metaphor creates metaphoric affordances that necessarily differ from the affordances of a tree metaphor for evolution. In the previous section of this dissertation, I described how the affordances of this method of representation are designed to address some of the metaphoric limitations of tree representations. Broadly speaking, maps are graphical representations that use spatial proximity to represent similarities between objects. For most maps, the objects being referenced in the representation are physical objects in space, for example landmarks used to aid in navigation. However, not all maps refer to external reality or to concrete objects with spatial dimensions. The dynamic evolutionary map has some of the affordances and constraints of typical maps, but does not have others. I will return to this subject in the next section.

The interactive features of the map are designed to create a fairly open-ended narrative structure that enables the user to create her own narrative pathway, within certain constraints. This type of interactivity allows a fair amount of meaningful interaction with the visualization, while providing a moderately structured experience that emphasizes certain aspect of evolution. For example, users begin their exploration of the map at the point of the origin of birds, and first encounter a text sidebar that introduces the purpose of the visualization and instructs them how to use it. While viewers are not initially restricted to this introductory text, they can read it at any time using links on the top menu. Viewers may explore the map both diachronically, by moving forward and backward through time, as well as synchronically, within each timepoint. One important aspect of design is that, at each synchronic timepoint, only a few groups are linked to

textual information, which may help limit information “overload” as users construct their own narrative progress. These features attempt to balance user engagement and exploration while providing a message communicating evolution.

New media theory suggests that interactive media provide a useful space to explore the ways in which scientific representations are not simply transparent depictions of reality. This type of exploration may help users construct a more nuanced understanding of the scientific decision process underpinning the pattern of evolution being depicted. In order to achieve this type of exploration, however, research in the learning sciences suggests that visualizations may need to be constructed with this feature as a primary goal. For example, a visualization might let users change the parameters of a simulation in order to explicitly explore underlying assumptions about how a model system operates. In this project, such exploration was a secondary goal; the primary goal was the communication of shared descent as the structural pattern of evolution. In order to facilitate users’ exposure to this space of exploration, textual elements were added to the visualization that explicitly address the topics of how scientists construct evolutionary models and what types of evidence are used to refine these models. The introductory text of the visualization also describes details of the assumptions that went into the creation of the visualization, which may also help them think about the underlying decision processes.

Finally, certain elements of the map design incorporate familiar visual conventions of website design. The use of familiar conventions helps users orient themselves more quickly to the technical operation of the visualization, and focus their attention on exploration and understanding the underlying model of evolution that is being presented (Tversky 37). These elements include the design of the framing interface that “holds” the map, provides a basic

navigation menu, and includes a sidebar space for text and image that enhance the interactive experience. The design of interactive components of the map such as “forward” and “fast-forward” buttons and the use of blue highlighting for hyperlinked features also provide familiar design elements for users.

Maps as spatial visualizations

At this point, it is useful to consider the concept of a map and its metaphoric affordances and constraints. The dynamic evolutionary map has some, but not all, of the metaphoric affordances of maps. In general, we can define a map as a visualization that uses spatial proximity to indicate similarity among map elements. There are many types of maps, however, and different types have different affordances. In the most common types of maps, the spatial proximity between map elements indicates the physical proximity of geographical features in the real world. These maps are used as tools for orientation and wayfinding, properties that do not apply to the dynamic evolutionary map. Other map-like visualizations are more metaphorical in nature, using a spatial representation to represent a non-spatial concept. The dynamic evolutionary map falls into the latter category of image. Therefore, some distinction between maps and visualizations in general should be drawn.

James Elkins describes maps as a type of representational “schema” commonly found in visual representations that are not intended to be artistic. Elkins defines schemas as images that are strongly notational and have highly constrained meanings for their creators and viewers, but that can also incorporate many types of graphical and conceptual elements (214). Elkins’ concept of schema has some similarities to Howard Gruber’s “image of wide scope”: a personal metaphor that provides structural support for one’s worldview, such as a personal experience-

based mental map of a city (Gruber, “Darwin’s ‘Tree’” 254). One major distinction is that images of wide scope are personal, while schemas are found widely within cultures, and even across cultures. Elkins identifies three types of schemas: maps, trees, and eggs (214-223); the tree schema, for example, is discussed extensively in the second chapter of this dissertation. One important distinction Elkins makes between maps and tree- or egg-like representations is that the latter are prescientific, while the former is related to scientific graphs (223).

Broadly speaking, maps that represent real-world geography fall into two categories: topological maps and geographical maps. Both of these map types share affordances for orientation, wayfinding, and reference to real-world geography (with some exceptions, such as maps depicting imaginary spaces), but differ in the importance of other affordances. For geographical maps, such as a map of a shopping mall, the map orientation and scale have meaning, as do the distance, size, and directional relationships between map elements. For topological maps, connectivity between elements is the primary feature of importance; for example, in a schematic of a subway system, distance between stops and direction of lines can be variable, but the order of stops on a line is preserved. This does not mean that real-world geography is completely unimportant for topological maps. For example, there is a “strong relationship in New York between the aboveground and the belowground” (Jabbour and Steele 79), but the destination (i.e., neighborhood) is still more important to the subway user than the actual configuration of the subway’s path (Jabbour and Steele 83).

Most people are more familiar with geographical maps than topological maps. Many geographical maps use grid systems that are related to cardinal directions, and are therefore related to graphs. Not all grid systems, however, are related to compass directions or even

straight-line systems. Star charts, for example, use a polar coordinate system; compass directions are important on such maps, as are distance from the zenith and angle from a reference point. Elkins uses the term “reference lines” to capture the important grid-like aspects of scaling, orientation, and direction of geographical maps (223-224). Grid systems make maps useful for scientific representation and calculation. Navigation charts can be thought of as “visual analogue computing devices for navigation” (Card, Mackinlay, and Shneiderman 3). Some maps with a high density of information dispense with a grid system (Elkins 228). Usability considerations may also cause map designers to omit a visual grid system, as in street maps located at the exits to subways. These maps are designed to facilitate orientation of subway riders to the aboveground street system and nearby landmarks, rather than to an underlying grid system (Ishikawa and Yamazaki 331).

Other maps do not use a grid system at all, and can be considered “unquantified” (Elkins 224). Like topological maps, these constructs share many, but not all, of the important features of the most common geographical maps. In early European maps, orientation was important (for example, orientation to Rome or the site of the Garden of Eden), but not direction or distance between map elements. Navigation maps constructed in the Marshall Islands emphasize cardinal orientation and angles between stars or islands, but not distance. Many early Chinese maps use variable perspective and distance to highlight important geographical features. Finally, some three-dimensional maps of native Greenlanders depict coastlines without reference to a consistent scale or cardinal directions (Elkins 224-225).

Barbara Tversky suggests that scientific visualizations, in general, are analogous to maps in that they use spatial proximity and such elements as lines and arrows to suggest relationships

of comparison, trends, and cause and effect (29-31). By this definition, many visualizations are map-like, though not maps in the strict sense of directly depicting geography. Both cognitive science and conceptual metaphor theory suggest that people often conceptualize abstract relationships in spatial terms, such as “good” or “difficult” being “up” (Tversky 31). The metaphoric affordances of visualizations that derive from spatial proximity or direction seem to be fairly common across cultures (Tversky 31), with some exceptions.

While Tversky refers to many types of diagrams as visualizations, within the field of information design, the term “visualization” has a specific definition. Visualizations are representations designed to visually render some properties of a set of data; modern information visualizations are computer-supported and often interactive, and often depict non-visible referents (Card, Mackinlay, and Shneiderman 6-7). Information visualizations instantiate mappings of data, often non-visible data, into visible formats (Card, Mackinlay, and Shneiderman 17). Many types of visualizations use spatial proximity of various types to indicate logical relationships between objects or concepts. These visualizations can be considered “non-spatial” mappings in that their referents do not correspond to real-world spatial features. We can think of non-spatial mappings as metaphors, in that they use spatial notation to represent concepts that are not naturally spatial, such as the evolutionary “distance” between species.

Some non-spatial mappings are largely linguistic in nature, while others have more map-like and graphical characteristics. For example, concept maps use lines to link paired words or phrases that have some type of relationship. Phrases are typically added to the lines make the connection between each pair of concepts explicit. Other largely linguistic visualizations use proximity or lines to represent connections between ideas, but leave the connection between

concepts implicit. More graphical types of logical visualizations include Gantt charts, treemaps, and circuit diagrams. These visualizations are commonly used to learn information, classify ideas, and solve problems.

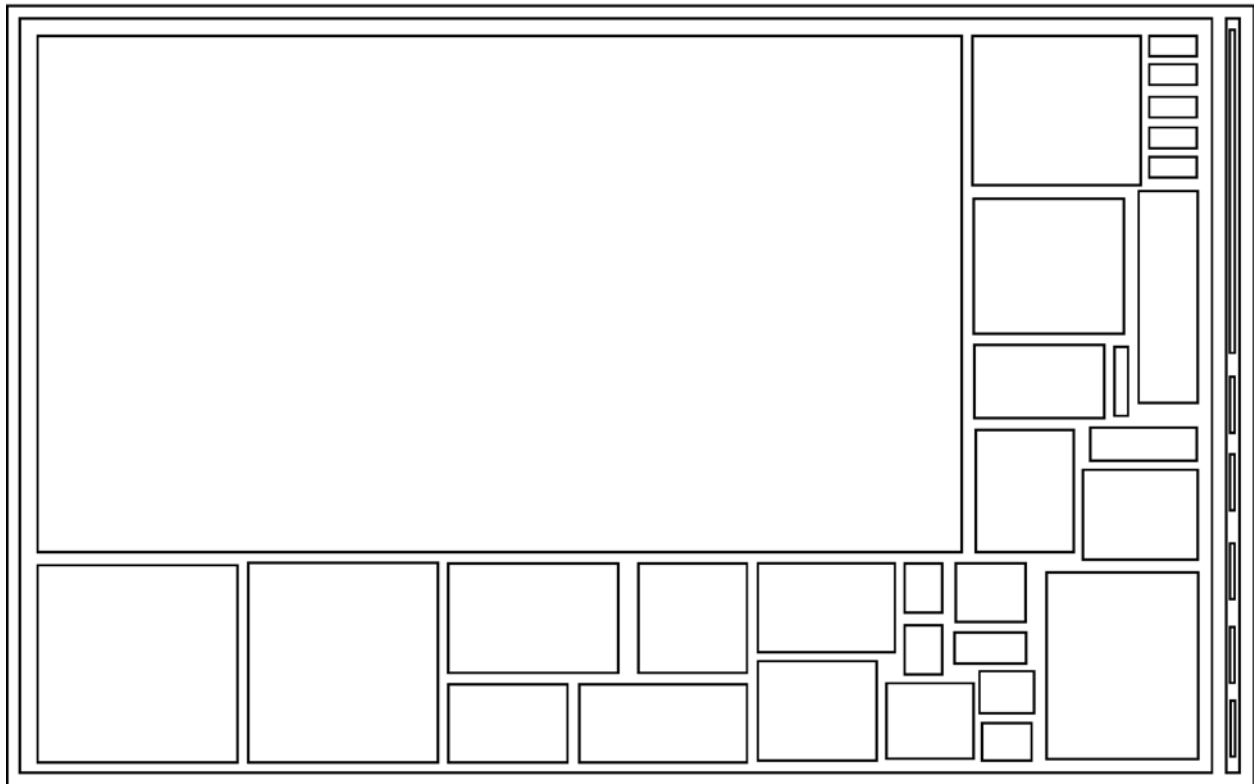


Figure 14: Rough treemap visualization of the number of avian species in each order

Treemaps, for example, display data using nested rectangles of sizes that correspond to some relative numerical parameter size, and allow individuals to display hierarchical data (typically displayed in tree structures) in a compact space (Johnson and Shneiderman 152).

Figure 14 is a rough (hand-drawn) treemap of the approximate number of bird species in each order. The outermost rectangle encloses all birds, and the next two rectangles enclose the two

major divisions of birds, Palaeognaths and Neognaths. Each order is nested within one of these two major divisions. Treemaps are good at displaying hierarchical structure and the relative sizes of groups (note that one order, the perching birds, makes up nearly half of the world's avian species), but are not designed to display non-hierarchical relationships among groups.

Non-spatial mappings use proximity to display logical relationships, rather than spatial relationships. These types of visualizations may carry with them the affordances of spatial maps, and can therefore be open to unintended interpretations. For example, while the meanings of Gantt charts are somewhat constrained by labels, different groups of workers may interpret meanings differently in workplace settings (Yakura 958). In figure 14, the most important spatial feature that implies relationships among boxes is whether boxes are nested at the same level. Proximity within a given level does not indicate degree of relatedness.

One specific example of a non-spatial mapping that is used in evolutionary biology is Sewell Wright's adaptive landscape model for population genetics. In this model (figure 15), Wright uses a topographical map metaphor to visualize optimal and suboptimal combinations of genes as peaks and valleys. In the model, which presents a simplification of a complex set of mathematical combinations, a population will "walk" along the adaptive landscape via mutation and natural selection until it reaches a peak (where it will continue to survive with a stable combination of genes) or valley (where it will be extirpated).

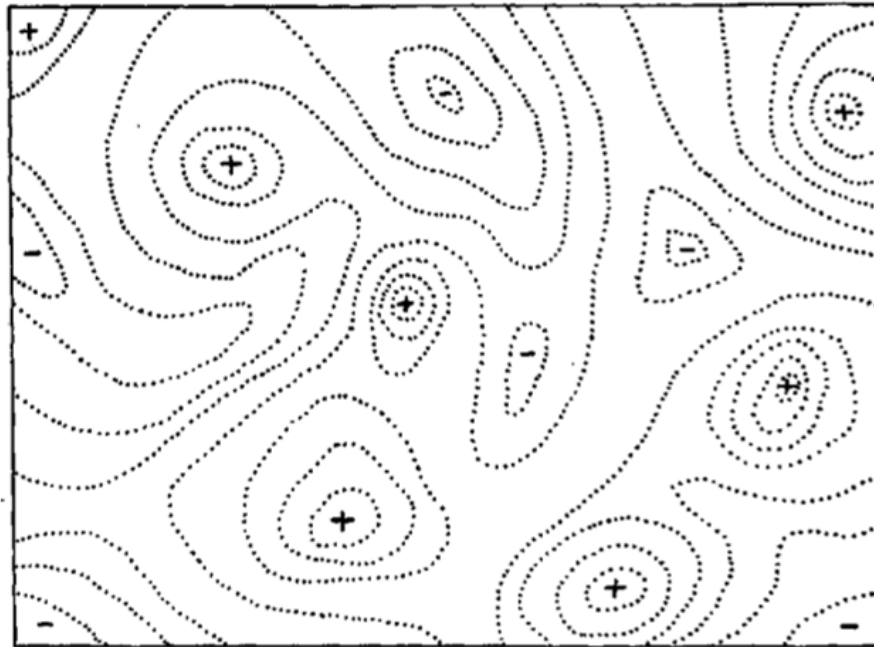


Figure 15: Wright's adaptive landscape, from "The Roles of Mutation." "Peaks" and "valleys" represent optimal and deleterious combinations of genes, respectively, and dotted lines represent "adaptive contours" with similar levels of ecological fitness

Wright's adaptive landscape is an example of a non-spatial image that can be interpreted in multiple ways, because it draws upon the conventions and affordances of topographical maps (Elkins 38). For example, genetics students often misinterpret the map as representing the physical movement of organisms along a physical landscape of "good" and "bad" ecological niches, rather than representing changing frequencies of gene combinations within populations of organisms. While the adaptive landscape model began as a metaphor for Wright's mathematics, it effectively *became* the theory for many geneticists who did not have his mathematical skills (Ruse 72-73). Wright's original diagrams have also been updated to take ongoing research on population genetics into account, such as by clustering peaks to indicate that similar combinations of genes can have similar levels of favorability (Ruse 74).

The dynamic evolutionary map easily fits into the definition of a visualization as a computer-driven spatial representation that uses proximity of elements to suggest something about their similarity. It is a non-spatial mapping, however, rather than a geographic or topological map. In this sense, the dynamic evolutionary map does not share some of the metaphoric affordances of maps, such as orientation, wayfinding, and direct connection to a geographical landscape. In other words, it shares some of the affordances of maps without fitting completely into the metaphor or schema of a map.

One way to view the dynamic evolutionary map is by placing it upon a continuum of visualization that, at one end, includes scaled geographic maps that refer to a physical landscape, and at the other end, includes metaphoric non-spatial mappings of logical similarity. Intermediate upon this continuum are topological maps, which are used for wayfinding, but which use a looser interpretation of scale and direction than do geographical maps. In both topological maps and the dynamic evolutionary map, relationships between points are important, as is the relationship between individual points and the starting point. The dynamic evolutionary map differs from a topological subway map in that distance between points uses a consistent scale, while there is no overall relationship of the map with a physical landscape.

The dynamic evolutionary map also shares some similarities with Wright's adaptive landscape map, in which the "ground," or total map space, represents a theoretical space of evolutionary adaptation. In the dynamic evolutionary map, the ground represents the potential evolutionary space across which birds have evolved. It differs from Wright's map in that the positions of any two groups of birds on the map have meaning relative to one another and to the origin point of birds; the distance between groups on the map is related to the genetic distance

between them in real life. Unlike in Wright's adaptive landscape, the dynamic evolutionary map is not completely unpinned from orientation; the central origin point, representing the genetic "location" of the first birds, remains on the map throughout. Finally, the dynamic evolutionary map shares a visual similarity with polar coordinate maps, but does not have a set orientation that corresponds to cardinal directions. The effective coordinates of any point on the dynamic evolutionary map are its: a) distance from the center, and b) placement within the field of other points. In a true polar coordinate map, the second coordinate would be fixed to a grid system with some reference to an external geography, such as a system of latitude and longitude lines.

Like Wright's adaptive landscape, calling this visualization a "map" might lead to misconceptions among its users related to the affordances of everyday maps. For example, users may have the misconception that what is being depicted is the spread of avian orders across a physical landscape, rather than a virtual space. Another possible misconception is associated with a teleological view of evolution. Viewers might assume that orders that travel upwards or rightwards (or, leftwards or down, depending on their cultural background), are more advanced or "better" than orders traveling in the opposite direction. Part of the purpose of the user evaluation described in the next chapter is to identify any such misconceptions.

Constructing the dynamic evolutionary map

The dynamic evolutionary map instantiates two primary strands of theory in an interactive tool for science communication. First, the theory of distributed cognition proposes that visualizations incorporate affordances that suggest appropriate actions and limit inappropriate actions. When these cues are integrated into mental models, learning occurs. Second, digital media theory suggests that interactive media both create a sense of engagement

and shared agency and provide a useful space to explore the ways in which scientific representations are not transparent representations of reality. This may help users construct a more nuanced understanding of the scientific decision process underpinning the pattern of evolution being depicted.

This visualization was designed to address some of the misconceptions that readers of tree-like visualizations of evolution may come away with, because of the metaphoric affordances of the tree of life. While this visualization incorporates some elements of various types of maps, it incorporates the map metaphor rather loosely, and may be better described as a “mapping” than a “map.” Nevertheless, it is analogous to a map, in the same sense as many scientific visualizations (Tversky 29-31).

In the second part of Chapter Four, I describe the technical methods used to construct the dynamic evolutionary map and instantiate the theoretical synthesis presented in the preceding section. The dynamic evolutionary map plots bird order relationships onto a dynamic two-dimensional space of genetic similarity and allows exploration of the relationships between orders throughout evolutionary time. The visualization also introduces users to key concepts that underpin our understanding of avian evolution and discusses the assumptions that scientists make when evaluating evolutionary evidence.

I begin this section by discussing the data sources that were used to construct the dynamic evolutionary map and provide factual information about bird orders, their evolution, and the scientific process. Next, I describe how the map was programmed and integrated into the final Web-based visualization. I conclude this chapter by describing how users interact with the

map. Screenshots from the visualization are used to illustrate various aspects of the map's operation.

Data sources used to create the dynamic evolutionary map

The dynamic evolutionary map visualizes the evolution of birds from the time of their origin to the present day. Three primary types of data were used to create the map: phylogenetic reconstructions of the relationships among modern bird orders, factual material about the characteristics of extant and extinct avian groups, and images of living and extinct birds and reconstructions of extinct species. The phylogenetic reconstructions provided the major source of data for the pattern of avian evolution, and the latter two sources of information were used to enhance descriptions of specific groups at various points in time.

This visualization follows the evolution of avian orders from the origin of anatomically modern birds, approximately 120 million years ago (MYA) to the present day. Orders are a taxonomic unit of rank between classes and families (figure 16). Taxonomists recognize about 34 extant avian orders, as well as an indeterminate number of fossil orders (Clements *et al.*). Avian taxonomy today is in a state of flux, however, primarily because analysis of genetic evidence is causing taxonomists to reevaluate traditional classifications that are based upon physical and ecological evidence. The dynamic evolutionary map follows a recent large-scale taxonomic study by Shannon Hackett and colleagues that differentiates among about 40 avian groups that are genetically distinct. Most of these groups correspond to traditional avian orders. I refer to this set of 40 groups as orders within the visualization in order to simplify its description. Although this is not completely taxonomically accurate, it is a fair approximation of the magnitude of

genetic distance between the groups, and might help viewers with some understanding of taxonomy grasp the scale of grouping being depicted in the map.

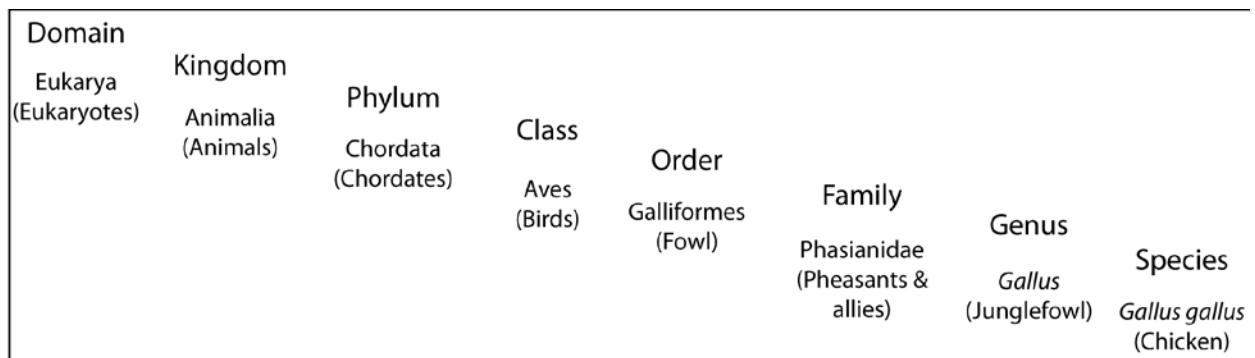


Figure 16: Eight-level system of taxonomic ranks

Two phylogenetic trees depicting the relationships among modern orders of birds were used to guide the development of the dynamic evolutionary map. Both are based upon a study by Shannon Hackett and colleagues that examined the DNA of 169 avian species at 19 gene positions and generated a phylogenetic tree to represent their relationships. The first tree used in this dissertation, figure 10, is from this study. Figure 10 shows the resulting pattern of relationships among bird orders. As in a family tree, orders that are connected more recently by an inferred common ancestor are more closely related than orders that share a more distant common ancestor. Additionally, the horizontal length of branches corresponds to the amount of genetic divergence that has occurred in each lineage since the time of their inferred common ancestor.

Phylogenetic trees should be regarded as hypotheses, rather than statements of certainty about the relationships among groups. Several factors contribute to uncertainty in such trees,

including sampling genes from small numbers of species, differences in results obtained by sequencing different genes, and the assumption of parsimony (i.e., groups with the fewest genetic differences are most closely related). For birds, the statistical analysis of molecular data is more difficult than for some other groups because birds apparently diversified very rapidly early in their history. This early “adaptive radiation” has resulted in “many distinctive, morphologically cohesive groups (e.g., owls, parrots, and doves) with few, if any, extant intermediary forms linking them to other well-defined groups” (Hackett *et al.* 1763). The Hackett *et al.* study includes samples of multiple genes from multiple species in an attempt to address these issues.

The second tree used in this dissertation comes from a study by Joseph Brown and Marcel van Tuinen that used the molecular data from Hackett and colleagues to estimate the timescale of the evolution of avian orders (figure 17). In this study, the authors used statistical analysis to model the rates of change of the gene sequences used by Hackett and colleagues to create their tree. Using this information, Brown and van Tuinen were able to calibrate the phylogenetic tree to geological time.

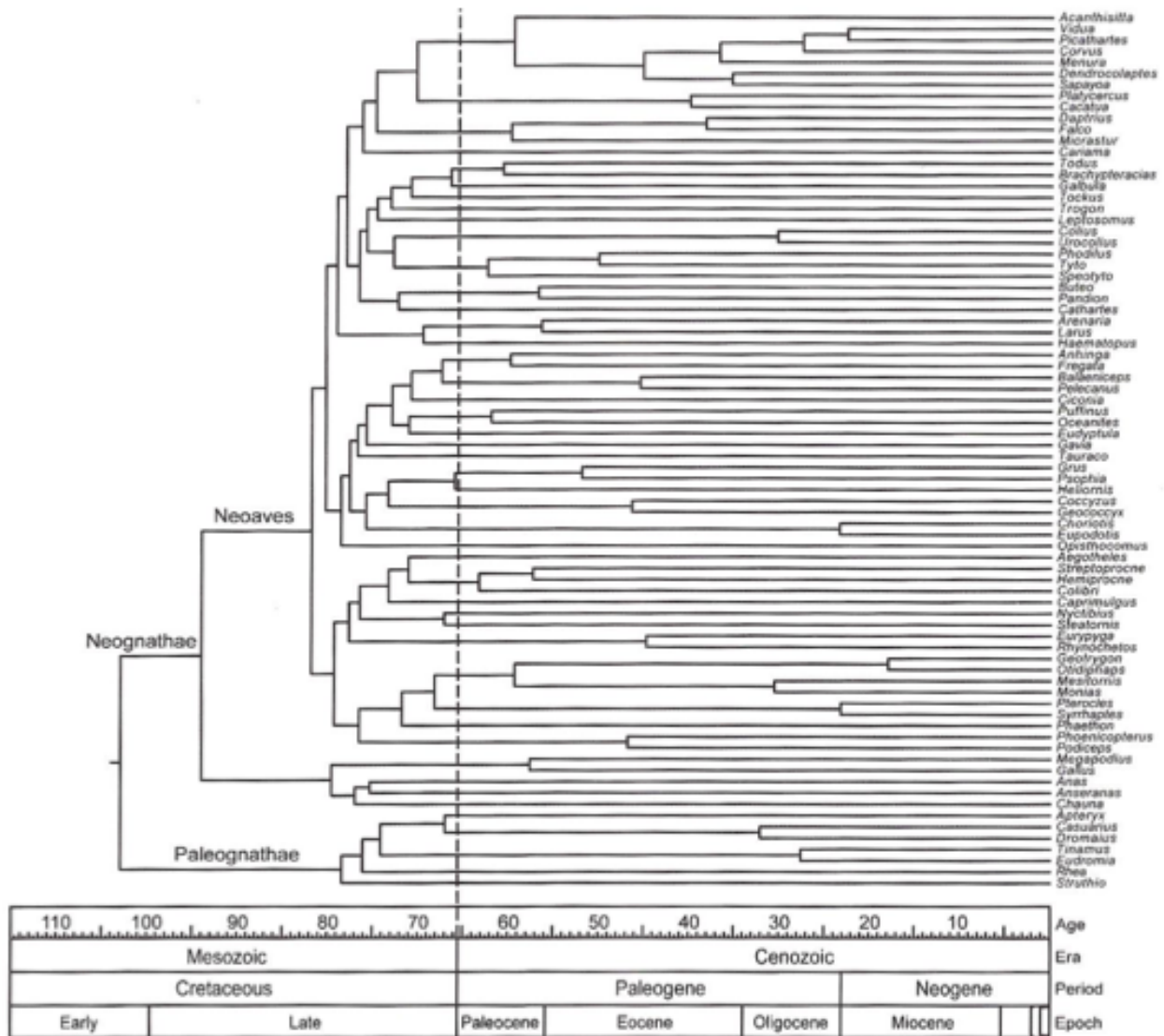


Figure 17: Evolution of avian orders over geologic time. Age is in millions of years before present; the dashed line corresponds to the end-Cretaceous mass extinction event. From Brown, Joseph W., and Marcel van Tuinen. "Evolving Perceptions on the Antiquity of the Modern Avian Tree." *Living Dinosaurs: The Evolutionary History of Modern Birds*. Eds. Gareth Dyke and Gary Kaiser. Hoboken: John Wiley and Sons, 2011. 3-8. Reprinted with permission from John Wiley and Sons

The age of modern bird orders and their pattern of evolution is a subject of current research. Early bird fossils date to 120 MYA (Kaiser and Dyke 5), and other groups of feathered

dinosaurs are tens of millions of years older. Fossil evidence for anatomically modern birds, as distinct from these early groups of birds that did not have key modern specializations for flight, dates to perhaps 75 MYA (Dyke and Gardiner). Most modern bird fossils are much younger (Brown and van Tuinen 307). Molecular evidence suggests a much older origin for modern avian orders; for example, perching birds or songbirds are known from 55 million year-old fossils, but molecular studies suggest that this group originated between 100 and 65 MYA (Barker 247).

Evolutionary dates that are derived from molecular evidence depend on several assumptions about the rate of mutation: whether rates are constant over time, whether rates are similar in different lineages, and whether individual mutations are independent or related (Brown and van Tuinen). While a technical discussion of these assumptions is beyond the scope of this dissertation, one important point is that molecular-based estimates of evolutionary ages, in general, have more systematic uncertainty than ages based upon fossil evidence. This relationship becomes more complex, however, in that many recent estimates of molecular age use fossil evidence to constrain the ranges of dates in their analysis.

The preceding discussion about uncertainty and methods of generating phylogenetic trees has a few implications for the creation of the dynamic evolutionary map. One implication is that there is underlying uncertainty in both the relationships among avian orders and the dates of origin and rates of divergence of each order. This uncertainty affected the map in a few ways. First, I used the timescale of evolution generated by Brown and van Tuinen (figure 17) as a broad guide to the timing of origins of avian orders, rather than a precise prescription. Second, I chose not to place a timeline on the map, and instead indicated the temporal range of events in the sidebar text. Third, a discussion of the differences between molecular and anatomical

evidence for evolution was incorporated into the sidebar text. Finally, the relationships among certain modern avian orders are currently uncertain, based upon both molecular and anatomical evidence, and discussions of these cases was also incorporated into the sidebar text.

In the final visualization, information about avian evolution and ecology and conservation concerns about bird orders was used to provide users with context for the dynamic evolutionary map. Users were provided with information about how scientists evaluate different types of evidence and use their conclusions to construct models of evolutionary relationships, as well as given information about important biological concepts that structure evolutionary patterns like extinction and adaptive radiation (events in which one ancestral species gives rise to many descendant species). This factual material was drawn from multiple data sources, and not cited within the visualization itself. Data sources for information about birds and evolution used in the visualization are summarized in Appendix A.

Images used to enhance the factual information were acquired primarily through the Wikimedia Commons and the US Fish and Wildlife Service's National Digital Library. All images are either in the public domain or are used according to the terms of their Creative Commons licenses. Attribution information appears in the caption of each image within the visualization.

Programming process

The visualization was completed in a three-stage process. First, relational maps of avian orders at different points in time were created using information about avian relationships from the two phylogenetic trees. Second, the relational maps were used as guides to program animated, clickable dots representing the orders onto an evolutionary space using ActionScript,

the programming language used to create Adobe Flash programs. Third, the resulting animation was integrated into a website built using HTML and CSS.

The first stage in creating the dynamic evolutionary map involved converting the information about avian orders in two phylogenetic trees (figures 10 and 17) to a map-like format. The overall visualization concept required the dots representing avian orders to radiate outward from a central point representing the origin of birds. The overall animation was created by mapping the present-day positions of the orders, and then animating them “backwards” toward the origin point in a series of stages. I assumed a constant rate of movement from the origin of each order to its final position.

Two factors controlled the ending position of each order (figure 18): the relative amount of genetic divergence among orders (represented by radial distance from the origin point), and the relative similarity (relatedness) among orders (represented by proximity of orders to one another). There are two major divisions (superorders) among birds: Palaeognathae (“old jaws;” including ostriches and emus) and Neognathae (“new jaws;” including most bird species). The rectangular map space was divided into two, based upon this major division. In the final iteration of this map, however, the Neognaths received more than half of the map space, because this group is proportionately much larger than the Palaeognaths and an equal division of space would have resulted in a very crowded Neognath half. Similarly, about two-thirds of the Neognath space was allotted to the Neoaves (“land birds”) grouping of orders, and slightly less than one-third was allotted to the Galloanserae (“fowl”) grouping.

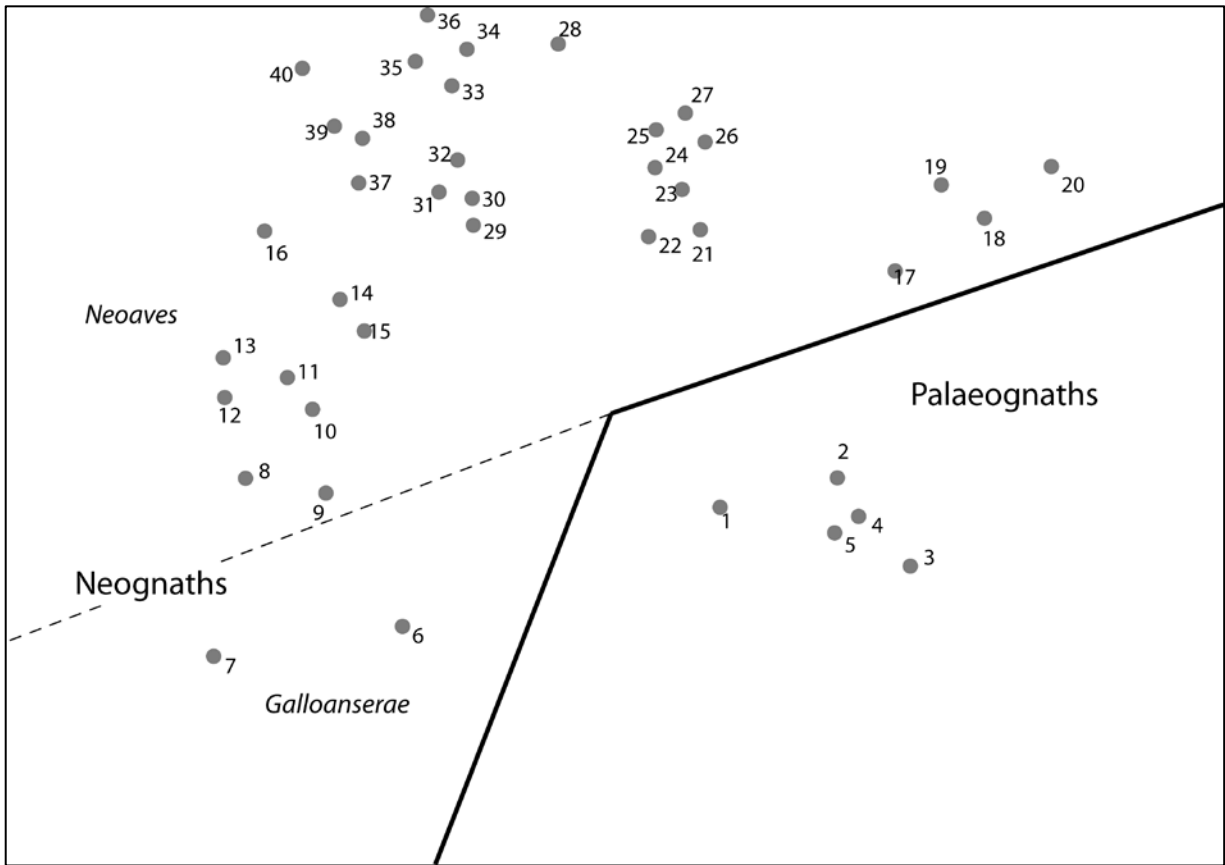


Figure 18: Schematic of the division of map space and ending positions of orders, used as a guide when animating the movement of orders from the central (origin) point. Dots represent the 40 avian orders

Once the major divisions of the map space had been determined, orders were placed into the appropriate division. Palaeognaths were positioned in the bottom right quadrant of the map, and Neognaths in the remainder. Positions within each division were determined by qualitatively plotting clusters of related orders according to their genetic distances (from the Hackett *et al.* map, figure 10) from one another and from the origin point. Once the final positions of orders were determined, a series of 13 plots of intermediate configurations was generated. These plots, plus the origin plot and present-day plots, were used to guide the creation of 15 total static

“keyframes” that allowed synchronic exploration of the positions of the orders. Animated transitions between static keyframes were achieved using a process called “tweening,” which creates ActionScript-based computer-generated motion between keyframes.

Using the Brown and van Tuinen diagram (figure 17) as a guide, the keyframes were linked to an animation timeline for avian evolution spanning approximately 105 million years. Each keyframe is positioned roughly seven million years after the preceding keyframe. The positions of the order dots in the keyframes is guided by the origin and present-day positions of the orders, as well as the hypothesized series of evolutionary divergence or splitting events that gave rise to each order. These splitting events were located in time on the Brown and van Tuinen map, and shown during the animated parts of the visualization as one dot splitting into two. Travel distance of the dots between keyframes was determined by dividing the final order positions by the total number of keyframes, and assuming a constant rate of motion for each order throughout the entire animation. Because of the subjective nature of the placement of the orders and the decision to show orders splitting from one another and traveling to final positions in close proximity, the final positions of the orders exhibit a degree of clustering. This clustering probably overemphasizes the genetic similarity among groups of orders.

The final step in completing the visualization was placing the Flash animation representing the dynamic evolutionary map into a HTML-based frameset (figure 19). Each dot in the animation keyframes was programmed with rollover text that shows the name of the order (or larger grouping) when a cursor is positioned over the dot. Some of the dots were also programmed with further interactivity. Clicking on one of these dots opens up an informational page with text and images about the order in a sidebar next to the map. Viewers advance or

reverse the map by clicking on forward and reverse buttons on the map itself. The appearance of the pages that make up the sidebar text and images is controlled by HTML and CSS scripting.

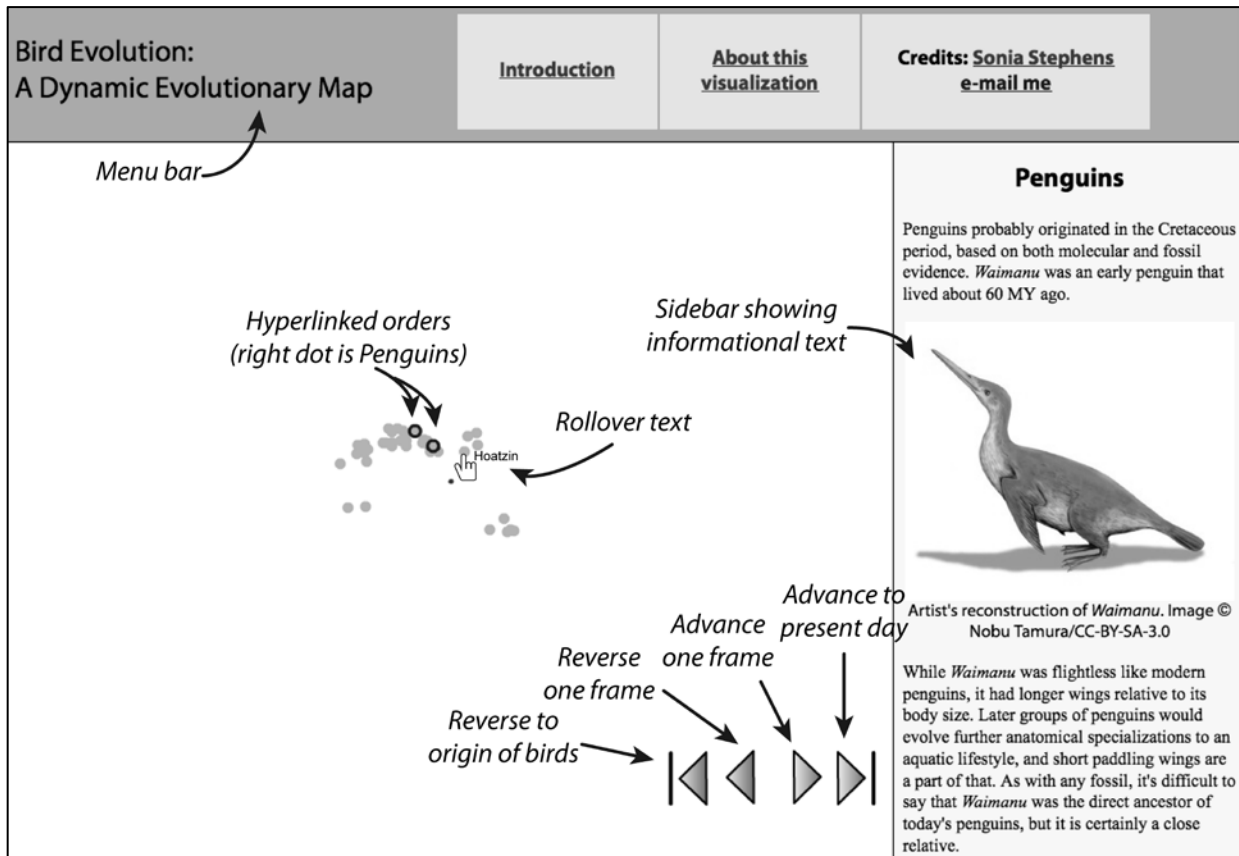


Figure 19: Screenshot of the dynamic evolutionary map in the frameset, with map features labeled

How users interact with the dynamic evolutionary map

In this final section of Chapter Four, I provide a detailed description of how users interact with the dynamic evolutionary map. The interactive visualization is accessible online at this site: <http://www.goo.gl/R8vFe> (please note that this URL is case-sensitive). This section represents

the synthesis of the theoretical and technical elements of this project, and provides screenshots to illustrate various map features.

Users begin their interaction with the visualization by first encountering two pages describing the dynamic evolutionary map and explaining how it works (figure 20). This introduction serves as an introductory orienting mechanism that draws the viewer in, but does not determine the order of his or her exploration of the visualization. The overall narrative flow of the visualization is largely constrained by the way that the viewer interacts with the timeline. For example, users access new textual information by selecting a new page via the interactive dots on the map, rather than navigating from page to page using the sidebar text itself. The combination of author-driven and user-driven narrative elements resulting from this interaction is designed to enhance user engagement with the visualization (Segel and Heer 1146).

When the visualization first appears, it is set to the first stop on the timeline, at the origin of birds. In evolutionary terms, however, this is more properly described as the point at which the last common ancestor of all modern birds existed. After reading the introductory material, users are instructed to click on the linked dot representing this last common ancestor. They are also told that they may explore forward and backward in time. Users always have the option of returning to the introductory information by using the “Introduction” and “About this visualization” links on the top menu bar.

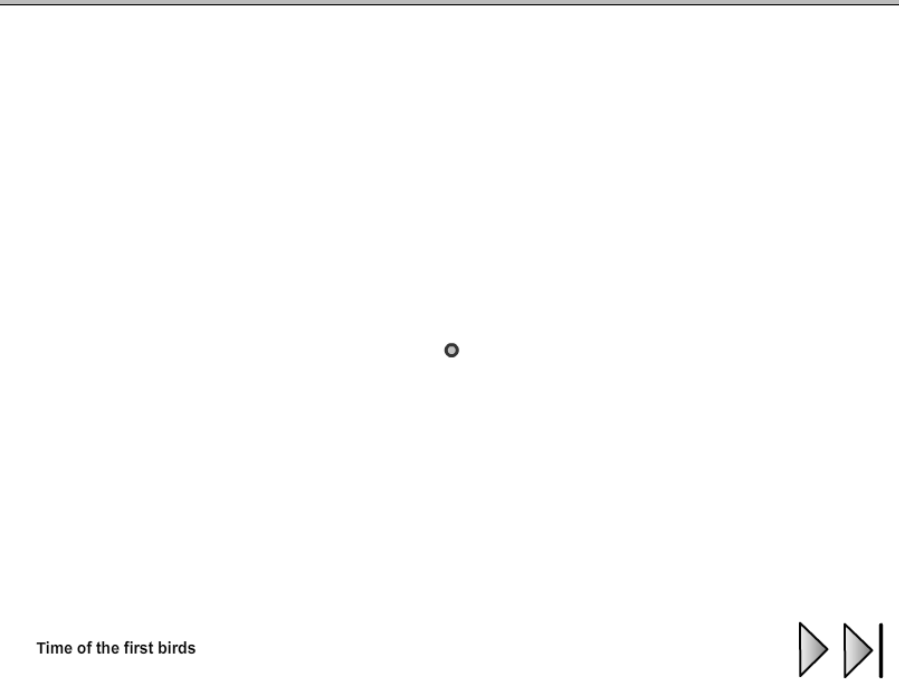
Bird Evolution: A Dynamic Evolutionary Map	Introduction	About this visualization	Credits: Sonia Stephens e-mail me
		<p style="text-align: center;">Introduction</p> <p>Where did the first birds come from, and how long have birds been around? How are modern birds related to one another? How have birds evolved, and changed over time?</p> <p>There are three main sources of evidence that scientists use to answer these questions:</p> <ul style="list-style-type: none"> • Anatomical similarities and differences among <i>living birds</i>. For example, modern perching birds all share a similar type of leg and foot anatomy that lets them grasp thin branches and easily perch on them. This specialized anatomy is shared by all species in the order Passeriformes, and is not found in other orders of birds. • Anatomical similarities and differences between <i>fossil birds and living birds</i> (and similarities and differences among the fossils, themselves). For example, the fossil bird <i>Vegavis</i>, dated to more than 65 million years ago (MYA), shares many similarities to living ducks and geese. • Molecular similarities and differences among <i>living birds</i>. 	

Figure 20: Screenshot of the visualization at the starting point, with the time set to the origin of birds

Diachronic exploration of the visualization largely drives the narrative structure that the user builds. When users click on the forward arrows, the map animates to the next stop in the timeline, as in figure 21. Clicking on either the button that advances to the present day or the “reverse” buttons skips the visualization to the specified point without playing the animation. Research on animated visualizations suggests that users of interactive animations value the ability to move backward as well as forward in time, as well as select different starting points for animated sequences (Fisher 337). This level of control may enhance the user experience.

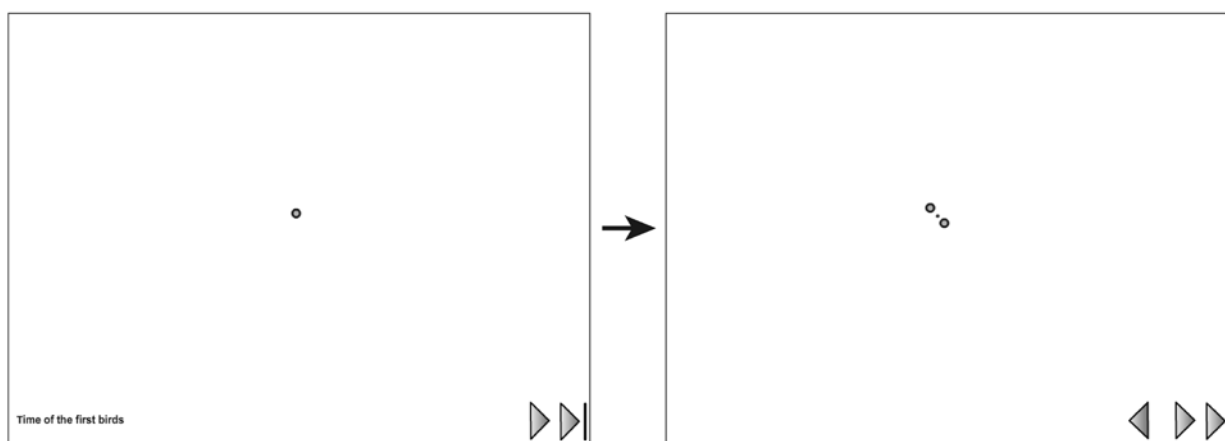


Figure 21: Transition between screens

As described previously, the dynamic evolutionary map does not provide a grid structure to help users orient themselves in the map space. A grid system was primarily omitted from the map design to avoid the suggestion of superiority or inferiority (i.e., teleological concepts) that might be afforded by a positive and negative grid system. In order to help users orient themselves as they explore the map, the point of origin of the last common avian ancestor is indicated by a small dot that remains in the same position throughout the entire visualization. Another way that the map may counter teleological ideas is by showing the pattern of evolution radiating from the center, rather than in a top-to-bottom or right-to-left orientation.

Most of the hyperlinked elements of the visualization provide information about individual orders, or larger taxonomic groups (e.g., Palaeognaths and Neognaths). Examples of this type of information are figure 19, which describes the ancestors of penguins, and figure 24, which discusses present-day perching birds. The map also provides textual information that explains important evolutionary principles or key evolutionary events. This information is

designed to support the communication of aspects of evolution that were difficult to visualize on the map. For example, one key event that shapes our understanding of how birds evolved is an event that occurred approximately 65 million years ago called an adaptive radiation, during which most of the modern avian orders split from one another. This is a prominent event in the map visualization, so a description of the causal process underlying the historical pattern is important (figure 22). This type of information helps address some of the causal explanations for evolution that are omitted from many evolutionary representations (O’Hara, “Homage to Clio” 150).


Bird Evolution: A Dynamic Evolutionary Map	Introduction	About this visualization	Credits: Sonia Stephens e-mail me
		<p>The major Neoaves adaptive radiation</p> <p>At around 65 million years ago (give or take 10 MY), the group of birds called Neoaves had a huge explosion of diversity. During this time, this group of birds developed many differences and many new orders evolved. What was going on?</p> <p>This pattern of evolution, where the descendants from a single ancestral group start developing new traits and splitting to form new groups, is called an <i>adaptive radiation</i>. Adaptive radiations usually occur under specific circumstances, for example when a species colonizes an island where it has very few competitors. In the island example, the lack of competition can mean that the descendants of the colonizing species have many ecological niches available to them, and so eventually adapt to fill those ecological niches as specialized species. On an evolutionary time scale, adaptive radiations happen very fast, but this process still can take hundreds or thousands of generations.</p> <p>This visualization follows molecular</p>	

Figure 22: Screenshot of the adaptive radiation event that gave rise to most modern avian orders

The second way by which users construct their narrative experience of the dynamic evolutionary map is through synchronic exploration during each “stop” on the evolutionary timeline. These individual stopping points allow users to compare the positions of different orders relative to one another and to the origin point. Rollover text that appears above each order helps the user orient himself to the location of each order. Users can also compare textual information about different orders at the same point in the timeline. In most cases, each order is linked to information specifically about that order. In some cases, however, multiple orders are linked to the same informational text, which occurs when there is an underlying reason to link these orders.

For example, figure 23 shows one such multiple linkage, in which five orders are linked to a single informational page. This particular example describes the process by which scientists create hypotheses of evolutionary relationships. In this example, these five orders (rails, cranes, and other groups) have historically been grouped together because of skeletal similarities. Recent molecular evidence, however, suggests that these groups are not, in fact, closely related. The text accompanying this group addresses the issue of assumptions and transparency in scientific hypothesis formation, as well as the types of evidence that underpin the structure of the visualization itself.




Bird Evolution: A Dynamic Evolutionary Map	Introduction	About this visualization	Credits: Sonia Stephens e-mail me
		<p>Rails and cranes</p> <p>There are two major groups in the order Gruiformes, Rails and Cranes. They tend to be long-legged, and are often either wading or ground-dwelling birds. Fairly certain fossil evidence for these birds dates to about 40 MY ago.</p>  <p>Clapper Rail. Image by USFWS</p> <p>Historically, scientists have used the Gruiformes as a "catch-all" category in which to classify long-legged, ground-dwelling birds. These include both species that are alive today and fossil species, like the Adzebills of New Zealand.</p>	
			

Figure 23: Screenshot of a multiply-linked group of orders

The only stopping points during which every order dot is hyperlinked are the first two points (figure 21) and the last point, representing the present day (figure 24). There are several reasons that information was not provided for each order during each time period. First, most orders of birds do not have fossil evidence across the entire timespan of their existence. Since the information about orders presented with the map primarily describes fossil evidence, this makes it challenging to describe something about each order during each time period. In fact, the discontinuity of the fossil record is an important feature of avian evolution that is explicitly referenced in the descriptive information.

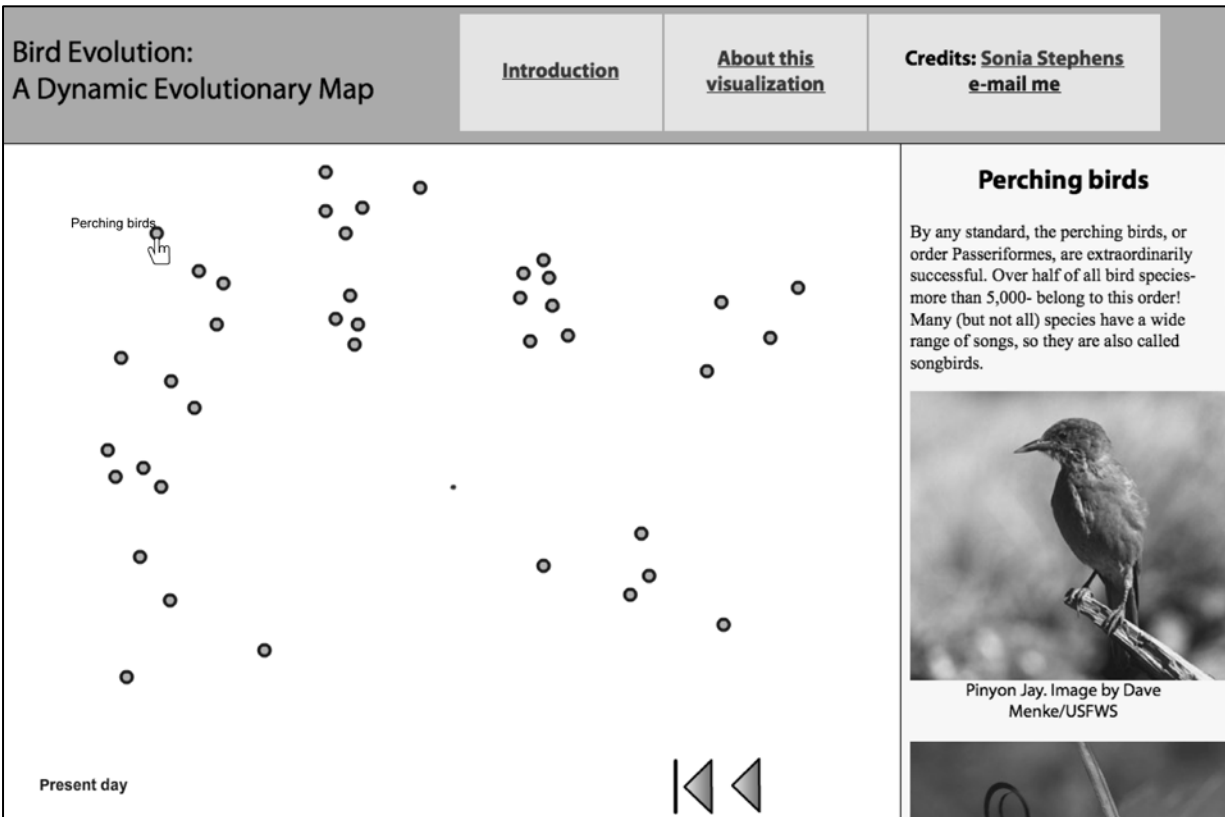


Figure 24: Screenshot showing the present-day genetic relatedness of bird orders

Second, presenting information about each order during each time period could easily introduce too much information to users. The map itself is the most important feature of the visualization as a whole, and presenting an excessive amount of textual information might cause users to lose sight of the overall pattern of evolution as presented by the map. Presenting an excessive amount of information might also result users feeling overwhelmed by facts and pictures. In the final visualization, information was presented about each order at least twice: once in the final present-day time period, and at least once during a previous time period. This allowed users to conduct at least a minimal level of diachronic exploration of each individual order.

Finally, the present-day description of each bird order provides photos of each group so that they can be visually compared, and describes the size of each group. Avian orders are widely variable in size (e.g., see figure 14), and the size of a given group has little to do with the amount of genetic diversification it has undergone since evolving from the last common ancestor of birds. This information may help users of the map contextualize the definition of the “success” of avian groups in an evolutionary sense, and counter teleological ideas about evolutionary progress. For example, successful orders could be defined as those with the most present-day species, or as those that have persisted to the present day regardless of group size. Teleology can also be inferred from the physical complexity of groups; the visualization addresses this explicitly by explaining that feature like jaw structure in the Palaeognaths and Neognaths do not make one group more “primitive” than the other.

The dynamic evolutionary map instantiates several lines of theory to build an original visualization that communicates about the pattern and process of evolution. The map is designed to avoid some of the metaphoric affordances that may suggest misconceptions to users that are found in tree-based visualizations, while keeping the affordances that are important for understanding evolutionary history. The question of whether the desired affordances are actually being communicated to visualization users will be addressed in the next chapter of this dissertation.

In Chapter Five, I describe a qualitative evaluation of the visualization that was conducted by two sets of participants: biology communication experts and biology novices. This two-part evaluation was designed to garner preliminary feedback on the affordances that the map suggests, as well as highlight any possible areas of confusion for visualization users. In this

chapter, I also outline some technical and conceptual limitations of the dynamic evolutionary map.

CHAPTER FIVE: USER INTERACTION WITH THE DYNAMIC EVOLUTIONARY MAP

In Chapter Four, I described the finished visualization that incorporates the dynamic evolutionary map, thus illustrating how the concepts theorized in Chapters Two and Three were instantiated. The fifth chapter of this dissertation synthesizes reactions of users to the visualization. This feedback will be used to support the suggestions for future research in Chapter Six.

In the first part of this chapter, I briefly describe the methods used to evaluate the dynamic evolutionary map. This two-part evaluation consisted of qualitative evaluations by both biology novices and subject matter experts. Biology novices were asked to run through a series of exercises using the map and then answer a set of questions aimed at evaluating the map's affordances. Subject matter experts were asked to evaluate whether the map addresses specific affordances about evolution. This dual evaluation helps assess the potential for using similar visualizations as a complement to traditional tools for evolution communication and education.

In the second part of the chapter, I present the results of the user feedback. I first summarize responses of the experts and novices. Next, I discuss potential conceptual affordances that the visualization proposes to users. It should be noted that the evaluation methods described in this chapter do not include direct comparison between the dynamic evolutionary map and a hypothetical tree-based visualization with a comparable type of interactivity. Therefore, the responses of users cannot be used to provide a one-to-one comparison between different types of visual metaphor. They can, however, be used to suggest affordances that may support the conceptual analysis of metaphoric conceptual connections. As I discuss in the next chapter, side

by side comparisons between the map and a comparable phylogenetic tree would be a logical next step in this research.

Evaluating the dynamic evolutionary map

The first section of Chapter Five presents the results of interviews with individuals who have interacted with the visualization. Participants who assisted in evaluating the map include individuals from the fields of science education and biology, as well as non-scientists. Participant interviews provide additional support for the argument that digital tools can be used to extend metaphors for science communication in intellectually and affectively appealing ways.

The evaluation of the map consists of two parts and was designed to assess the cognitive affordances the visualization suggests to users. The first part of the assessment consists of input from subject matter experts who have experience teaching introductory biology (two participants), or who both teach biology and conduct research on the use of diagrams for teaching about evolution (one participant). The second part of the assessment involves directed use and subsequent feedback on the experience of using the map by biology novices.

The subject matter experts were asked to evaluate the extent to which the dynamic evolutionary map exemplifies the science of evolution. Subject matter experts were contacted via e-mail. If they chose to participate in the evaluation, they were e-mailed a brief explanation of the research and a document with instructions to access the visualization and a list of questions about its potential affordances. These documents appear in Appendix B.

Experts were specifically instructed to explore the visualization with an eye toward identifying affordances or associations about evolutionary processes that it may suggest to biology novices. They were next asked to describe their general impressions of the visualization,

in terms of its utility as a general education or communication tool for evolution. Finally, they were asked to answer a series of questions about potential associations or affordances of the dynamic evolutionary map. These included questions about common descent, teleology, the passage of time, ancestor-descendant lineages, cladogenesis (evolution by lineage branching) and anagenesis (evolution within a lineage), and the scientific rationale that underpins our understanding of avian evolution. Respondents were directed to skip any of the detailed questions if they had already addressed particular issues in their initial observations.

Novice participants in the evaluation were undergraduate students at the University of Central Florida. Novices were recruited from technical writing and literature courses that I was teaching at the time, and offered extra credit in their course for participating. Students who chose not to participate were offered the alternative of completing a reading response assignment for extra credit, so that neither group was advantaged or disadvantaged for their choices. Participants were asked several questions about their understanding of evolution and of birds, and then asked to do a guided exploration of the visualization while answering questions about what they were seeing. There were no indications that any of these students had more knowledge of evolution and biology that can be expected of a typical undergraduate student, with one exception, a novice who ranked their understanding of birds as “expert.” The assessment materials used by novices can be found in Appendix C.

Novice participants were directed to interact with a series of subsections of the dynamic evolutionary map in several stages in order to direct their attention toward specific features of the map. During each stage of exploration, the fourteen participants were asked to answer questions on a paper-based questionnaire designed to elicit information about the affordances of the map.

They were given one hour to complete the questionnaire. Novices were guided to use the map in a more structured way than they might choose on their own. This structured approach was designed to focus their attention on specific elements of the visualization so that their responses could be used to evaluate its conceptual affordances. Therefore, the user experience was not entirely naturalistic, as compared to how a user might encounter the visualization in an informal communication setting; in an educational setting, the user experience would probably have some sort of structure comparable to that given to novice participants.

Novices were first directed to read the “Introduction,” “About this map,” and “Ancestor of modern birds” information pages. Second, they were asked to concentrate on the part of the map containing the Palaeognaths and answer questions about the overall evolution of this group and the relationships of its members. Third, novices were asked questions about the evolution of Palaeognaths and Neognaths and the evidence used to place birds in these groups. Fourth, novices were directed to specific groups throughout the map and asked to answer questions about shared descent, ancestor-descendant relationships, and the evolutionary timescale. Finally, novices were asked to explore the map as a whole and answer questions about teleology, the concept of evolution occurring as changes to groups rather than individuals, the types of evidence that affect ideas about evolutionary relationships, and their overall experience using the map.

After the initial set of evaluations by novices, I observed that the study participants spent most of their time focusing on the text elements of the visualization, rather than the dynamic evolutionary map itself. Because the questionnaire was paper-based, and participants were able to complete it largely at their own pace, they may have been disposed to research the questions

thoroughly by focusing on the text before replying. In order to better evaluate the dynamic evolutionary map itself, I conducted a second set of novice evaluations with five different participants.

This evaluation took place in a guided fashion: I verbally asked each participant a question about the map, and directed them to use the map to answer the question. Participants were told to focus on the map part of the visualization, although they could use the text to help them answer the questions. The order of the tasks was presented similarly to the first novice evaluation: read the introductory information, answer questions about Palaeognaths, compare Palaeognaths and Neognaths, answer questions about specific groups, and then give feedback about the overall design of the map. The verbal direction and questioning method also gave me the opportunity to ask follow-up questions that helped clarify the meaning of responses. Verbal participants only received verbal guidance beyond that given to the paper-based participants in one instance, when a participant was prompted to go back in time to answer a time-based question. In both evaluations, a small number of participants requested verbal clarification on where to find specific extinct groups and why only some dots were hyperlinked.

Expert evaluation summary

In this section, I will summarize and comment on the results of the expert evaluation of the dynamic evolutionary map. Out of the seven experts e-mailed to request assistance with feedback for the visualization, three returned feedback. Each of the three largely directed their comments toward potential uses of the visualization in classroom settings, rather than toward informal science communication settings. The questions for experts and instructions for accessing the visualization can be found in Appendix B, along with the full responses of the

expert evaluation. Two experts returned questionnaires by e-mail, and I met with the third for a face-to-face discussion.

Expert One, who has a background in microbiology, felt that the visualization might be an appropriate tool to “promote active learning” in the classroom. Expert One may have been envisioning the map’s use as part of a formal process of instruction; for example, the expert compares it to concept mapping exercises for learning evolutionary terms. The expert felt that the map was a good way to illustrate common descent, though also suggested that a consistent timeline would improve the user experience. The expert felt that the map was unlikely to promote teleological misconceptions, and that the visualization method helped to illustrate both cladogenesis and anagenesis, stating “...both shared characters helped me to construct the mechanism of evolution.” Expert One also felt that the passage of time was emphasized as students compared modern-day and past species (though presumably a timeline would strengthen the depiction of time). Finally, this expert felt that the scientific evidence for evolution was “well explained.” This expert did not offer much elaboration of their comments, but the other two respondents did.

Expert Two’s analysis focused on suggestions for improving the visualization. Expert Two, who has a background in systematics and evolution education, felt that the introduction and text about various groups were informative, but that the introduction could benefit from the addition of material that described the mechanisms and evidence for evolution. Because this material was not the primary focus of this project, it was not emphasized in the introduction and may have been overlooked in the text in which it appeared. For example, discussions of biogeography (appearing on one Perching Birds screen), derived characters (appearing on the

Ratite screen), and convergent evolution (on the Hawks and Eagles screen) represent key aspects of evolution and might instead be emphasized in the introductory material. In regards to evidence for evolution, the expert felt that there should be a greater emphasis on morphological character evidence, which could complement the molecular evidence and provide a “concrete (vs. abstract) scaffold for learners.” This visual evidence would complement the text-based explanations already present. Finally, the expert felt that the concept of orders as ancestor-descendant lineages was not well explained in the text.

Expert Two also suggested emphasizing two specific “hooks” that could draw in viewers: the information that birds are dinosaurs, and the recent molecular-based rearrangement of the phylogeny of birds of prey. This rearrangement splits a long-held traditional grouping of birds, and suggests that falcons are more closely related to parrots than to hawks and eagles; therefore “birds of prey” is not a valid taxonomic category. The expert suggested that emphasizing these types of interesting facts might increase viewer engagement. These comments and the ones that precede them primarily focus on the text content of the visualization, and would primarily have relevance if future development of the visualization focused on both the map and the supplemental text.

Expert Two offered four major criticisms of the map as depicted as a space of evolutionary change. First, evolutionary space in the scientific sense is multi-dimensional (including time, ecological niches, and physical space), not a two-dimensional space as depicted on the map. The expert did not get a sense of this from the simplicity of the visualization, but acknowledged that this was a difficult concept to get across and suggested that combining the map with supplementary visualizations might help with this issue. The visualization was not, in

fact, designed to depict evolutionary space as a theoretical construct, but these comments do offer suggestions for potential future development of this project. The second major criticism the expert offered was that the concept of genetic similarity or distance on the map space was unclear, i.e., the meaning of the proximity of dots was not explained well. This potential problem with the map could be addressed in a straightforward manner by a clear explanatory statement in the introduction.

The third major criticism of the map visualization itself was the lack of a consistent timeline. Even though the introduction stated that each stop in the timeline represented an increment of about nine MY, Expert Two could not keep track of the time while clicking through the animation. The expert emphasized that a timeline would provide support for an understanding of the evolutionary timescale; this understanding in turn is important for an understanding of evolutionary history. I will discuss the possible advantages and disadvantages of including a timeline in future iterations of this project in the next chapter.

The fourth major criticism of the map was the lack of a branching structure that would provide a constant reminder of the shared descent of the orders. The expert felt that the lack of this structure made it difficult to see the importance of shared descent and cladogenesis. For example, “I have to argue for a tree or trees of some kind to provide a time element and more importantly a topology that provides immediate and comparable estimates of relationships. In other words it provides time and space dimensions that aid in synthesizing learning. Maybe the answer is a hybrid of some kind.” While the expert felt that the visualization was “largely neutral” to teleological interpretations, the complete absence of a tree was, on balance,

detrimental for fostering other important conceptual associations. Again, I will discuss the implications of including a branching feature in the next chapter of this dissertation.

Finally, Expert Two commented on several graphical features that were awkward to use, such as the navigational buttons. The expert also felt that the unlabeled dots (unless rolled over) were uninformative: “I lose the relative relatedness of groups when taxa are not highlighted (I realize they can be rolled over, but without that they become one dot among many).” Expert Two suggested that inclusion of a branching feature (e.g., superimposing the dots on a phylogenetic network) would help preserve these associations.

Expert Three has a background in genetics and evolutionary biology. Like Expert Two, this expert was concerned with the lack of a tree structure or timeline in the visualization. Expert Three explained that the branching tree pattern is a key part of biological theory, and would also help viewers infer relationships among orders once they are at the end of the visualization (present day). The expert suggested either incorporating a tree element as a phylogram alongside the map part of the visualization, or as a radial or semi-radial tree onto the map itself. Either tree could “grow” as the dots in the map part of the visualization moved across the screen. One other feature of a tree that might prove useful would be to create clickable nodes at the divergence points of groups in order to highlight the hypothesized common ancestor.

Expert Three also commented on a few confusing graphical features in the visualization. First, the expert pointed out that the direction and rate of movement of the dots was not consistent. For example, some orders draw closer to unrelated orders as the animation progresses, thus implying that these groups are growing more similar over time. Second, some of the text screens that are linked to multiple dots are linked because they are describing the close

biological relationship between the groups (e.g., Parrots and Falcons), while others are linked because they describe convergent evolution or other shared characteristics that are not related to degree of relatedness. The expert suggested that this was confusing, because the text did not explain why viewers saw grouping with different rationales behind them. While none of the novice participants expressed confusion about this feature, as will be discussed shortly, this might be an issue to return to in future evaluation. Expert Three reiterated that a tree structure might help orient viewers in both of these situations.

In summary, the experts all suggested that the dynamic evolutionary map might have applications in the biology classroom, though Experts Two and Three stressed specific changes that would improve its usability. The two key visual features that the experts felt were missing were a branching tree structure and a timeline. Experts Two and Three also suggested several conceptual and textual elements that they felt would help viewers avoid misconceptions when learning evolutionary concepts, such as an increased emphasis on evolutionary mechanisms. In Chapter Six, I will discuss the theoretical implications of the expert evaluations and propose ways that their suggestions might be incorporated into future iterations of this visualization. I will also specifically address the theoretical and practical issues that would arise if a branching structure were incorporated into this visualization, which was developed as an alternative to traditional tree-based representations of evolution.

Novice evaluation conceptual categories

In this section, I will summarize and comment on the results of the novice evaluation of the dynamic evolutionary map. The instructions and questions for novices can be found in Appendix C, along with the full responses of the novice evaluations. As stated previously, a

paper-based questionnaire with instructions was used for the initial set of novice evaluations, and verbal guidance was used for the second set. There were 14 participants in the first set of evaluations, and five participants in the second set. I will first summarize these evaluations separately, and then discuss the similarities and differences between their results.

Participant responses were evaluated according to whether they included concepts belonging to a set of seven broad categories of conceptual affordances. Because questions elicited different types of responses, different categories applied to different questions. There is some overlap in these categories; specific examples are discussed below. In addition, many responses included terminology that fit into multiple categories. Finally, while responses to most questions fit into the major conceptual categories, there were several focused questions for which responses were better characterized for each individual question. I describe these responses near the end of the next section. The seven major categories, which are adapted from those used by Catley, Novick, and Shade (869), are as follows:

1) Evolutionary comparisons: Responses that explicitly compared two or more groups of birds were categorized according to the nature of the evolutionary relationship. There are six types of response:

- a) evolving to/from, or through a transition stage
- b) ancestor/descendant or common ancestor
- c) relatives/related (not further specified)
- d) belong to the same/different group on map (not further specified)
- e) have similar/different physical characteristics
- f) cannot determine relationship

As suggested by Catley, Novick, and Shade, the first type of response indicates an anagenic (change within a group) understanding of evolution, which is less sophisticated than an understanding of ancestor-descendant relationships (869); the second response type reflects a more sophisticated understanding of evolution, and the remaining three response types are indeterminate.

2) **Evolutionary processes:** Responses that included descriptions of evolutionary processes *without* making explicit comparisons between groups were categorized by the evolutionary pattern or causal mechanism being described. There are eight types of processes in this category:

- a) genetic causes (evolution via mutation)
- b) environmental causes (e.g., role of environment or human influence)
- c) geographic causes (i.e., because of location)
- d) directional or purposeful change (e.g., filling niches, avoiding predators)
- e) loss or acquisition of a trait with no mention of a causal mechanism (e.g., Ostriches lost the ability to fly)
- f) generic processes (e.g., speciation, splitting or diverging, fitness)
- g) extinction
- h) simple description of pattern (no causal explanation or sophisticated terminology)

3) **Teleological judgments:** Responses that included teleological references were coded according to the basis upon which primitive or advanced characteristics were inferred. There are seven types of response:

- a) based on location on the map

- b) based on geographical location in the real world
- c) based on physical description or images
- d) based on inferred relationship to an ancestor
- e) based on diversity or rate of evolution
- f) seems primitive/advanced (no further explanation)
- g) there is no difference/unable to tell (included because one question was about primitiveness)

4) **Geographical location:** Responses that mentioned geography as a defining characteristic of a group or groups were noted in this category. These responses suggest that participants may have been inferring that the location of groups on the map is indicative of their location in the real world. There is overlap with the first three categories; this category summarizes geographic references across the entire evaluation.

5) **Time:** Responses that explicitly mentioned time are noted in this category. There is overlap with all the other categories; this category summarizes temporal references across the entire evaluation. There are two types of response:

- a) generic (e.g., over time, earlier/later)
- b) specific (references to years or events in the map timeline)

6) **Nature of scientific classification:** Responses that described the different types and relative importance of scientific evidence for evolution are categorized here. There are five types of responses. Three describe types of evidence:

- a) molecular
- b) anatomical/fossil

c) environmental

Two types describe weighing evidence:

d) evidentiary types carry the same weight

e) evidentiary types carry different weights

7) **Cladogenesis and anagenesis:** Responses that explicitly mentioned evolution by splitting (cladogenesis) or change within a group (anagenesis) are noted here. This category completely overlaps with the evolutionary comparisons and evolutionary processes categories. It summarizes the proportion of responses in each category across the entire evaluation.

Novice evaluation results

The results presented in this section are organized according to the conceptual categories under which participant responses were classified. I present the results of the geographical location, time, and cladogenesis/anagenesis categories in table Five at the end of this section, because these summary categories applied to nearly all the questions.

Demographic information about novice participants in the paper-based evaluation can be found in Appendix C. This information was not collected during the follow-up verbally guided evaluation, but those participants were of similar age and academic major to the first group. The majority of participants (nine out of 14) reported having taken high school biology plus an introductory biology course, three had taken only high school biology, and two reported taking high school biology plus an introductory college course and one advanced college course. The mean number of years since taking a biology course was 3.2 (SD=5.0); five participants were currently taking a biology course, five took one within the last two years, and four last took biology between four and 17 years ago. On a scale of one to 11 (with one indicating no

knowledge and 11 being expert), participants ranked their understanding of birds a mean of 3.6 (SD=2.0), and their understanding of evolution a mean of 2.4 (SD=1.5). Most students were English, technical writing, and computer science majors; other majors were biology and interdisciplinary studies. There were seven male and five female participants in the paper-based evaluation. In the verbally guided evaluation, there were two male and three female participants.

Four questions were coded into the evolutionary comparisons and evolutionary processes categories, as well as the geographical location, time, and cladogenesis/anagenesis categories. Three of these questions were presented to participants in both the paper-based and verbally directed evaluations, and one was only presented in the verbally directed evaluation. Table One presents the evolutionary comparisons and evolutionary processes results for these four questions. For each question, the results for the paper-based and verbally guided evaluations are separated to enable comparisons between the types of responses that were given.

Table 1: Questions coded into both the evolutionary comparisons and evolutionary processes categories

		Evolutionary comparisons						Evolutionary processes							
		a	b	c	d	e	f	a	b	c	d	e	f	g	h
III-1(both): How would you describe what has happened to this group of birds (Palaeognaths) over time to the present day, in your own words? Be as specific as you can.	Paper evaluation					2		3	5	1	1	7	9	1	1
	Verbal evaluation	1	1		1	1			1		1	1	3		
IV-1(both): How did these two groups of birds (Palaeognaths and Neognaths) arise, in your own words?	Paper evaluation	7	2			6		2	1	1		5			1
	Verbal evaluation	1	1												
IV-3(both): Do these two groups (Palaeognaths and Neognaths) seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?	Paper evaluation	3	4			3		1	4		1	1	5		5
	Verbal evaluation								1				4		
I-1(verbal): Click through the animation until you reach the present day. You can click on the linked dots to learn more about the orders. In your own words, how do you describe what is being represented on the screen?	Verbal evaluation	1	1		1	1			1		1	1	3		

Evolutionary comparisons a=evolving to/from, or through a transition stage; b=ancestor/descendant or common ancestor; c=relatives/related (not further specified); d=belong to the same/different group on map (not further specified); e=have similar/different physical characteristics; f=can't determine relationship.

Evolutionary processes a=genetic causes; b=environmental causes (e.g., role of environment or human influence); c=geographic causes; d=directional or purposeful change (e.g., filling niches, avoiding predators); e=loss or acquisition of a trait (no causal mechanism); f=generic processes (e.g., speciation, splitting or diverging, fitness); g=extinction; h=simple description of pattern (no causal explanation or sophisticated terminology).

Questions III-1 (both paper-based and verbal) and I-1 (verbal only) were similar, in that they were designed to elicit information about how participants interpreted the overall pattern of animation. In the paper-based evaluation, however, participant responses seemed to be based largely upon the text accompanying the map. Responses to both questions varied widely. Many

participants made explicit comparisons between the Palaeognaths and Neognaths, even though they were not prompted to do so. Examples (both from Question III-1) include “Less diversified or slow to evolve, compared to Neognaths.” and “It seems like it only spread out a little from the first ancestor. It only has five dots... the other dot just blew up and spread all over.” Since these two groups originated in the first splitting event depicted on the map, it appears that several respondents found the differences in diversification between these groups to be an important feature of the map.

For Question III-1, most of the responses included some combination of terms describing splitting or adapting and a physical trait or traits; for example, “This group of birds split into three different species including some flightless birds which are classified partly by their lack of keeled breastbones.” and “Ancestor split: Neognaths and Palaeognaths. Palaeognaths eventually split into ratites (four orders, no keeled breastbone, flightless), and Tinamous (one order, keeled breastbone, can fly). All orders came to be mostly ground-dwelling.” These answers suggest that participants were using both the map animation and the text and pictures of birds to help answer this question. In a few cases, answers suggested that participants were conflating distance on the map with real-world geographic distance. I will discuss these responses later in this chapter.

Question IV-1 was intended to elicit information about the participants’ understanding of the mechanisms of evolution. Most of the responses focused on descriptive features (primarily the jaw and pelvis anatomy), rather than causal mechanisms; e.g., “They diverged based on jaw structure and further diversified from there.” A few responses mentioned causal processes (e.g., “From adaptive radiation.”) or used terms that suggested a more sophisticated understanding of evolution (e.g., “They are descendants of dinosaurs.”) These responses in general suggest that

the visualization may not support a sophisticated understanding of evolutionary mechanisms, though it might do a better job of supporting an understanding of evolutionary pattern.

In Question IV-3, all participants were able to discern that the Neognath superorder diversified much more than the Palaeognath superorder. Responses seemed to be based upon both the map and on text elements. For example, “The map clearly shows that the Neognath group diverged into many other groups, while the Palaeognath group had five diverging groups which could not compare in amount” references the map as the source of information, while “Most birds today are Neognaths because they are found on both land and water” references information drawn from the text (though the causal reasoning in the latter answer is not accurate). A few answers referenced one specific event highlighted on the map, an adaptive radiation that occurred in the Neoaves (a subgroup of the Neognaths), e.g., “At some point, one group became really diverse. I think it said their predators became extinct. And there was something about radiation.” The most common causes given for the differences in diversity between these groups were environmental factors, such as habitat. As with Question IV-1, some of these responses reflect a more sophisticated understanding of the causal mechanisms for evolution than others. For example, the concept that environmental factors (rather than mutation and natural selection) are responsible for changes in traits is a common misconception among biology students (Alters and Nelson 1895).

Five questions were coded into the evolutionary comparisons, geographical location, time, and cladogenesis/anagenesis categories. Two of these questions were presented to participants in both the paper-based and verbally directed evaluations, one was presented only in

the paper-based evaluation, and two were only presented in the verbally directed evaluation.

Table Two presents the evolutionary comparisons for these questions.

Table 2: Questions coded into the evolutionary comparisons category

		Evolutionary comparisons					
		a	b	c	d	e	f
III-2(both): How would you describe the relationship between the Ostriches and the Tinamous, in your own words?	Paper evaluation	3	1	1	1	2	1
	Verbal evaluation		1	1	4		5
V-1(both): Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl (Ducks + Geese + Swans)? Why do you think so?	Paper evaluation	5	1	2	8	7	
	Verbal evaluation	3			3		
V-3(paper): How would you describe the relationship between the Seriemas and the extinct Terror Birds, in your own words?	Paper evaluation		1	4	2	2	6
I-2(verbal): For orders that are close together, what type of similarity is being displayed?	Verbal evaluation			1		5	
III-3(verbal): How would you describe the relationship between the Tinamous and the extinct Moas? Why do you say so? Are there any other clues to their relationship?	Verbal evaluation	1		2	2	3	

Evolutionary comparisons a=evolving to/from, or through a transition stage; b=ancestor/descendant or common ancestor; c=relatives/related (not further specified); d=belong to the same/different group on map (not further specified); e=have similar/different physical characteristics; f=can't determine relationship.

Questions III-2 and V-1 were designed to elicit whether participants used the pattern of splitting in the map animation to determine how closely two given orders were related. About one-third of the responses to Question III-2 in the paper-based evaluation used terms that suggested that information from the map was used to determine the relationship, for example “Ostriches and Tinamous come from the same super group of birds (Palaeognaths). Tinamous do have a keeled breastbone and can fly, unlike other ratites. Even though Tinamous can fly, they

are generally ground-dwelling. Ostriches are also ground-dwelling.” Many of these descriptions, however, also included references based on the text and images. In the verbal evaluation, a follow-up question asked participants how closely they thought the groups were related. Several answers to this follow-up question indicated that participants were at least in part using the map; for example “Kind of close- not as far apart as others. Like Tinamous and this one. But not the closest within this group” (while pointing to Perching Birds). While it is difficult to make inferences from only five participants, these results suggest that the second group of participants was relying more on the map than the text and images to make comparisons.

Question V-1 required participants to compare the relationships between two pairs of avian orders. Most of the responses to this question correctly answered that Waterfowl and Land Fowl were more closely related than Flamingos and Land Fowl, and a large majority based their answers at least in part upon the pattern of animation on the map (e.g., “Land Fowl and Waterfowl are more closely related, as Flamingos branch off with Grebes and Tropicbirds.”) Physical characteristics were also commonly mentioned as helping participants determine relationships, for example “Land Fowl and Waterfowl because those two groups stayed together longer and share many characteristics.” Only one participant stated that Flamingos and Land Fowl were more closely related; this person based their answer on the proximity of the groups only on the present-day screen, and did not move the map backwards to answer.

While Questions V-3 (paper-based) and III-3 (verbal) asked about the relationships between two different groups of birds, in each case, one group was an extinct order and the second group was the extant closest living relative of that order. This question seemed confusing to several participants who had difficulty finding the extinct order, because the information about

the extinct group was obtained by clicking on the dot corresponding to the modern order at the appropriate point in the timeline (e.g., Terror Birds are found on the Seriema dot about 50 MY ago). In either example, participants could have found the correct answer in the text. Many answers, however, were based on comparisons of the physical traits of the groups. This question was designed to determine in part whether novices would assume that the extinct groups were the direct ancestors of the extant groups, a possibility because they came before them on the same dot. Only two participants (one from each evaluation) gave this response.

Question I-2 (verbal) was intended to elicit how clearly participants were making the association between distance on the map and genetic similarity. Responses were largely based upon physical features and habitat of the groups, indicating that they were not making this association. Only one respondent mentioned relatedness in a general sense, and this person seemed unclear: “Maybe how they’re related? Or the features they share in common.”

Two questions were coded into the nature of scientific classification, geographical location, time, and cladogenesis/anagenesis categories. One of these questions was presented to participants in both the paper-based and verbally directed evaluations, and one was presented only in the paper-based evaluation. Table Three presents the nature of classification response types for these questions.

Table 3: Questions coded into the nature of classification categories

		Nature of classification				
		a	b	c	d	e
IV-2(both): If a scientist found a bird fossil, how would he or she decide which of these two groups (Palaeognaths and Neognaths) the fossil belongs to? Why would he or she use this evidence, and not something else?	Paper evaluation	3	14	1		2
	Verbal evaluation	1	5	1		
VI-4(paper): What types of evidence do scientists use to decide how to group species of birds into orders? Do all these types of evidence have the same value, or do some seem to be more or less important than others?	Paper evaluation	6	11			8

Nature of classification a=molecular; b=anatomical/fossil; and c=environmental. Two types describe weighing evidence: d=evidentiary types carry the same weight; e=evidentiary types carry different weights

The text descriptions of the Palaeognaths and Neognaths described two anatomical traits that differentiate these groups, the structures of the jaw and the pelvis. Most responses to Question IV-2 mentioned some combination of these traits. A few answers suggested that participants gained insight into the differential weighing of molecular and anatomical evidence, for example, “The scientist would have to closely examine the fossil to see what type of bone structure does the bird have to then classify it. Also molecular mapping would help the scientist figure out where the bird is from. This works since it helps override weaknesses in other forms of evidence.” Other answers suggested that participants gained insight to the concept of convergent evolution (in which unrelated groups develop similar features because of similar selective pressures) and the distinction between shared ancestral and shared derived characteristics (the latter being more useful when constructing phylogenies). Responses mentioning these concepts included “First the physical traits are looked at to find similarities and then these findings are compared to molecular evidence if possible. The traits chosen for focus must be homologies for the birds to be closely related. Sometimes similarities arise from convergent evolution which is

confusing to true phylogenetic classification” and “Genetic/molecular evidence- seems more accurate, based on DNA. Skeletal structures/physical appearance- seems less accurate as with other species of birds, common structures does [sic] not denote a relationship or common ancestry.”

Question VI-4 was only included in the paper-based evaluation because it was based on an in-depth reading of the text information; the verbally directed participants were asked to use the text as little as possible. This question was intended to gather information about participant understanding of the scientific evidence that underpins the pattern of evolution being displayed. While a majority of participants recognized that different types of evidence carry different weights, most incorrectly identified fossil or anatomical evidence as being more important than molecular evidence, even though the text stated that molecular evidence is considered more important. For example, “Physical characteristics are the greatest determiner in which a bird is placed into a group. The value seems to vary, as greater general characteristics, such as long legs, could outweigh values such as the size of the beak.” This misconception might reflect the abstract nature of molecular evidence, in combination with frequent textual references in the visualization to physical traits and pictures of the birds (which obviously illustrate physical features).

One question, presented in both the paper-based and verbally directed evaluations, was coded into the teleology, geographical location, time, and cladogenesis/anagenesis categories. Table Four presents the teleology response types for these questions.

Table 4: Questions coded into the teleology category

	Teleological judgments						
	a	b	c	d	e	f	g
VI-1(both): Do any bird orders seem more advanced than others? Why or why not? If so, which ones?			5		6		3
	1		4		1		2

Teleological judgments a=based on location on the map; b=based on location in the real world; c=based on physical description or images; d=based on inferred relationship to an ancestor; e=based on diversity or rate of evolution; f=seems primitive/advanced (no further explanation); g=there is no difference/unable to tell

Question VI-1 was designed to explicitly elicit information about the nature of teleological concepts that novice participants might hold. The idea that evolution is purposeful and directed is a widespread misconception (Alters and Nelson; Sinatra, Brem, and Evans); it is likely that many participants already hold teleological concepts, although this was not directly tested in this study. In the paper-based evaluation, teleological concepts were approximately evenly split between two types of reasons: those based upon the physical features of the birds (e.g., “Perhaps birds of prey are the most advanced because they developed grasping claws to better catch prey and kill with beaks. Flamingos with their adaptations of long legs and filter feeding are equally as advanced in a different direction.”) and those based upon the diversity of the groups (e.g., “The Neognaths multiplied and evolved so much more than the Palaeognaths, which stayed behind and ultimately only produced five species of bird.”). In the verbal evaluation, most reasons were based on physical features. Finally, a few participants in both evaluations were uncertain how to define or determine the meaning of “advanced,” though in a few cases they appeared to be basing this judgment on physical features (e.g., “No, all the birds are different so it’s hard to compare them.”).

Participants would have gained information about physical features from the visualization's text and images, while information about diversity could have been gained from either text or from the dynamic evolutionary map itself. Interestingly, the verbally directed participants, who in general took much less time to read the text, still largely based their ideas about "advancement" on the physical descriptions of birds, rather than on the differential diversity of different areas of the map. Only one participant used distance on the map from the origin of birds to support ideas about advancement. These results suggest that at least some of the teleological affordances found in tree-shaped diagrams may not be found in the map visualization.

Responses to the six remaining questions were more appropriately characterized individually, rather than being coded into the primary conceptual categories other than the categories of geographical location, time and cladogenesis/anagenesis. Four of these questions were presented to participants in both the paper-based and verbally directed evaluations, one was presented only in the paper-based evaluation, and one was only presented in the verbally directed evaluation.

Question VI-2 (in both evaluations) asked "Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?" Eleven responses from the paper-based and four comments from the verbally directed evaluations referred to size, shape, or physical traits; for example, "The Hoatzin definitely comes across a bit primitive. The physical features of this bird make it seem so." These responses suggest that novices did not make the connection between distance from the center of the map and genetic distance from the ancestral bird (i.e., a dinosaur), and were instead relying on features like large size, predatory nature, and

flightlessness that they may associate with dinosaurs. Interestingly, one respondent suggested that relying on such “dinosaur-like” features was inaccurate: “I feel like [Palaeognaths] sort of are, but the ancestral birds are small. I think people usually say Ostriches are like dinosaurs, but from the information presented you can’t really say that so much.”

The other responses to Question VI-2 from the paper-based evaluation (with one response each) referred to diversity, seeming primitive (without specifying in what sense), groups farther back in time on the map, and “not sure.” One response from the verbally directed evaluation, “The older ones. Palaeognaths and Neognaths,” may have indicated a more sophisticated understanding of evolution, in that earlier groups had diverged less from the dinosaur ancestor. Interestingly, the visualization text explicitly emphasized that birds are, in fact, classified as dinosaurs, but none of the novices replied that all birds are equally similar to dinosaurs (being dinosaurs themselves).

Question VI-3 (in both evaluations) asked “What happened to the original ancestral bird species?” Responses to this question were more varied. Eight paper-based and one verbally directed respondents said that it became extinct. Three paper-based and two verbally directed respondents said that it branched, split, or diversified. Two paper-based and three verbally directed respondents said that it evolved into another species or adapted (e.g., “The original ancestral bird had to change over time to adapt and this led to all these different types of birds.”). Several answers suggested that the original birds either became extinct or evolved, for example “They became extinct or evolved and branched out.” Finally, one paper-based respondent said that it still exists today, and one paper-based respondent was unsure.

These answers largely reflect a view of evolution in which the subjects of evolutionary history, species, are seen as individuals, rather than as loose populations of individuals. Robert O'Hara argues that the species-as-individual view of evolution creates a sense of closure in our view of evolutionary history, and this sense in turn can foster a teleological view of evolution ("Homage to Clio" 152). Very few of the responses to this question suggested a more sophisticated view of evolutionary subjects as ancestor-descendant lineages, rather than as individuals. One example that suggests the former view is "The ancestor of the modern birds survived the Cretaceous-Tertiary mass extinction. It is questionable which is the original ancestral bird species. There are bird and bird-like dinosaur ancestors." I discuss this issue further in the next chapter.

Question VI-6 (paper-based)/VI-4 (verbal evaluation) asked "Did using the evolutionary map change your understanding about bird evolution? If so, how?" Again, responses to this question varied widely. Four paper-based and two verbally directed respondents mentioned branching, expansion, or divergence; for example, "The map helped me visualize the proportions that different divergences produced." Other respondents mentioned different aspects of the pattern that the visualization illustrated, including "I didn't know about the two groups at the beginning. And the adaptive radiation was when the dinosaurs went extinct;" and "The map helped me visualize the proportions that different divergences produced." One participant explicitly referenced a branching pattern, which suggests that they may have been making associations between the map and previous exposure to tree-based diagrams: "I never thought there were several distinct groups. I would have thought they evolved in a more linear way. It's easier to see the branching like a tree, and not as linear." Finally, several responses mentioned

learning about the degree of similarity among groups; for example “It did, [the dots] helped me gauge the actual distance between a bird and its relationship with other birds.”

Question VI-7 (paper-based)/VI-5 (verbal evaluation) asked “Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?” Question VI-6 (verbal evaluation only), which was similar, asked “Do you have any general comments about the design of the visualization, or the interface itself?” These questions were designed to inquire about any difficulties participants had with the visualization. The most common aspects of the visualization that were disliked were the lack of a permanent timeline that helped them keep track of where they were in time, the fact that not all the order dots were linked to information on each screen, and the fact that the cursor sometimes covered the roll-over labels. There were no comments about difficulty with using the navigation buttons. Other comments suggested that the initial proliferation of orders was crowded and confusing, and that it was not clear what the distance between orders represented. Finally, five participants commented on the images that went along with the text, either finding them useful, expressing a desire for images that showed skeletal structure to better enable comparison among groups, or requesting that the images be directly integrated with the map itself.

Several participants replied to these questions with additional comments about what they had learned from the visualization. One positive aspect of the visualization seemed to be the ability to go backwards in time; for example, “I think the visualization of the species moving away from each other (and getting closer if you move backwards in the visualization) helped understand relationships among the groups.” “Branching” and “spreading out” were mentioned several times as memorable properties of the visualization. These comments suggest that

participants gained an understanding of the importance of both cladogenesis and anagenesis in evolution. They may also, however, support the teleological motif of the “cone of increasing diversity” (Gould 63), as discussed in Chapter Two of this dissertation.

Responses that suggested associations with cladogenesis and anagenesis were found across nearly all of the questions asked in both the paper-based and verbally directed evaluations. Comments related to time and geography were also included as responses to many of the questions. Because these conceptual affordances of evolutionary visualizations were concepts of interest in this study, I have noted the prevalence of such references across all the questions in table Five.

Table 5: Geographical location, time, and cladogenesis/anagenesis categories for all questions

		Geography	Time		Cladogenesis	Anagenesis
			a	b		
I-1(verbal): Click through the animation until you reach the present day. In your own words, how do you describe what is being represented on the screen?	Verbal evaluation	1	5		2	5
I-2(verbal): For orders that are close together, what type of similarity is being displayed?	Verbal evaluation				4	3
III-1(both): How would you describe what has happened to this group of birds (Paleognaths) over time to the present day?	Paper evaluation	4	9	1	7	10
	Verbal evaluation	1	5		3	4
III-2(both): How would you describe the relationship between the Ostriches and the Tinamous, in your own words?	Paper evaluation		5			6
	Verbal evaluation		4			4
III-3(verbal): How would you describe the relationship between the Tinamous and the extinct Moas? Why do you say so? Are there any other clues to their relationship?	Verbal evaluation		1			1
IV-1(both): How did these two groups of birds (Palaeognaths and Neognaths) arise, in your own words?	Paper evaluation	2	10		2	7
	Verbal evaluation		1		2	5
IV-2(both): If a scientist found a bird fossil, how would he or she decide which of these two groups (Palaeognaths and Neognaths) the fossil belongs to? Why would he or she use this evidence, and not something else?	Paper evaluation	1			1	
	Verbal evaluation					
IV-3(both): Do these two groups (Palaeognaths and Neognaths) seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?	Paper evaluation		7	2	4	
	Verbal evaluation	1	2		1	1
V-1(both): Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl (Ducks + Geese + Swans)?	Paper evaluation		7	1	1	5
	Verbal evaluation		4			2
V-2(both): Based on the map, how long ago did the Cuckoos + relatives and Penguins last share a common ancestor?	Paper evaluation			13		
	Verbal evaluation			5		

		Time		Cladogenesis	Anagenesis
		Geography	a		
V-3(paper): How would you describe the relationship between the Seriemas and the extinct Terror Birds, in your own words?	Paper evaluation		2		
VI-1(both): Do any bird orders seem more advanced than others? Why or why not? If so, which ones?	Paper evaluation		4	1	6
	Verbal evaluation				1
VI-2(both): Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?	Paper evaluation				1
	Verbal evaluation		1		
VI-3(both): What happened to the original ancestral bird species?	Paper evaluation		6	2	6
	Verbal evaluation			2	3
VI-4(paper): What types of evidence do scientists use to decide how to group species of birds into orders? Do all these types of evidence have the same value, or do some seem to be more or less important than others?	Paper evaluation		2		1
VI-5(paper): Why do scientists change their minds about how to classify birds into groups? Can you give an example of this from the map?	Paper evaluation		3		2
VI-6(paper)/VI-4(verbal): Did using the evolutionary map change your understanding about bird evolution? If so, how?	Paper evaluation		3	1	3
	Verbal evaluation		5		
VI-7(paper)/VI-5(verbal): Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?	Paper evaluation		4	2	1
	Verbal evaluation		2		
VI-6(verbal): Do you have any general comments about the design of the visualization, or the interface itself?	Verbal evaluation		2		

Time a=generic reference (e.g., earlier, later); b=specific reference (e.g., 65 million years ago)

One of the questions that the novice evaluation was intended to address was whether the dynamic evolutionary map's use of a map metaphor suggested spatial affordances to its users that might lead to misconceptions about the evolution of birds. For example, would users

associate the virtual evolutionary space with real-world geography? I discuss this issue further in the next chapter of this dissertation, and summarize the very few responses that suggested that this might be the case here. Such responses included two answers to Question III-1: “They have diversified based off of location. The actual branching into separate species is limited and the primary similarity is flightlessness.” and “It evolved slowly, and after a certain point... Those birds didn’t change much, but their geographic position didn’t change much. They went from one group to three and then stayed at five.” The same individual who offered the latter response to Question III-1 also gave a geography-based response to Question VI-5: “The Palaeognaths evolved more slowly- not as many birds relocated to that particular area.” No other participants made multiple geographic references of this type, which suggests that there might not be strong affordances for this misconception.

Another question of interest was how well the dynamic evolutionary map would convey the concept of time. One question (V-2) asked participants to date a specific event in the visualization, the Neoaves adaptive radiation that took place about 65 MY ago. All but one participant out of 19 were able to give an exact date for this event (which was stated in the text), though some of the dates were incorrect; four participants based their estimates on the ages of fossils described in the text of the present-day screens, and two participants apparently based their estimates on counting the number of backwards clicks required to get to the adaptive radiation screen.

There were a few other references to specific dates or events (such as the Neoaves adaptive radiation) in the answers to other questions (e.g., Question V-1, “...Where Flamingos are relatives of the diving Grebes, fowls were an original diversification of the Neognaths within

the first 20 million years of their divergence from Palaeognaths.”). There were also a larger number of references to relative time, such as describing the sequence of events or rates of evolution (e.g., “...The main difference in the groups is flying ability which accounts for the geographic location and ability to evolve easier/faster.”). Finally, there were a small number of apparent time-related misconceptions that appeared in responses. For example, one participant associated distance from the origin of birds with age: “As time went on, species branched out. Older ancestors stayed close to the center and newer species branched out.” The inclusion of a timeline that appeared consistently throughout the visualization might have helped participants conceptualize time better. Research in the learning sciences suggests that neither biology students nor the general population of college students has an accurate understanding of the long timescales involved in evolution (Catley and Novick 329), so this is an important future consideration.

References to cladogenesis (e.g., splitting, branching) appeared in about 13% of responses, and references to anagenesis (e.g., adaptation, evolution, change) appeared in about 29% of responses. While both of these evolutionary mechanisms are important concepts, cladogenesis is particularly important in that it describes how species form. Research in the learning sciences suggests that evolutionary diagrams that do not include trees do not suggest cladogenesis to students, and may therefore be less suitable for communicating about evolution (Catley, Novick, and Shade 878). The results of this study suggest that participants were using the evolutionary map to support concepts of cladogenesis and anagenesis, at least to some extent. Responses that support this include “I never thought there were several distinct groups. I would have thought they evolved in a more linear way. It’s easier to see the branching like a tree, and

not as linear.” and “The map clearly shows that the Neognath group diverged into many other groups, while the Palaeognath group had five diverging groups which could not compare in amount.” Nevertheless, such comments were only found in a minority of responses, suggesting that the map may not be suggesting these affordances to viewers.

In general, the primary differences between the paper-based and verbally directed evaluations seemed to arise from the different amounts of time that participants spent reading the text elements of the visualization. In the next chapter, I address the implications of this focus for the evaluation results. One aspect of the verbally directed evaluations that offered additional insight into potential difficulties with the visualization was being able to see what technical aspects participants were struggling with, such as confusion about which dots were clickable or difficulty finding extinct groups. Verbal interaction during the second evaluation also enabled me to ask follow-up questions that, in many cases, clarified participants’ reasoning or the bases for their previous statements.

In the final chapter of this dissertation, the feedback from both novice users and expert evaluators will be used to support suggestions for future development of the dynamic evolutionary map and similar visualizations. In Chapter Six, I compare the affordances and constraints of the map and the tree of life and discuss theoretical and technical areas of further research. I then conclude by discussing the broader implications of this project for the public communication of science.

CHAPTER SIX: CONCLUSION

In this dissertation, I have demonstrated how theories from several areas of research can be used to guide the creation of a communication tool that targets a specific problem in science communication. In this chapter, I revisit the theoretical synthesis and conceptual affordances of the dynamic evolutionary map, discuss the implications of user feedback for this project, and suggest possible future directions for this type of research. I then conclude the dissertation by examining the broader implications of the research results for science communication and the public understanding of science.

In the first part of the chapter, I review the theoretical synthesis that contributes to the structure of the dynamic evolutionary map. I then briefly discuss how the map is situated within the history of visualizations of the relationships among organisms, or the Natural System. I next discuss the similarities and differences in conceptual affordances and constraints between the map and the tree of life metaphor for evolution. I contrast the affordances and constraints of each visual metaphor and discuss areas of alignment and disagreement. Finally, I discuss the implications of the user feedback and what the expert and novice responses suggest about the map.

In the second part of the chapter, I discuss the technical operation of the map and suggest ways that it might be improved. I first focus upon small-scale technical details that might improve map function or user interaction. Next, I compare this project with other interactive visualizations of evolution and briefly discuss ways that it is unique. Finally, I describe potential future directions for research with the dynamic evolutionary map that make use of large-scale changes to extend its applications into other areas of research and practice.

The dynamic evolutionary map is a concrete example of using new digital tools to rethink traditional science communication challenges. While digital tools have promise for transforming science communication and education, different conceptual problems must be met by different solutions. This dissertation both theorizes and demonstrates a way to apply new technologies to a specific communication problem. In the final part of this chapter, I discuss how this project fits into the broader community of research on science communication, and suggest possible connections to the fields of education and evolutionary biology.

Theoretical synthesis

In this dissertation, I have drawn theoretical strands from the studies of metaphor, distributed cognition, new media and visualization design, and the learning sciences, and combined these concepts to create an interactive tool for science communication. The dynamic evolutionary map illustrates the evolutionary history of birds in an interactive visualization that is designed to communicate several important aspects of biological theory. In this section, I will briefly revisit the theoretical components of this project and describe how they support this visualization.

The field of metaphor studies contributes several components to this project. First, metaphor is used several ways within the sciences and for science communication. Within the sciences, metaphor is often used to construct models of scientific concepts and processes that exemplify important aspects of the subject being represented by emphasizing certain properties and omitting others (Elgin 1). As large-scale metaphors, images of wide scope can be used to support emotional, as well as intellectual, investment in the research projects of individual scientists (Gruber, “Darwin’s ‘Tree’” 255). Metaphor can also be useful when new concepts and

results are being incorporated into scientific frameworks across disciplines (Brooks 446) or when new concepts are being communicated to the public at large (Bucchi, “Of Deficits” 63).

Because metaphors help us make connections between familiar domains of understanding and new ideas, metaphor plays an important role in science communication and the public understanding of science. The traditional tree of life has been a dominant metaphor for biological evolution since Charles Darwin’s time, and phylogenetic tree structures are a crucial part of contemporary evolutionary biology. In this project, the field of metaphor theory has been used to suggest ways that the conceptual affordances of evolutionary trees can be modified to create a new base metaphor for representing the pattern of evolution. In general, maps can be considered visual metaphors when they are not representing physical geography with spatial proximity. The dynamic evolutionary map illustrates the genetic distance among avian orders on a theoretical space of evolutionary adaptation and shows viewers how orders have moved across that virtual space as they have differentiated from their dinosaur ancestors over time.

The second primary research area that contributes to this project is cognitive science; in particular, the theory of distributed cognition. This theory proposes that both tools and visualizations incorporate affordances that suggest appropriate actions and constraints that limit inappropriate actions. As we interact with visualizations, they become part of our thinking processes, and form a coupled internal and external cognitive system (Zhang and Norman 116). The particular affordances and constraints of each different type of visualization can foster unique associations in the viewer or user. When the associations facilitated by this coupled process are integrated into our mental models, learning occurs.

The theory of distributed cognition provides a useful framework for visualization research in general (Liu *et al.* 1178). In this project, it helps link the more theoretical metaphoric concepts with the applied aspects of the dynamic evolutionary map. For example, this theory provides a framework for examining the specific affordances and constraints found in tree-based and map-based visualizations for communicating about evolution. Although this connection is not explicitly described in depth in this dissertation, the theory of distributed cognition also informs the rationale for gathering empirical user feedback for the visualization.

The third related group of areas that help support the theoretical foundation of this project are the fields of new media theory and visualization design. These fields provide important concepts that support the design of the visualization, as well as enhancing the theoretical dimension of this project. First, concepts from visualization design have informed the design of the visualization in several important ways. The field of visual culture describes both how social and community conventions guide the creation and interpretation of visuals (Kostelnick and Hassett 25) and how material technologies of representation can constrain visual conventions (Kostelnick and Hassett 106). In this dissertation, the interactions between convention and materiality come into play when outlining the many forms of historical depiction of the Natural System in pre- and post-Darwinian times. Material considerations are also at the forefront of the dynamic evolutionary map, which harnesses digital technologies both directly in its programming and indirectly in the phylogenetic analysis upon which the map was based.

The field of information design contributes several important elements to this project, such as the importance of layering information (Tufte, *Envisioning Information* 61) and the appropriateness of using qualities of relative motion and proximity for conveying information

(Card, Mackinlay, and Shneiderman 30). These elements influenced the overall design of the visualization, which uses motion and information presented in several formats on the screen. One particular concept that was inspirational in creating the dynamic evolutionary map is Edward Tufte's idea of a visual "confection:" an assemblage of "image-events" arranged on a visual field (*Visual Explanation* 121). The dynamic evolutionary map has confectionary elements in its juxtaposition of the dynamic map with the sidebar of text and images, as well as in the elements of synchronous and diachronous exploration of avian history.

Another set of important theoretical concepts from digital media studies suggests that interactive media both create a sense of engagement and shared agency and provide a useful space to explore the ways in which scientific representations are not transparent representations of reality. First, meaningful action is important in interactive design because it can create a sense of shared agency between viewer and text, leading to a strong sense of engagement. In order to facilitate this sense of engagement, both the narrative structure and the type of interactivity should be appropriate to the task that the user is trying to accomplish (Segel and Heer; Yi *et al.*). In this project, these considerations have informed the selection of methods of interactivity and the narrative constraints on user exploration of the visualization.

Finally, evolutionary theory and research in the learning sciences also inform this project. The body of previous empirical work on the use of tree diagrams in formal education settings helped suggest key affordances to include in the visualization and the current understanding of how visuals contribute to scientific understanding. Research on evolution education in general helped me identify the relative importance of various mechanisms that contribute to the theory of

evolution, as well as some of the sources of student misconceptions about evolution in formal settings.

Historical visualizations of the Natural System

The dynamic evolutionary map follows in a long tradition of experimentation in visualizing the relationships among organisms. In Chapter Three, I described various ways in which scientists and natural philosophers have visualized large-scale biological relations among species, or Natural Systems. While I began my discussion of this tradition of visualization with the early Eighteenth-Century Great Chain of Being or *scala naturae* (figure 8), hierarchical systems for organizing life certainly go back further in history. Aristotle first described a hierarchical Natural System based upon the type of soul and capacity for movement a species possessed. In this system, species were arranged strictly from complex and perfect to simpler and imperfect; no evolution between ranks of the hierarchy was possible (Gontier 521).

By the mid-Eighteenth Century, increased knowledge of the complexities of the natural world led scientists to begin to classify species based upon shared characteristics, rather than philosophical states of perfection. Visualizations of the Natural System reflected a growing awareness that life was too complex to be placed into a single hierarchy (O’Hara, “Diagrammatic” 2747). New types of visualizations included map-like images of affinities among biological groups (figure 9), mathematically-based geometrical “circles of affinity” (figure 12), and diagrams that incorporated both a sense of history and a more complex branching hierarchical system (figure 6). These three very different types of visualizations illustrate biological relationships in different, creative ways, but none of them incorporates a naturalistic explanation of the mechanism that produced these patterns.

Darwin's theory of evolution based upon natural selection provided that explanation. After Darwin published *The Origin of Species*, shared descent became the crucial mechanism that shaped the pattern of the Natural System. Tree-like illustrations became the dominant means of visualizing evolution, and map-based and other depictions became much less frequently used (though see figure 13 for a hybrid tree and map diagram). Today, highly schematized branching phylogenetic tree diagrams have a central place in the field of evolutionary biology, largely because they are constructs that exemplify important aspects of evolutionary theory. The visual metaphor of the tree allowed illustrators to invoke the passage of time and concept of change, as well as shared descent. Growth and change over time are important components of the theory of evolution, as seen in Darwin's own tree-like diagrams (figures 1 and 2). Nevertheless, the most widely used tree diagrams today share common technologies of representation (e.g., paper and ink) with earlier map-like and geometrical Natural Systems.

The visualization in this project differs from most traditional visual representations of evolution in three ways: by using a map metaphor based upon shared descent, by including animation, and by incorporating semi-structured user interactivity. Its visual form draws upon two representational motifs, affinity maps and evolutionary trees, though it combines these elements in a novel way. It departs from traditional representations of the Natural System in its animation and interactivity. These elements facilitate the depiction of change over time and enhance the ability of the reader to interact with the visualization. In the next section, I focus upon the affordances and constraints of the dynamic evolutionary map and discuss how the design and interactive elements may facilitate different conceptual understandings than those suggested by traditional tree diagrams for evolution.

Affordances and constraints of the dynamic evolutionary map

One of the important points that this dissertation was designed to demonstrate is that digital tools can be harnessed to create a tool for communication that incorporates important conceptual affordances about evolution that are different from the affordances communicated by tree-based visualizations. In this section, I discuss how the dynamic evolutionary map instantiates certain evolutionary affordances while not incorporating others and compare the affordances of the dynamic evolutionary map with those communicated by tree-based diagrams. The dynamic evolutionary map was designed to communicate the large-scale pattern of evolution, or macroevolution, of birds from their origin until the present day. In Chapter Four, I described three broad categories of evolutionary concepts that could be suggested by visualizations: concepts exemplified in tree diagrams that I wished to retain in the map; concepts exemplified in tree diagrams that I wished to exclude from the map; and concepts that are not well represented in either tree diagrams or in the map. I will first discuss these categories, and then touch upon the novel affordances of this map-based visualization.

The first group of concepts that I will discuss is comprised of affordances of tree-based diagrams that suggest important aspects of evolutionary theory. As such, I tried to retain these affordances in the dynamic evolutionary map. They include common descent, cladogenesis and anagenesis, continuity from ancestral to descendant species, and the passage of time.

- **Common descent**, or descent with inheritance from common ancestors, both provides a mechanism for evolutionary pattern and explains the patterns of difference and similarity that we see among species. As discussed previously, the concept of common descent differentiates pre-evolutionary and evolution-based descriptions of the Natural System.

Tree-based diagrams suggest common descent by the overall structure of the tree that connects different groups. The dynamic evolutionary map suggests common descent in the branching pattern of movement of the dots that split from a central origin, and then move across the map space in a radial pattern. While both types of diagram suggest common descent, they do so in different ways. In tree diagrams, the connection between groups remains in the image the entire time the viewer is looking at it, while in the dynamic evolutionary map the connection between groups is more ephemeral, and based on movement rather than a persistent visual connection.

- **Cladogenesis** (evolution by lineage splitting) and **anagenesis** (evolution within a lineage) are suggested in tree diagrams by the branching pattern of the tree and growth of the limb from the branch point, respectively. In many tree diagrams, it is important to note that both of these processes may be obscured by the details of the illustration. For example, the branching of lineages is more apparent in phylogenetic trees (e.g., figures 10 and 17) than in more elaborate tree-based representations like figure 4, which depicts a central “trunk” of evolution, rather than a continuously branching structure. It is also not apparent in figure 4 that the growth of branches from the trunk signifies any change in the group named at the end of each branch. In the dynamic evolutionary map, movement illustrates these evolutionary patterns. Cladogenesis is represented by dots splitting and moving apart, and anagenesis is represented by the movement of dots across the map space. As with shared descent, this movement-based mode of representation primarily provides visual affordances for cladogenesis and anagenesis as the viewer is interacting with the visualization.

- **Continuity** from ancestral to descendant species is a concept that is present in evolutionary trees, but that may not be interpreted correctly. Where older Natural Systems like the *scala naturae* showed a continuous scale of relationships, tree diagrams show viewers a set of taxa connected by branch points representing hypothetical common ancestors. When branch points are not labeled, they may be overlooked or thought of as “missing links” that indicate uncertainty, rather than a specific hypothesis about evolutionary relationships. In the dynamic evolutionary map, continuity is to an extent depicted more strongly by the motion of continuous dots across the map space. An important caveat is that the dots might suggest continuity too strongly because they do not change color or shape over time, and might therefore suggest to viewers that avian orders have remained fundamentally the same over time. I discuss this possibility in more detail later in this chapter.
- **Time’s passage** is an important aspect of the evolutionary process. Tree diagrams, however, can be interpreted as showing either the evolving pattern of life over time, or as showing a hierarchical arrangement of groups within a single time period. In other words, the sense of time passing that the tree is meant to convey may become blurred in diagrams that are not explicitly tied to a temporal dimension, as is figure 1. In the dynamic evolutionary map, time is tied to the visualization as the viewer advances or goes backward through the animation. There is no continuous visual reminder of the time scale, however.

The second pair of concepts that are suggested by tree diagrams can be considered to be conceptual constraints that limit evolutionary understanding or contribute to misunderstandings about evolution. The dynamic evolutionary map was designed to avoid evoking these concepts, both related to the pattern being displayed: differentiation between trunk and branches, and the metaphor of upward progress.

- **Differentiation between trunk and branches** in tree diagrams may foster a few types of misconceptions in viewers. First, the trunk of the tree obscures the large-scale branching pattern of evolution, and may simplify deep evolutionary history or suggest that evolution in the distant past occurred via different mechanisms than it does in more recent history. Second, the selective “pruning” of branches in the distant past can suggest a direction or “main line” of evolution. Species that flourished in the distant past are effectively obscured from view or pruned away in tree diagrams. The dynamic evolutionary map avoids the distinction between trunk and branches by depicting all the groups on the map in the same way, as uniformly sized dots. Second, there is no “main line” of evolution on the map; all groups radiate from the center so as to avoid a predominant direction of movement.
- **Upward progress** can be suggested by several elements in tree diagrams, thus fostering misconceptions about teleology and directed evolution. For example, on trees that are labeled, different groups may be described as “primitive” or “advanced,” or only certain derived groups within a lineage may be labeled. On the dynamic evolutionary map, all groups are labeled with rollover text, and each group is highlighted with additional information at least twice. A second way that tree diagrams can suggest directed or

progressive evolution occurs when some parts of the tree are much more detailed than others. Again, the map avoids differential resolution by including similar amounts of detail about groups across the span of the diagram. The third and perhaps most significant way that tree diagrams suggests teleology is by placing some groups at the top of the tree, and others beneath them. This placement of some groups above others automatically suggests a hierarchy. Hierarchy can be deliberately implied (e.g., figures 3 or 4), or unintentionally implied, as in modern phylogenetic tree diagrams that are flipped onto their sides in part to try to avoid implying superiority of some groups over others (figures 10 and 17). This directional and hierarchical aspect of trees is avoided in the dynamic evolutionary map by animating the visualization in a radial pattern.

The third group of concepts that I present here includes several important aspects of evolutionary theory that are not well visualized in either tree diagrams or in the dynamic evolutionary map. These concepts are either difficult to address with this type of visualization, outside the scope of this project, or both. I will return to several of these concepts later in this chapter, when I discuss future directions for development of this visualization.

- **The unit of evolution** is the clade, or ancestor-descendant group, rather than the individual. Small-scale evolution, or microevolution, occurs when the frequencies of genes within a population change. Over time, these changes in gene frequencies lead to macroevolution as populations become genetically different from their ancestors. The dynamic evolutionary map, as well as many tree visualizations, focuses on the large-scale pattern of evolution, so the changing composition of groups of organisms is not visually apparent. At any given point in time in either the map animation or in an evolutionary

tree, each group is fundamentally different from the previous point in time, although it is still represented by the same dot (on the map) or branch (on a tree). Viewers may infer that the dot or branch represents an individual, rather than a group, and this inference can contribute to the misconception that evolution is directed in a specific direction.

- **The causal forces** that shape the pattern of evolution are also not well represented in either evolutionary trees or the dynamic evolutionary map. As just discussed, both trees and the map focus on the pattern of macroevolution, rather than the forces that help shape the pattern. While text in the visualization does describe some evolutionary processes, the pictorial elements of the map do not exemplify these processes by themselves. As with the previous element, the focus on pattern can suggest that evolution occurs in a directed, rather than stochastic manner.
- **The pattern of evolution** in many tree visualizations, as well as the evolutionary map, depicts the evolution of one group of organisms through splitting and diversification from a single origin to the present day. This pattern suggests that evolution leads to a continuous increase in diversity and does not capture the complexity of the evolutionary pattern that includes extinctions that trim the tree over time. In the dynamic evolutionary map, extinction is largely addressed within the descriptions of individual present-day orders, rather than by adding dots for orders that are now extinct. Additionally, the map does not include a depiction of horizontal gene transfer, though this does not occur between avian orders.

Finally, the map-based visualization scheme in this project suggests additional concepts that are absent from tree diagrams, and which may be conceptual constraints that suggest

evolutionary misconceptions. Both of these concepts derive from the spatial nature of maps. I briefly describe them here, and in the next section discuss whether map users seemed to hold related misconceptions.

- **Spatial movement** through the real landscape is implied in the map by the dots that move across the map space. One of the events that can trigger cladogenesis is the physical separation of populations, which may then differentiate and form different species. Spatial movement is not the only mechanism by which populations can become separated, however; other important mechanisms include the erection of physical barriers between populations and mutations resulting in behavioral or other barriers to reproduction. Similarly, anagenesis is not necessarily tied to movement across a physical landscape (though anagenesis is often metaphorically conceptualized as the drift of a population across a genetic landscape, as in figure 15). The spatial movement of dots across the screen may, therefore, overemphasize the importance of physical movement in the real world in shaping the pattern of evolution.
- **Geographical location** is primarily suggested in the dynamic evolutionary map in the final disposition of orders across the map space. For example, viewers might infer that the map space is oriented similarly to common projections of world maps, and that Perching Birds (located in the upper left corner) are therefore found primarily in Alaska (which is located in the upper left of both North American and world maps used in the United States). While there are no geographical outlines on the map space, and viewers are told that it corresponds to a virtual genetic space, this might lead to misconceptions.

What evaluation results suggest about the visualization

In the previous section of this chapter, I described the conceptual affordances and constraints of the dynamic evolutionary map from a theoretical perspective. In this section, I discuss the implications of the user feedback and what the expert and novice responses suggest about the map from an empirical perspective. In the section that follows this one, I outline some of the potential areas of improvement for this visualization that were highlighted during the user evaluation.

The first affordance that this visualization was designed to communicate is common descent. The results of the novice feedback suggest that participants had very few problems recognizing that the movement of orders across the map space was indicative of their biological relationships. The responses do, however, suggest that participants largely viewed the orders as individual units, rather than as collections of individuals. I will return to this point shortly, but its significance here is that the ancestor-descendant aspect of common descent may have been unclear. Experts Two and Three felt that a branching structure of some type would provide additional cognitive support for viewers' understanding of common descent, a suggestion that I will return to later in this chapter. Interestingly, the degree of recognition of relationships among orders seems to contradict the experts' concerns that the lack of a constant branching structure might limit this understanding.

There was a modest level of usage of terms related to cladogenesis in the novice responses, as well as about twice as many terms related to anagenesis. Because this study did not make explicit comparisons between the dynamic evolutionary map and a tree diagram, it is difficult to make broader generalizations about the magnitude of these responses. Expert Three

was particularly concerned about the ability of the visualization to support an understanding of the importance of splitting events in forming new biological groups. In contrast to this expert's concerns, nearly all of the participants used branching, rather than the final proximity of orders, to evaluate the degree of relatedness between orders. As with shared descent, these results suggest that the movement of dots was in fact very helpful in visualizing patterns of relationship.

The novice participants largely seemed to be aware of the passage of time, because there were many general references to time passing. The lack of a timeline may have made it difficult to tie this awareness to an understanding of exact dates. For example, all but one participant were able to estimate a date for the Neoaves adaptive radiation in the visualization; two participants based their estimates on clicking backwards from the present day, and the rest based it on dates they found in the text (some of which gave them incorrect estimates). This suggests that the lack of a timeline was at least inconvenient for users who were asked to estimate a date. Experts Two and Three also specifically suggested that a timeline of some sort should be added to the visualization. I return to this suggestion in the next section of this chapter.

The map did not appear to suggest many conceptual constraints related to teleology, and the expert evaluators felt that its design minimized this possibility. When novices were directly asked which groups of birds seemed more "advanced" than others, they expressed uncertainty about which groups were more advanced, and largely ended up using physical characteristics to determine advancement. This question was deliberately open-ended and intended to get the participants to think about what constituted their own criteria for advancement and reveal how these ideas interacted with the visualization. While the fact that most novices ultimately did rank some groups as more advanced than others does suggest that they do have teleological ideas

about evolution, this is not surprising, based upon past research in the learning sciences. It does appear that the map part of the visualization may not have directly contributed to these misconceptions. For example, only one participant used distance on the map from the origin of birds to support ideas about advancement, which suggests that novices largely did not connect map distance or proximity to the original ancestral bird with “advancement.”

One of the concerns with modifying the underlying metaphor of this visualization from a tree to a map was that users would conflate distance on the map with distance in the real world. The second possible conceptual limitation related to the map metaphor was connecting the movement of the dots on the map with spatial movement in the real world. Participants were not explicitly asked to infer what the map suggests about the movement of birds in the real world. Only a small number of responses directly connected the real-world location or movement of birds with the movement of the dots in the virtual evolutionary space, though a larger number of responses referred to the movement of the dots themselves. These results suggest that there might not be strong affordances for this misconception. Two possible explanations for this are that the map metaphor might not be explicit enough for novices to entangle the affordances of maps with those of the visualization, or that novices are familiar enough with the conventions of non-spatial mappings that they do not immediately assume that the visualization represents real-world geography.

As expected, the visualization did not seem to support a robust understanding of the causal forces that shape the pattern of evolution. When novices were asked directly about why certain groups of birds are different, they primarily described the physical features that distinguish the groups from one another. There were a few references to the map itself, such as

citing the Neoaves adaptive radiation as the origin of many groups. Because the map's visual elements did not suggest the causes of groups differentiating, participants likely relied on a combination of their previous understanding of evolution and the visualization text to infer causal mechanisms. As with evolutionary mechanisms, the units of evolution were not emphasized in the evaluation, and novices probably based their responses to a large degree on their previous understanding. Novice responses to a question about the original ancestral bird species largely reflected a view of evolution in which the orders were seen as individuals, rather than as populations of individuals. The responses to other questions mentioned group membership much more frequently than ancestor-descendant relationships, which lends support to this idea. Experts Two and Three each made several specific recommendations that could enhance the emphasis on evolutionary mechanisms and units of evolution in future iterations of the map; I discuss these later in this chapter.

No questions were asked about the pattern of evolution that the map displayed; therefore, the empirical results do not add much information to concerns about the possible conceptual constraints from the pattern that was depicted. There were few references to pattern in novice comments. For example, all the novices recognized that the Neognaths are much more diverse than the Palaeognaths, and several responses suggested that participants assumed this diversity made the Neognaths more advanced than the Palaeognaths. There were also a few references to extinction, though it is not clear whether participants thought about extinction because of the map or because of the text. Later in this chapter, I discuss ways that the visualization's pattern of evolution might be changed in order to avoid possible misconceptions by users.

Finally, one important aspect of the map that may not have been communicated well was the representation of genetic similarity by distance on the map. Expert Two, for example, pointed out that the introductory text did not clearly state what map distance represented. The novice feedback did not clarify whether this was the case. In the first evaluation, participants largely based their explanations of similarities and differences among orders on the pictures and descriptions of the birds, rather than on the map. In the verbal evaluation, a question was added to clarify this issue, and the responses were similar. It seems clear that participants recognized that the proximity of dots was related to relationships of orders, but the text and images seemed to be more appealing as a source of explanation than the map itself.

In this project, there was a need to balance the development of the map as a new visual metaphor for evolution, as opposed to developing it as a full-fledged teaching tool. For example, the visual features in this project were primarily designed to communicate the pattern of avian evolution. The relative emphasis on the mechanisms of evolution was much lower. The expert evaluators were, however, primarily evaluating the visualization as a tool for science education (based both upon their backgrounds and on how they were asked to focus their evolution efforts). This created a slight misalignment in emphasis between the approach of the evaluators and the overall goals of the project. The expert evaluators did uncover several important limitations in the visualization, such as the lack of a timeline and the need to better describe the meaning of distance on the map. While some of the expert comments went beyond the original design intent of the project, their suggestions would potentially be very useful if this visualization was developed further as a classroom biology education tool.

Another issue raised because of the attempt to balance the metaphoric and educational aspects of the map was the novice participants' apparent focus on the text and images, rather than on the map itself. This focus somewhat limits the utility of their responses in evaluating the visual metaphor. In the next section, I describe some of the potential areas of improvement for this visualization that were highlighted during the user evaluation by both experts and novices. Later, I discuss some specific directions for map development that would improve its design for purposes of quantitative evaluation, and that might also extend its usability in various settings.

Technical aspects of the dynamic evolutionary map

There are several aspects of the visualization that might be improved in the areas of technical operation, visual design, and content. In this section, I focus upon small-scale design or technical changes that could potentially improve usability or appeal of the map. I will explore several additional relatively larger-scale issues later in this chapter.

The first potential area of improvement for the visualization is less technical than textual. As discussed previously, expert evaluators pointed out several areas where aspects of the map were not explained as clearly as they might have been. The most noticeable example is likely the lack of explanation that the distance between dots corresponds to genetic distance. In another example, many of the novice participants also seemed confused about which orders were hyperlinked and which were not, even though linked dots were outlined in dark blue in keeping with the conventional textual convention that indicates a link. Clear explanations of both of these elements in the introduction might help users understand the map better.

Another explanatory element that might improve the user experience is explaining in the introductory material that users would be seeing two different types of informational screens:

information about orders and information about evolutionary mechanisms (e.g., convergent evolution and adaptive radiation). While novices did not explicitly express confusion about this feature, one of the expert evaluators did. Again, enhancing the introduction might users avoid confusion when confronted with information that has two different organizational rationales.

Finally, one of the experts and a few of the novices suggested including different types of evidence for evolution. Specifically, they suggested including more information about skeletal structures, with accompanying photos or diagrams. Comparative images of skeletal structures might, for example, help viewers make connections between the morphological and molecular classification of birds. Alternatively, including even more pictorial material might draw viewers' attention away from the central map image. It is clear from the novice evaluations that users had a tendency to focus on the text and images, rather than the map, to answer questions. Future iterations of this visualization would have to balance the different visual elements in order to achieve desired communication results.

The second area for future improvements encompasses the interactive properties and design of the visualization. There is a significant amount of overlap between these two categories, as some possible aesthetic changes would affect the interactive features and vice versa. For example, changes could be made to the rollover labels that show the names of the orders. While most of the feedback about the rollover labels was positive, a few comments suggested that people still lost track of which order they were looking at. Making the labels a permanent part of the map (rather than just appearing on rollover) would help with this problem, but would also introduce excessive visual complexity to the map, particularly in the earlier stages when dots are quite close together. Another way to help users track the progress of orders might

be to have the dots leave a “trail” behind them that shows the path they have followed. This method of tracking would effectively introduce a tree-like branching element to the map, which creates a significant theoretical change in the visualization; because of the scale of this potential modification, I will discuss the possibility of including tree-like elements later in this chapter.

Another way to help users track the positions of specific orders on the map is to use color. For example, color could be used to delimit related groups of orders (e.g., Palaeognaths could be colored in shades of green and blue and Neognaths in reds and yellows), thereby helping users differentiate among groups. An alternative use of color might be to indicate changes in genetic composition of groups. In this case, the dots might slowly change color as they move away from one another and differentiate. Color here could be a cue that the nature of orders changes as they split and diversify from one another. This might be a positive affordance in that it suggests the important concept that orders themselves fundamentally change over time; in other words, the unit of evolution is a group with a changing genetic composition, rather than a unitary entity whose properties remain the same over time. This particular evolutionary concept is one that the map currently does not portray well, so this latter use of color might be very beneficial.

There are a few potential drawbacks with the use of color: first, adding a color variable increases the information density of the visualization; while this might be positive, it might also override the importance of other visual cues, such as distance on the map and genetic similarity. Second, from a usability perspective, the use of color as an information source should be approached carefully because of individuals who have difficulty discriminating among certain hues. Third, the use of color specifically to indicate genetic differentiation might strengthen a

teleological or directed understanding of evolution; for example, red might be associated with vibrancy and aggressiveness, or a change from pastel to bright hues might suggest that a group is evolving “toward” a goal in a directed manner. Adding color as a variable might be useful, but would also make the affordances of the visualization more complex.

One fairly simple addition to the visualization that would improve its connection to the evolutionary scale of time is a timeline that remains on screen throughout the user’s exploration. Both novices and experts suggested that adding a timeline would be a useful feature. I did not include a timeline in the current iteration of this project because I was concerned that novices would connect precise dates to branching events that were only loosely placed on the timeline, and thereby gain an incorrect understanding of the timing of evolutionary events. While this is still a concern, it is also possible that the popular conception of geological time is imprecise enough (e.g., Catley and Novick) that map users would only gain a very general understanding of the timescale, regardless of the precision of the events placed upon it. If that is the case, the benefits of including a timeline would outweigh the potential drawbacks.

Another potential use of a timeline would be as a navigation bar. In the current visualization, users can animate the map forward from one time point to the next, skip backward to the last point or to the origin of birds, or skip forward to the present day. The only animated segments of the visualization are the individual steps forward in time. The novice feedback suggests that users were able to get a sense of how the dots continuously changed position from one time point to the next; in other words, the ability to skip around in the visualization did not break the pattern of movement that the dots were showing. In fact, a few comments suggested that the ability to skip backwards (rather than watch a longer backwards-moving animation) was

a useful feature. An alternative way to include both animation and the ability to skip would be to use a timeline as an additional navigational bar. Viewers could use forward and reverse arrows to animate the map either forward or back, or else skip to specific time points by clicking on the timeline. This would make deliberate exploration easier, while preserving the continuity of movement displayed in the animation.

The structure of the current visualization separates types of content: frames divide a top navigation bar, the map on the left, and a sidebar for text and images on the right. This creates clear divisions between types of content, utilizes conventions of website design that should be familiar to most users, and might help users focus on the relatively simple visual features that are present. This type of division of space might be considered somewhat outdated, however, as more contemporary website design allows a fluid integration of text and visual elements. For example, in a different style of presentation, the map could take up more of the screen, and the text and images could appear in callout windows above the relevant dots when viewers click on them. This type of construction could make the visualization more appealing to users. The current appearance of the visualization should be considered a first approach for testing how the map concept actually operates; I discuss some possibilities for more sophisticated design later in this chapter.

One final element of the visualization that might be changed relates to the transitions between time points. In the current visualization, the sidebar text does not refresh or advance when the user moves to a new point in time. This has the effect of decoupling the map from the text, and might be confusing to users. None of the novices or experts mentioned this as a significant problem, but it might be somewhat confusing. One way to change this feature is to

program the visualization to automatically change the sidebar text when the user moves through the timeline. Such a feature could be used to enhance the temporal aspects of the visualization. For example, advancing to the next time point might pull up an introductory screen with information about what we know about that specific period in Earth's history. Adding this type of information would provide context for the events in avian evolution that were occurring at the same time, but might also distract users from the central focus of the visualization- the map itself.

Comparisons with other projects

Contemporary research on evolution visualizations in the learning sciences largely focuses upon understanding the ways that phylogenetic trees and other tree-based diagrams provide support for learning evolution in classroom settings (e.g., Cranfill and Moe; Maroo and Halverson; Matuk and Uttal; Novick and Catley). A few projects exist that are designed to evaluate the affordances of evolution visualizations or develop new methods for visualizing evolution in informal communication settings (e.g., Maddison *et al.*). The majority of these projects that do incorporate visuals as organizing features rely on tree diagrams. One final group of studies focuses upon the affordances that different types of interactivity add to phylogenetic tree visualizations for biology research (e.g., Carrizo). A selection of these projects is discussed in Chapter Three of this dissertation.

Phylogenetic trees instantiate important components of the theory of evolution, and as such provide support for evolutionary thinking and hypotheses about phylogenetic relationships. Learning to read, use, and construct phylogenetic trees is therefore an important part of biology students' education. In informal settings like museums, a wider range of visualizations and

displays are used to communicate about evolution (e.g., Giusti; MacDonald). Nevertheless, the tree of life as a metaphor for evolution is clearly still important in informal settings.

The dynamic evolutionary map differs from these projects in that its approach to changing the affordances of evolution visualizations explicitly modifies a conventional visual metaphor for evolution, rather than making the conventional metaphor interactive or simply adding explanatory materials to it. This methodology does not oppose the map to other methods of visualization, but does set it up as an alternative approach. While other research projects primarily work within the conventional tradition of visualizing evolution, the dynamic evolutionary map presents an alternative interpretation of evolutionary pattern that appears to support evolutionary understanding among biology novices. Presenting evolution in multiple media, formats, and metaphoric frameworks provides a variety of intellectual and affective affordances to which viewers might make connections. As a result, the map could clearly serve as a useful complement to phylogenetic trees in either a classroom or informal communication setting. It is interesting to contemplate, however, how the map might be modified to extend its use beyond that of an adjunct to tree visualizations. In the next section of this dissertation, I consider some of these possibilities.

Future directions for research with the dynamic evolutionary map

As outlined previously in this chapter, there are several ways in which the dynamic evolutionary map might be modified in order to improve its technical function. While I focused upon specific technical modifications in the previous discussion, in this section I will expand my focus to include larger-scale modifications of the visualization that open up additional avenues of

research. These potential research directions might extend the range of communication situations in which the dynamic evolutionary map can be used.

The first potential large-scale modification of the visualization involves integrating a branching structure or tree diagram of some type with the map. Two possibilities for such an element immediately present themselves. First, the pathways of the dots could trail lines behind them, thus displaying the branching pattern of movement in a more persistent fashion than is presently the case. Although novice comments suggest that the branching pattern of evolution was to some extent implied by the pattern of motion, the expert evaluators were concerned that the pattern of movement should be reinforced. The second possibility for incorporating a branching element would be to add a branching diagram, perhaps a traditional phylogenetic tree, as an accessory to the map. Inclusion of a branching structure in either form might promote the acceptance of the dynamic evolutionary map as a tool for formal science education. As discussed previously in this dissertation, phylogenetic trees are central to evolution education, and are used in several ways to support an understanding of evolutionary processes. Therefore, adding this element might expand the range of potential uses of the visualization.

Integrating a branching structure with the map raises interesting questions about the affordances that would be communicated by such a combined visualization. The central focus of this project has been to find a way to communicate evolutionary pattern with digital tools that facilitate a new visual metaphor. If a tree or branching structure were added to the visualization, would its conceptual affordances outweigh those of the map? How much impact would the map metaphor have on viewers if a branching pattern is also present? If visualization viewers are more familiar with tree diagrams from other contexts, they might concentrate on the familiar

structure and pay less attention to the novel map element. Would adding trailing lines to the movement of the dots strengthen the potential misconception that movement of the dots symbolizes physical movement of unitary entities through space? Alternately, could the lines be interpreted as representing a “family tree” of avian orders that might support viewers’ understanding of branching events in evolution?

There are several ways that a branching structure might be accommodated within the visualization that might minimize potential conceptual conflicts with the primary map visualization. For example, users might be able to toggle the branching structure on and off as they wished. Another option would be to make the map the central focus by placement, size, and serving as the interactive part of the visualization; in other words, the tree would be a clear adjunct to the map, instead of the other way around. Finally, introductory material could contextualize the visualization in such a way that the map is emphasized.

Another approach that lets us consider the inclusion of a tree element is Edward Tufte’s concept of a visual “confection:” “a multiplicity of image-events” assembled on “the still flatland of paper” (*Visual Explanation* 121). For Tufte, confections combine selected events along multiple “strands of story,” and create collage-like images that interpret narratives across space and time. While Tufte’s description of confections does not explicitly consider interactive elements, the dynamic evolutionary map could be considered a type of confection that juxtaposes “stories” at various time points along the narrative threads that make up the tale of avian evolution. These stories are told with both text and images, adding various layers to the exploration of the story of birds. The map provides the central image upon which viewers orient themselves to the visualization as a whole. Adding a tree element to the visualization, as well as

a timeline, as discussed previously in this chapter, could enrich the graphical layers of the confection further.

We could also consider other elements that would enhance the map, such as the suggestion from one expert of providing direct comparisons of physical features of birds in order to facilitate connections between molecular and structural evidence for evolution. From a confectionary perspective, integrating additional visual information creates a more multi-layered and versatile communication tool. Finally, one way of creating a more tightly focused narrative structure might be to focus on specific events that forced changes in the scientific understanding of avian evolution, such as the discovery that birds are dinosaurs and the recent rearrangement of the phylogeny of birds of prey. Emphasizing these elements could draw users, particularly younger users, into the confectionary narrative.

One complication of building additional elements into the visualization is that, by increasing its complexity, it becomes more difficult to disentangle the affordances being communicated by one part of the visualization from those communicated from another part. In the initial novice evaluation of this project, many of the responses suggested that participants were focusing more upon the text and pictures than on the map itself. The text-heaviness of the visualization may have made it more difficult to distinguish the affordances being communicated by the map from those suggested by the text. In order to obtain more robust information about the conceptual affordances of the map metaphor, it would be appropriate to simplify the text and focus upon the interactive map. One important limitation of this project is the absence of direct comparison between the dynamic evolutionary map and a similarly interactive visualization with an underlying tree structure. Creating a simplified version of the visualization would facilitate

future research making direct, quantitative comparisons between these two visual metaphors. It would also address the concern that the novice participants may have been paying more attention to that text and images than the map itself. Since such research could support the integration of the map into classroom or informal communication settings, this is an important consideration.

The second way to take the design of the dynamic evolutionary map in a different direction is by changing the groups that are included on the map. Specifically, there are no extinct (i.e., fossil) orders represented by their own dots on the map. While the visualization does include information about extinct groups of birds, this information is linked to the dots representing their hypothetical closest relatives. One of the effects of not including extinct orders is that the overall pattern of movement shows a rapid diversification and then constant expansion of birds. While this does represent the evolutionary pattern of extant orders, it both reduces the complexity of avian evolution by not including orders that became extinct and may contribute to a teleological understanding of evolution as a process of constantly increasing diversity (Doolittle and Baptiste; Gould).

The reason fossil orders were not included in the visualization was that the map is based on molecular evidence, and therefore only includes orders with living representatives. In many cases, the classification of fossils is disputed, so it would be difficult to integrate them into the map. For example, the fossil pseudo-toothed birds have variously been considered to be closely related to waterfowl, to albatrosses, and to pelicans (Mayr 59), all of which are in different locations on the dynamic evolutionary map. Nevertheless, future iterations of this project could incorporate fossil orders into the map and add to the discussion of the complexities of classifying birds based upon both fossil and molecular evidence. Another way to introduce the concept of

extinction would be to begin the visualization by showing both the ancestor of all modern birds and its contemporaneous avian and non-avian dinosaur relatives. Several of the groups of birds whose descendants live today coexisted with a variety of other dinosaur orders; modern birds are the only dinosaurs that survived the Cretaceous-Tertiary mass extinction. Including these other groups would dramatically illustrate the effect of the mass extinction, as well as introduce the importance of contingency in evolution.

A third way to incorporate larger changes into the design of the visualization is to make the animation of the dots more dynamic. In the current map, when one order splits into two, the animation simply shows two orders sliding out from the first. The splitting events that result in the formation of new orders are important features of evolutionary history, and a more elaborate type of event might emphasize their importance better. For example, the original order might stretch or expand, and then two new groups might slowly pinch off from it like bubbles forming. Color could also be used to indicate that the genetic composition of the two groups was changing during the splitting event. Animating the splitting events in a more dynamic manner would help tie the large-scale pattern of evolution to the smaller-scale changes in genetic composition that occur within groups to cause splitting. Within formal biology education, for example, this link between large-scale and smaller-scale evolutionary processes is crucial for learning how evolution works (Catley 768). If the dynamic evolutionary map included affordances that suggested this process, it might be more useful in a formal educational setting.

Changing the underlying computational structure of the visualization could facilitate the final group of large-scale modifications that I will discuss. As described in Chapter Four, the pattern of movement of orders on the map was created by plotting the present-day positions of

orders in an evolutionary space relative to one another and to the ancestral bird, and then animating the orders from the origin point out to their final positions in a stepwise process. The present-day positions of orders and timing of branching events were estimated by referring to two phylogenetic trees representing avian evolution (figures 10 and 17). The effect of this design method is to create a rather contingent and qualitative character in the map and to limit the range of display options of the orders. For example, the placement of the dots over the course of the animation is determined by how they were placed on the stopping point screens. In order to change the speed or direction of a dot's motion, one would have to reposition the dot on each sequential screen manually.

Other types of computational frameworks could enable a more flexible approach to the display of data in the visualization. For example, if information about orders at each time point were placed into a database, it would be easier to update the visualization by changing the database parameters. Many digital media researchers, including Lev Manovich, argue that the underlying computational structure of the database is one of the defining forms of new media (214). A database structure potentially allows each new encounter with a digital text to be new, as readers make new connections between different parts of the text and pull up information in new configurations. In the dynamic evolutionary map, database-linked information about orders could encompass text and pictures as well as dot position information. If, for example, a new fossil Terror Bird were discovered in Florida 30 million years ago, one could enter that information into the database, link it to the appropriate order at the appropriate point in time, and the user could easily see the new information. Thus, a database-driven redesign of the

visualization could make it more adaptable to different communication settings in response to new information.

A database-driven visualization could also facilitate a more customizable user experience. The dynamic evolutionary map is a communication tool, and therefore is intended to convey a specific message about evolution. There are, however, several user-driven elements, most notably features that enable synchronic and diachronic exploration of the pattern of avian evolution. Novice feedback suggests a few ways that the types of interaction afforded by the visualization might be enhanced to provide more individualized exploration of the map. For example, dots could be programmed to stay highlighted as the user moves forward and backward in time, and so allow users to follow the evolution of a specific group that interests them. Information about each group throughout time might be stored in the database, and the animation made more flexible; this would allow the user to focus on a specific group during the time periods for which information is known about it and animate through the rest of the timeline, rather than having the timeline animate forward in fixed intervals for all groups. Another feature might allow users to zoom in on one particular group of birds, and follow its descendant groups over time. Lessons about the mechanisms of evolution could also be integrated into the customized narrative at appropriate points, thus addressing one limitation of the visualization noted in the expert evaluation.

These types of enhanced interactivity would give users more control over their own narrative experience of the visualization. More robust types of user interaction with the evolutionary narrative would effectively enhance the co-creation of meaning between user and program. This type of interactivity has the potential to be more effective at engaging users and

achieving communication (McDaniel 382). It may, however, require a different underlying programming architecture from the ActionScript- and HTML-based method currently being used.

Finally, future research related to this project could also be extended into the more computationally based field of information design. Phylogenetic trees are created by parsimony analysis, an analytical technique that compares a series of dichotomously branching trees to find the tree whose shape requires the fewest number of changes in the traits being analyzed. Two key aspects of these trees are that relationships between groups are always resolved in nested pairs (i.e., any group will be most closely related to only one other group), and that any pair of relationships can be rotated around a branch point without changing the relationship being depicted (i.e., as long as the connecting points stay the same, the tree can be reconfigured in many possible ways).

One of the challenges for creating this visualization was formulating a way to depict this bifurcating and flexible tree in a more constrained two-dimensional space. As described in Chapter Four, I resolved this challenge by dividing the map space into quadrants, and arranging groups of related orders in the quadrants. Because of the rotatable connections on a phylogenetic tree, the placement of groups *within* quadrants was somewhat arbitrary. In other words, the fact that flamingos and bustards are located on the edges of the Neoaves quadrant (figure 18) is largely meaningless. They could be arranged much more closely to one another on the map, as long as these two orders were co-located with the other orders that are most closely related to them. Thus, the configuration of orders on the map space is not solely based on genetic

similarity, but includes a subjective element. Viewers might be introduced to misconceptions about how birds are related, based upon the way they are displayed on the screen.

The best way to remove this subjective element of order placement from the visualization might be to use the mathematical data (e.g., percent similarity between orders) as a starting point for laying out the visualization, rather than a phylogenetic tree, which already has topological constraints built into it. Under this scenario, the data could be analyzed using a method that would directly result in an “affinity map,” as in figure 9. An affinity map created by analyzing the underlying data would be more accurate than the map created for this project. Such an analysis would be computationally intensive; the study that generated the phylogenetic tree used in this project looked at 19 different genetic locations in 169 avian species (Hackett *et al.* 1763). Also, a major potential drawback of the affinity map method is that it could completely eliminate the branching pattern of shared descent that is an important aspect of evolutionary theory. Future research might take a hybrid approach, which could combine an affinity map of orders that accurately shows genetic similarity with a branching pattern that shows a hypothesis of ancestral relationships.

Implications for science communication

Now that I have reiterated the theoretical structure and empirical findings of this project, and suggested future avenues of research, I will discuss its broader implications for science communication and the public understanding of science. As discussed in the previous section of this chapter, there are various changes that could be made to the dynamic evolutionary map itself in order to expand its possible ranges of uses into the educational realm in addition to the area of

informal science communication, so I will also discuss educational implications of this project. Finally, I will sketch possible implications of this project within the sciences.

This project has potential applications in two distinct informal communication settings: museums and other learning centers and online. These two types of settings have largely different physical affordances and opportunities for interaction with individuals who can help interpret the visualization. Nevertheless, some commonalities link the different ways this project can help inform each type of communication.

The first point at which the results of this project can be brought to bear on both online and museum- or learning center-based science communication is in what it adds to our understanding of how to develop multiple models for visualizing a scientific concept. Multiplicity of models is important because different visualizations exemplify different aspects of scientific concepts, and may therefore suggest different cognitive affordances to viewers. The affective dimensions of visualizations are also important. Individuals may be attracted to different types of diagrams, or become engaged by different types of interactivity. By presenting multiple visual interpretations of scientific concepts, science communicators can increase the chances that the public will make cognitive or affective connections with their subject matter. This project demonstrates one approach for generating new models for science communication by evaluating and revising the visual metaphors that underlie existing models.

The second way that this project can be used to inform informal science communication is by serving as an example of a visualization that endeavors to incorporate a narrative structure and interactive features that engages users in meaningful interaction. While the user evaluation of this project was not explicitly designed to evaluate the affective user response to the types of

interactivity that the visualization incorporates, both the expert and novice evaluators offered several suggestions that might improve these features. In the preceding text, I have outlined a few specific ways that the current visualization might be reworked to enhance its interactivity. These results could therefore be used to suggest design possibilities for other, similar, interactive science visualizations.

A third way in which this project can inform the field of science communication is in its attempt to address the idea of transparency in scientific diagrams. Scientific representations highlight certain aspects of the thing they represent, while deemphasizing others (Elgin 1). While subject matter experts might understand the decision process that determines what aspects of an object are emphasized, subject matter novices may not. Novices may therefore interpret visualizations as transparent; i.e., as unmediated, “true” depictions of reality, rather than as metaphoric representations that are necessarily incomplete.

In this visualization, the introductory text explained the difference between different types of evidence for evolution, and supplemental text about different avian orders discussed why the classification of birds has undergone major revisions. Both of these factors contribute to the underlying pattern of the visualization that could otherwise be unexplored or taken for granted by viewers. The exploration of transparency was, however, a secondary feature of this visualization. I have previously described how this project suggests more elaborate database-driven types of visualizations that would afford different types of viewer interactivity and formats of data display. The concepts of transparency and the underlying hypotheses that underpin the graphical representation might be better explored in such an interactive

visualization. The exploration of transparency might be done in many types of science visualizations, such as temperature reconstructions that communicate about global warming.

Most museums incorporate several different types of displays and interactive tools for informal science communication within exhibits (e.g., Giusti), and tree diagrams that represent the pattern of evolution are often prominent in these exhibits (e.g., Giusti; MacDonald). In these settings, problems of interpretation can arise when visitors are unfamiliar with the representational conventions of tree diagrams. For example, prior understandings of evolutionary concepts and unfamiliarity with phylogenetic trees can interfere with correct interpretation of trees, and in many cases tree diagrams themselves suggest misconceptions about evolution (MacDonald 26). Labels are often used to provide context for trees and other display objects, but in many of these settings, it is difficult to fully interpret the visual conventions for visitors.

This project demonstrates an alternative approach to visualizing evolution that could be combined with a phylogenetic tree-based display to facilitate visitors' interaction with evolutionary ideas. The design of the dynamic evolutionary map affords creative exploration of evolutionary history, and if it were enhanced with a timeline and other features as previously described in this chapter, it could be used to provide the conceptual evolutionary structure to underpin visitors' experience with physical museum displays, such as fossil or stuffed birds. Birds may also be an appealing group of organisms for museum visitors, and their descent from the ever-popular dinosaurs could easily draw visitors in to learn about them. Therefore, this project might be adaptable to a museum setting, as well as serve as an example of integrating multiple types of information into an interactive format for visualizing evolution.

Visual elements are important aspects of the design of digital media and science communication, and are therefore central tools in both online science communication and networked informal learning. The dynamic evolutionary map is currently located online, and so its capabilities for online informal science communication are fairly self-evident. One question that remains is how this project fits into current trends in the burgeoning field of online science communication. In the preceding parts of this chapter, I have outlined several ways that this project could be enhanced to better convey certain evolutionary concepts or to enhance its capability for meaningful interaction. For example, this project could be expanded into an interactive website that allows users to manipulate the way that avian evolution is being displayed, or could be redesigned to focus on scientific transparency and the assumptions that underlie avian phylogeny.

Current projects in online science communication take many different forms, as discussed in Chapter One of this dissertation. Three major genres include discussion-based blogs and social networking sites (Minol *et al.*), participatory public science (Bonney *et al.*; Friedman *et al.*; Roth and Lee; Trumbull *et al.*), and game-based systems that could be configured to communicate science (McDaniel; Von Ahn and Dabbish). The visualization created in this project does not fit into any of these genres, so in many ways it represents a more traditional narrative-based approach to science communication. This does not necessarily represent a weakness for this project. For example, one of the potential problems with using unstructured science visualization tools in participatory science settings is that participants in these projects may not understand which tools are best suited to visualize specific types of information (e.g., Thompson and

Bonney). This visualization may therefore present a more structured approach to visualizing evolution that provides more support for a novice audience.

As discussed previously in this chapter, the dynamic evolutionary map has the potential to be used as an alternative or complement to traditional phylogenetic trees in formal educational settings. It is specifically designed to address conceptual limitations of the tree of life as a traditional educational metaphor. Its novel structure and interactivity may help make it engaging for digitally savvy students, and exposure to multiple methods of visualizing evolution could help students overcome preconceived misconceptions about evolution, which is an important area of research in the learning sciences. If some of the major concerns of the expert evaluators were addressed, their feedback suggests that the educational community is eager to incorporate tools like this one into the classroom.

Another consideration for education is that this visualization is programmed using ActionScript and HTML, both formats that can be read by a large number of computer users. It is therefore designed to be accessible online to a wide audience. In a broad sense, digital tools can provide access to novel educational resources and connect information in new ways that are becoming characteristic of Twenty-first Century communication. One caveat is that Flash, the program that reads ActionScript, requires a plug-in to read. Although this program is free, some devices such as tablets do not currently offer support for it as of this time of writing. Therefore, there are technical considerations involved with the possible future use of this visualization.

For the broader educational community, this study provides an example of ways to use new digital tools to rethink traditional education challenges. While digital tools have promise for transforming science communication and education, different issues must be met by specific

solutions. Evolutionary biology is one such communication challenge, particularly in certain regions of the United States. There are many conceptual and social challenges for evolution education; therefore, novel and useful tools to enhance this topic should be of general interest to the educational community at large. While this project does not address conceptual and social barriers to accepting evolution, it may help educators approach the subject from a different angle, and so support learning.

In addition to its implications for science communication and education, this project has implications for the field of evolutionary biology itself. Information visualization research, in general, opens up exciting possibilities for the innovative display of information. In intellectual fields, new technologies and techniques for displaying data can help support creative thinking and spur the development of novel solutions to problems. If the dynamic evolutionary were developed as a computationally based supplement to phylogenetic trees, it could be used to create affinity maps for displaying evolutionary datasets. Such affinity maps could complement the phylogenetic trees used for data visualization by evolutionary biologists. Unlike the affinity maps of the Nineteenth Century, these maps would be based upon quantitative data, and could therefore potentially be used in data analysis, as well as data display.

Perhaps more importantly, affinity maps would give biologists an alternative way to support their thinking about evolution, and would help enhance the field's collective conceptual schema for picturing evolution. Visualization plays an important role in the sciences, and the field of evolutionary biology is no exception. Classic images like Darwin's tree of life (figures 1 and 2) and Wright's adaptive landscape (figure 15) have become part of most biologists' understandings of macroevolution and microevolution, respectively. While the dynamic

evolutionary map does not rest upon groundbreaking innovations in statistical and mathematical techniques, as do these images, it does suggest a potentially useful new approach to visualizing biological data. From one perspective, a computationally based affinity map would simply involve taking a transverse slice through a phylogenetic tree. Another way to look at such a map, however, is that it offers a novel perspective that suggests a third dimension in a structure that is normally viewed flattened into two dimensions. Such a map could therefore enrich biologists' tree-based thinking, and help them both conceptualize and share more complex ideas about the relationships among groups of organisms.

Finally, the methodology used in this project can be applied to other scientific concepts, either to aid in visualizing these concepts within the sciences or for communication of these ideas with the broader public. In this dissertation, I have described a method for applying digital tools to visualizations of important scientific concepts that analyzes the metaphoric affordances of existing visualizations, identifies categories of affordances to retain or add and conceptual constraints to discard from a new visualization, and applies digital tools to the creation of a new visual metaphor for each concept. While the dynamic evolutionary map does not exemplify all of the important concepts of macroevolution, it does represent a novel approach to visualizing evolutionary pattern. This visualization has some overlap with traditional tree-based visualizations, but it also extends both the array of conceptual affordances represented in such tools and the range of communication settings in which such visualizations can be used.

This project opens up a new approach to designing science visualizations that can be used to take traditional methods for constructing such models in new directions. By identifying the areas where we can apply digital tools to metaphoric affordances and constraints, science

communicators can productively harness the computational power and possibilities for interactive user engagement that these tools provide. This dissertation synthesizes theories of conceptual metaphor and distributed cognition to provide an empirical framework that supports this approach. From the fields of new media and visualization research, it draws suggestions for the visual and narrative design of visualizations that provide meaningful interaction to their users. Finally, it shows that historical experimentation in visualizing scientific concepts can help us generate innovative approaches to science communication, when coupled with modern digital tools.

While the dynamic evolutionary map is not a revolutionary example of innovation from the perspectives of statistical methodology or visual design, it does represent an important step forward in the synthesis of scientific, design, and metaphor theory, as applied to a specific problem of communication. This project demonstrates that these theories can be used to guide the construction of a visualization for communicating a scientific concept in a way that is both novel and grounded in theory. The results of empirical evaluation of this visualization suggest that this approach has been at least partially successful in communicating evolution differently than in existing tree-based visualization methods. Future enhancement and testing of this visualization would help refine these successes. There are several potential applications for the visualization created in this project in the fields of informal science education, formal education, and evolutionary biology. Moreover, the approach suggested in this dissertation can potentially be extended into other areas of science and science communication. By placing birds onto the dynamic evolutionary map, this dissertation points to a way forward for visualizing science communication in the future.

APPENDIX A: VISUALIZATION DATA SOURCES

Table 6: Data sources for information about birds and evolution used in the visualization

Topic	Data Source
General information	<p>Cech, Rick, John B. Dunning, Jr., and Chris Elphick. "Behavior." <i>The Sibley Guide to Bird Life and Behavior</i>. Eds. Chris Elphick, John B. Dunning, Jr., and David Allen Sibley. New York: Alfred E. Knopf, 2001. 51-79. Print.</p> <p>BirdLife International. "IUCN Red List of Threatened Species." Version 2011.1. Web. 26 July 2011.</p> <p>Clements, James F., Tom S. Schulenberg, Marshall J. Iliff, Brian L. Sullivan, Chris L. Wood, and Don Roberson. "The Clements Checklist of Birds of the World." Version 6.6. 23 Aug. 2011. MS Excel. Web. 10 Aug. 2011.</p> <p>Futuyma, Douglas J. <i>Evolutionary Biology</i>. 3rd ed. Sunderland, MA: Sinauer, 1998. Print.</p>
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Bustards	<p>Mayr, Gerald. <i>Paleogene Fossil Birds</i>. Berlin: Springer, 2009. <i>SpringerLink</i>. Web. 10 July 2011.</p> <p>Tobias, Joseph A. "Bustards (Otididae)." <i>Grzimek's Animal Life Encyclopedia</i>. Eds. Michael Hutchins, Arthur V. Evans, Jerome A. Jackson, Devra G. Kleiman, James B. Murphy, Dennis A. Thoney, et al. 2nd ed. Vol. 9: Birds II. Detroit: Gale, 2004. 311-330. <i>Gale Virtual Reference Library</i>. Web. 18 July 2011.</p>
Cuckoos and relatives	<p>Laymon, Stephen A. "Cuckoos, Roadrunners, and Anis." <i>The Sibley Guide to Bird Life and Behavior</i>. Eds. Chris Elphick, John B. Dunning, Jr., and David Allen Sibley. New York: Alfred E. Knopf, 2001. 332-335. Print.</p> <p>Martinez, Juan Gabriel. "Cuculiformes (Cuckoos, Anis, and Roadrunners)." <i>Grzimek's Animal Life Encyclopedia</i>. Eds. Michael Hutchins, Arthur V. Evans, Jerome A. Jackson, Devra G. Kleiman, James B. Murphy, Dennis A. Thoney, et al. 2nd ed. Vol. 9: Birds II. Detroit: Gale, 2004. 91-100. <i>Gale Virtual Reference Library</i>. Web. 21 July 2011.</p> <p>Mayr, Gerald. <i>Paleogene Fossil Birds</i>. Berlin: Springer, 2009. <i>SpringerLink</i>. Web. 10 July 2011.</p>
Rails and cranes	<p>Archibald, Gorge W. "Cranes (Gruidae)." <i>Grzimek's Animal Life Encyclopedia</i>. Eds. Michael Hutchins, Arthur V. Evans, Jerome A. Jackson, Devra G. Kleiman, James B. Murphy, Dennis A. Thoney, et al. 2nd ed. Vol. 9: Birds II. Detroit: Gale, 2004. 23-36. <i>Gale Virtual Reference Library</i>. Web. 14 July 2011.</p> <p>Armistead, George R. "Limpkin." <i>The Sibley Guide to Bird Life and Behavior</i>. Eds. Chris Elphick, John B. Dunning, Jr., and David Allen Sibley. New York: Alfred E. Knopf, 2001. 251-252. Print.</p> <p>Armistead, George R. "Rails, Gallinules, and Coots." <i>The Sibley Guide to Bird Life and Behavior</i>. Eds. Chris Elphick, John B. Dunning, Jr., and David Allen Sibley. New York: Alfred E. Knopf, 2001. 246-250. Print.</p> <p>Mayr, Gerald. <i>Paleogene Fossil Birds</i>. Berlin: Springer, 2009. <i>SpringerLink</i>. Web. 10 July 2011.</p> <p>Organ, Chris L., and Scott V. Edwards. "Major Events in Avian Genome Evolution." <i>Living Dinosaurs: The Evolutionary History of Modern Birds</i>. Eds. Gareth Dyke and Gary Kaiser. Hoboken: John Wiley and Sons, 2011. 325-337. Print.</p> <p>Seng, William J. "Cranes." <i>The Sibley Guide to Bird Life and Behavior</i>. Eds. Chris Elphick, John B. Dunning, Jr., and David Allen Sibley. New York: Alfred E. Knopf, 2001. 253-255. Print.</p> <p>Taylor, Barry. "Rails, Coots, and Moorhens (Rallidae)." <i>Grzimek's Animal Life Encyclopedia</i>. Eds. Michael Hutchins, Arthur V. Evans, Jerome A. Jackson, Devra G. Kleiman, James B. Murphy, Dennis A. Thoney, et al. 2nd ed. Vol. 9: Birds II. Detroit: Gale, 2004. 45-67. <i>Gale Virtual Reference Library</i>. Web. 14 July 2011.</p> <p>Worthy, Trevor H., and Richard N. Holdaway. <i>The Lost World of the Moa: Prehistoric Life of New Zealand</i>. Bloomington: Indiana UP, 2002. Print.</p>

APPENDIX B: EXPERT EVALUATION QUESTIONS AND RESULTS

E-mail instructions and questions for experts

The following text is taken directly from the evaluation instructions and questions that were e-mailed to experts:


Introduction

Illustrations such as the evolutionary “tree of life” are designed to overcome barriers to understanding evolution and provide a phylogenetic framework for thinking about evolutionary pattern and processes. However, misunderstandings about evolution may arise from how we depict the tree of life in graphical form. The interactive visualization that you are being asked to evaluate is an attempt to address some of the limitations of the tree of life as a visual metaphor for macroevolution.

In general, please explore the visualization with an eye toward identifying affordances or associations about evolutionary processes that it may suggest to biology novices (either students or the general public). Your feedback about the design of this visualization is greatly appreciated.

Instructions:

- 1) Begin by going to the visualization website at <http://goo.gl/R8vFe> (this is a shortcut to the site; the full URL is <http://physics.ucf.edu/~yfernandez/shs/birds/homeframe.html>). It should look like this:

Bird Evolution: A Dynamic Evolutionary Map	Introduction	About this visualization	Credits: Sonia Stephens e-mail me
		<p style="text-align: center;">Introduction</p> <p>Where did the first birds come from, and how long have birds been around? How are modern birds related to one another? How have birds evolved, and changed over time?</p> <p>There are three main sources of evidence that scientists use to answer these questions:</p> <ul style="list-style-type: none"> ▪ Anatomical similarities and differences among living birds. For example, modern perching birds all share a similar type of leg and foot anatomy that lets them grasp thin branches and easily perch on them. This specialized anatomy is shared by all species in the order Passeriformes, and is not found in other orders of birds. ▪ Anatomical similarities and differences between fossil birds and living birds (and similarities and differences among the fossils, themselves). For example, the fossil bird <i>Figgoia</i>, dated to more than 65 million years ago (MYA), shares many similarities to living ducks and geese. ▪ Molecular similarities and differences among living birds. Species with more similar DNA sequences should be more closely related than species with very different DNA. For example, the genes of a sparrow and a starling (both perching birds) are much more similar to one another than they are to the genes of a duck. <p>These three types of evidence complement each other, and often the strengths of one type of evidence can help overcome a weakness in another type. For example, a 65 million year-old fossil of a duck-like bird pretty much tells us that this duck-like species was living 65 MYA. Unfortunately, fossils are rare—they form under very unusual environmental conditions, so the fossil record is</p>	

- 2) Read the “Introduction” and “About this visualization” pages (accessed via links on the top frame of the screen).
- 3) Explore the map with the goal of evaluating its potential use as a tool for communicating about evolution. Jot down notes if you wish during your exploration.
- 4) Please answer the following questions about your experience. Answer Part 1 in as much detail as you can, then move on to the remaining questions.

Part 1: Please describe your general impressions of the visualization, in terms of its utility as a general education or communication tool for evolution. In particular, what associations or affordances about evolution is it likely to suggest to viewers who are biology novices?

Part 2: For each remaining question, if you have already addressed a specific topic in your “general impressions” comments, you may skip the question.

- 1) How well do you think this visualization conveys the concept of common descent? Are there elements of the visualization that suggest this concept to users? Are there elements that might lead to misconceptions among users?
- 2) Are there elements of the visualization that might suggest teleological misconceptions to users? Are there elements that might help users avoid such misconceptions?
- 3) How well do you think this visualization conveys the relationship of macroevolution to the passage of time? Are there elements that might suggest time-related misconceptions to users?
- 4) How well do you think this visualization depicts avian orders as ancestor-descendant lineages, rather than as individuals? Are there elements of the visualization that might lead to misconceptions about this aspect of macroevolution?
- 5) How well do you think this visualization conveys the concepts of cladogenesis and anagenesis? Is there a good balance in emphasis between these mechanisms of evolution, or does it seem that one mechanism overshadows the others?
- 6) How well do you think this visualization conveys the scientific rationale that underpins our understanding of avian evolution, in terms of types and weighing of evidence?
- 7) Do you have any final comments or suggestions that would improve this visualization as a potential tool for communication or education about evolution?

Thank you again for your feedback and time.

Comments from Expert #1

(General impressions): Appears very appropriate and gives clear information throughout the animation. Also provides helpful information about the various terminologies, clarifies and further explains about the ideas about change over the time. Made it easy to read and not overwhelming. I think this pedagogy should help students to promote active learning. Also this will help students to practice concept mapping exercise but more interactive.

Question 1 (common descent): Yes, good solution for students to exercise and understand the concept. Yes, but maybe a timeline could be provided from the time of first bird to the present day, when we click on each bird example. No.

Question 2 (teleological misconceptions): No.

Question 3 (passage of time): It helps to compare the phylogenetic divergence among groups and relation to very distant species. No misconceptions.

Question 4 (orders as ancestor-descendant lineages): Very good.

Question 5 (cladogenesis and anagenesis): Balanced, both shared characters helped me to construct the mechanism of evolution.

Question 6 (scientific evidence for evolution): Very well explained.

Question 7 (suggestions for improvement): I have gained more knowledge about avian evolution using a different approach besides trees and branches showing offshoots into specialized groups.

Comments from Expert #2

(General impressions): Intro is informative - 3 lines of evidence etc. suggest including more e.g., convergent evolution, biogeography, see later. Notes on various groups are informative without being overwhelming. Suggest a separate references section with links when appropriate.

Whereas clicking on the first circle gets you some background on birds as avian dinosaurs, without clicking on it you can navigate through the whole site without knowing this really important and to me exciting “hook”. Overall while I realize this is a visualization of a molecular data set I am concerned about the lack of morphological character evidence. I realize this can be very difficult to provide but characters are referenced several times under particular groups. I see it as an important concrete (vs. abstract) scaffold for learners “Oh so those groups that share character x are more closely related than to group b”. Apart from the text on Neoaves I could not find any reference to the mechanisms of cladogenesis/speciation/adaptive radiation. The site asks learners to take it on trust that these patterns are the result of unknown (to them perhaps) processes. This might also help the premise that the dots represent populations of individuals (taxa) and that these processes, while mediated through the individuals that make up these populations, are only retrievable from taxa over evolutionary time. You might consider adding some of this to the intro or have another section maybe on processes?

The site states the map is a result of both studies projected onto a landscape of evolutionary change, which is a great concept, but this does not come across to me from a bunch of dots on a blank screen. Evolutionary space is multi-dimensional; at least time, space, niche- not as currently depicted. Not sure how to address this. Have you looked at providing supplementary resources such as evograms that synthesize many elements?

I found the navigation a little cumbersome and constantly hit the wrong button but that might well be me but certainly labeling the buttons would help. Because it is not stated, what does the spacing between circles mean? Why are some clustered closely others farther apart? You need to explain this genetic distance concept for novices.

Your discussion of derived characters in the ratite notes I think is very important and should be highlighted elsewhere, as it is a central concept in understand phylogenetics.

I lose the relative relatedness of groups when taxa are not highlighted (I realize they can be rolled over, but without that they become one dot among many. Don't know how to resolve this with including a tree - a phylogram I guess.

Discussion in perching birds on importance of biogeography could maybe be highlighted more (see earlier comments).

There is no time scale. Even though you state each increment is 9 million years, without a relative scale on the screen its impossible to keep this in your head and the deep time dimension has been show to be a major impediment to understanding evolution.

My screen got stuck on Rails and Cranes I could not access other groups e.g., sun bitterns probably just a bug.

As already noted I think you need an upfront discussion of convergent evolution. It's buried in the raptors notes. I would argue that the implication of this phylogeny -that falcons are more closely related to parrots than they are to hawks and owls etc. is very powerful and would be interesting to learners. So birds of prey as a group does not exist – that's neat stuff and I would argue a good hook to draw learners in.

Finally, the present day screen is just a bunch of unnamed dots (unless rolled over) with odd unexplained spaces. There is no structure. I know I am biased and you are trying to overcome limitations of trees, but I have to argue for a tree or trees of some kind to provide a time element and more importantly a topology that provides immediate and comparable estimates of relationships. In other words it provides time and space dimensions that aid in synthesizing learning. Maybe the answer is a hybrid of some kind. I speak more of this later.

Question 1 (common descent): For me, not very well without a tree and difficult to follow this process through time.

Question 2 (teleological misconceptions): This type of visualization is largely neutral to such interpretations and as such it can be considered to be a strength.

Question 3 (passage of time): Very poorly. See previous notes.

Question 4 (orders as ancestor-descendant lineages): As already noted I do not think the concept of lineages comes through with this type of visualization. Adding an upfront explanation that the dots represent populations of individuals (taxa), which are operated on by particular processes would help even without the support of a tree of some kind.

Question 5 (cladogenesis and anagenesis): The visualization does little to convey either, especially cladogenesis. The mechanism of branching is not described and without the structural support of a branching diagram it is extremely difficult to envisage.

Question 6 (scientific evidence for evolution): As is, not very well. It is only discussed in the intro. Maybe a final screen that reiterates the three lines of evidence presented in 2-3 different ways, including the phylogenies (see below).

Question 7 (suggestions for improvement): I suggest that students explore the present day evol. space then get them to compare with the published phylogenies and/or “present day” screen gets superimposed on a tree or directed network – some hybrid visualization might work well.

Comments from Expert #3

Expert Three preferred a face-to face discussion about the visualization to filling out the questionnaire. This section summarizes that discussion. Overall, the expert liked the concept behind the dynamic evolutionary map. The main concern seemed to be the lack of a tree structure. The expert emphasized out that he is not a bird expert, so the main focus of his comments was on the visualization itself.

He first asked for clarification on which criterion determines the splitting pattern of orders in the visualization: hypothesized ancestry (i.e., orders that stay together longer are more closely related) or hypothesized timing of order formation (i.e., the timing of the splits is based upon temporal information). After I clarified that it was the latter, Expert Three suggested either adding a component that shows time so that the timing of splits can be seen, or adding a tree-like structure to clarify how groups are related. The second question Expert Three asked was whether the axes of the visualization are indicative of anything specific. I showed him the first phylogram upon which the visualization is based (figure 10), and explained that the distance of dots from the center and relation to other dots are the important dimensional relationships in the visualization.

In his comments, Expert Three suggested that the motion of dots is occasionally confusing: some seem to change direction (i.e., move closer to unrelated orders) or speed as the viewer clicks through the animation. Most of his other comments were related to the lack of a

tree-like element in the visualization. He explained that the branching tree pattern is a key part of biological theory, and would also help viewers infer relationships among orders once they are at the end of the visualization (present day). He suggested two possible ways to incorporate a tree element. First, one could incorporate a phylogram alongside the map part of the visualization, and this separate tree could either grow or become highlighted over time as the viewer manipulates the map. A second possibility could be to incorporate a radial or semi-radial tree onto the map itself; this tree would “grow” by tracking the movement of the dots across the map space.

In the cases where multiple dots are highlightable at once (i.e., any dot in the linked group is linked to the same text), there seem to be two rationales for this: some groups are similar because of shared ancestry, while other groups are similar due to convergent evolution. Expert Three suggested that this is somewhat confusing. Having a tree would help show which of these multi-dot groups are grouped because they illustrate something about having a common ancestor, and which are grouped because of earlier classification based upon morphology or convergent evolution. Other possible ways to help with this issue include putting the information that these groups *used to* be grouped together but no longer are on top of the description, or including a statement in the introduction that explains this (e.g., “This is what you’ll see…”).

Expert Three suggested that if there were a tree, it would be interesting to have clickable nodes, to see what the common ancestors of related orders are. Another use of a tree could be to minimize visual confusion. For example, if one added a “tracking” tree, one could just use the tree lines until the Neaves radiation is reached, which would minimize the visual confusion of

all the dots bursting out at once. One could then add the dots in at a time point when it became easier to differentiate them.

APPENDIX C: NOVICE EVALUATION QUESTIONS AND RESULTS

Paper instructions and questions for novices

The following text is taken directly from the evaluation instructions and questions that novice participants used in the first part of the evaluation. Fourteen people participated in this part of the evaluation.

Part I:

Please answer the following questions about yourself.

I-1) How many classes have you taken in which you learned about evolution?

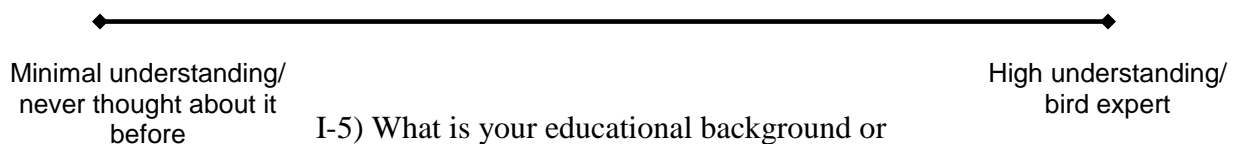
- a) Just high school biology.
- b) High school biology + introductory college biology.
- c) High school + intro college biology, plus an advanced college biology course (e.g., genetics or ecology).
- d) High school + intro college biology, and several advanced college biology courses.

I-2) How long ago was your last class in which you learned about evolution?

I-3) Please place an “X” on the line below to indicate your level of understanding of birds *in general*.



I-4) Please place an “X” on the line below to indicate your level of understanding of how birds are *scientifically classified*.



major? (e.g., humanities, fine arts, social sciences, natural sciences, engineering, etc.)

Part II:

Step 1: Begin by going to the visualization website at <http://goo.gl/R8vFe> (this is a shortcut to <http://physics.ucf.edu/~yfernandez/shs/birds/homeframe.html>).

Step 2: Read the “Introduction” and “About this map” pages (accessed via the links on the top frame of the screen).

Step 3: Click on the dot on the first screen and read about it. Then move on to the next stop in the timeline.

Part III:

For this part of this evaluation, you should concentrate on the right-hand dot (“Palaeognaths”) and what happens to it over time. Take a few minutes to move the timeline forward and explore this group of birds until you reach the present day. You should read about each dot that is linked to information (not all dots will be linked). Feel free to move both backwards and forward in the timeline. For now, focus your attention on only the lower right corner of the map.

When you are done exploring, please answer the following questions. You may interact with the map to help you answer them.

III-1) How would you describe what has happened to this group of birds over time to the present day, in your own words? Be as specific as you can.

III-2) How would you describe the relationship between the Ostriches and the Tinamous, in your own words?

Part IV:

For this part of this evaluation, you will be asked questions related to the two groups of birds that appear during the second stop in the timeline (when there are only two dots on the map). You may interact with the map to help you answer the questions.

IV-1) How did these two groups of birds arise, in your own words?

IV-2) If a scientist found a bird fossil, how would he or she decide which of these two groups the fossil belongs to? Why would he or she use this evidence, and not something else?

IV-3) Do these two groups seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?

Part V:

For this part of this evaluation, you will be asked questions about groups of birds all over the map. To answer each question, you should first find the dot representing the present-day group (or groups) that the question is about, and then work your way “backwards” through time on the map if you need to.

V-1) Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl (Ducks+Geese+Swans)? Why do you think so? (Hint: these groups are found in the bottom left.)

V-2) Based on the map, how long ago did the Cuckoos+relatives and Penguins last share a common ancestor? (Hint: these groups are found in the top right.)

V-3) How would you describe the relationship between the Seriemas and the extinct Terror Birds, in your own words? (Hint: the Seriemas are found in the top left.)

Part VI:

For the last part of this evaluation, you will be asked some questions about your overall experience using the map. You may interact with the map to help you answer the questions. Please base your answers upon what you learned when looking at this map, rather than your prior understanding of birds.

VI-1) Do any bird orders seem more advanced than others? Why or why not? If so, which ones?

VI-2) Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?

VI-3) What happened to the original ancestral bird species?

VI-4) What types of evidence do scientists use to decide how to group species of birds into orders? Do all these types of evidence have the same value, or do some seem to be more or less important than others?

VI-5) Why do scientists change their minds about how to classify birds into groups? Can you give an example of this from the map?

VI-6) Did using the evolutionary map change your understanding about bird evolution? If so, how? (A sentence or two is fine).

VI-7) Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?

This is the end of the study. Thank you for participating!

Results of paper-based novice feedback

Table 7: Results of paper-based feedback from novices

Question	Response
Demographic questions	
I-1: How many classes have you taken in which you learned about evolution?	1. B 2. B 3. B
a) Just high school biology	4. B
b) High school biology + introductory college biology	5. A 6. B
c) High school + intro college biology, plus an advanced college biology course (e.g., genetics or ecology)	7. B 8. C 9. A 10. B
d) High school + intro college biology, and several advanced college biology courses	11. B 12. B 13. A 14. C
I-2: How long ago was your last class in which you learned about evolution?	1. One year ago 2. 17 years ago 3. 2 years ago 4. Current semester (a class in which biology/evolution was mentioned). Prior to, I took a class in bio in high school about 6 years ago. 5. Current semester, am learning about human evolution in Human Species class. 6. Spring 2010. 7. Current semester in Biology II 8. Current semester 9. 4+ years ago 10. Current semester 11. 2 years ago 12. Around 10 years ago 13. 7 years ago 14. About 1 year ago

Question

Response

	1. 1
	2. 7
I-3: Please place an “X” on the line below to indicate your level of understanding of birds <i>in general</i> .	3. 2
	4. 5
	5. 1
	6. 7
“Minimal understanding/notice them around sometimes” to High understanding/have studied them or are a birdwatcher”	7. 3
	8. 6
	9. 2
	10. 2
(scale of 1-11)	11. 4
	12. 2
	13. 4
	14. 4
	1. 0
	2. 6
I-4: Please place an “X” on the line below to indicate your level of understanding of how birds are <i>scientifically classified</i> .	3. 0
	4. 3
	5. 1
	6. 4
	7. 5
“Minimal understanding/never thought about it before” to “High understanding/bird expert”	8. 5
	9. 1
	10. 2
(scale of 1-11)	11. 2
	12. 2
	13. 0
	14. 3
	1. Creative writing
	2. Creative writing
	3. Computer science
	4. Technical writing/social work
	5. Technical communication
I-5: What is your educational background or major? (e.g., humanities, fine arts, social sciences, natural sciences, engineering, etc.)	6. English/computer science
	7. Biology
	8. English
	9. Information technology
	10. Technical communication
	11. English literature
	12. Information technology
	13. Technical communication
	14. Interdisciplinary: biology, women’s studies, writing

Question

Response

I-4: Please place an “X” on the line below to indicate your level of understanding of how birds are *scientifically classified*.
 “Minimal understanding/never thought about it before” to “High understanding/bird expert”
(scale of 1-11)

- 1. 0
- 2. 6
- 3. 0
- 4. 3
- 5. 1
- 6. 4
- 7. 5
- 8. 5
- 9. 1
- 10. 2
- 11. 2
- 12. 2
- 13. 0
- 14. 3

I-5: What is your educational background or major? (e.g., humanities, fine arts, social sciences, natural sciences, engineering, etc.)

- 1. Creative writing
- 2. Creative writing
- 3. Computer science
- 4. Technical writing/social work
- 5. Technical communication
- 6. English/computer science
- 7. Biology
- 8. English
- 9. Information technology
- 10. Technical communication
- 11. English literature
- 12. Information technology
- 13. Technical communication
- 14. Interdisciplinary: biology, women’s studies, writing

Question	Response
<p>Palaeognaths</p> <p>III-1: How would you describe what has happened to this group of birds over time to the present day, in your own words? Be as specific as you can.</p>	<ol style="list-style-type: none"> <li>1. Became flightless. <li>2. Many of the adaptations caused species in the group to become extinct. The loss of the ability to fly led to larger legs and no keeled breastbone. Most of the species today inhabit areas where human population density is low. <li>3. Over time and due to the environment bird[s] had to adapt and started to change to respect to one another, started to divide into groups and show different characteristics. <li>4. It seems that the Palaeognaths have attained divergent characteristics relative to where they live. The environment plays a significant role in this bird type's evolution. It is hard to find which presently could be Palaeognaths, however just seeing the changes it is easy to say that many lines of evolution opened up. <li>5. Birds have evolved and changed features over time. Their ancestors had teeth, bony tails, and wing claws like reptiles. Adaptive radiation enabled the birds to adjust to their environment with different beak, wing, feet, and body design. <li>6. They have diversified based off of location. The actual branching into separate species is limited and the primary similarity is flightlessness. <li>7. This group of birds split into three different species including some flightless birds which are classified partly by their lack of keeled breastbones. <li>8. Because of the environments in which the Palaeognaths dwell, the need for evolution is minimal, as large species such as the Emu and Ostrich have no real natural predators, and the grassland-dwelling Tinamous has an adapted ability to fly to escape what little predators do dwell within their habitats. Humans remain the biggest threat to Palaeognaths, as the tendencies of hunting or expansion of habitat mix with the generally low rate of reproduction for the Palaeognathae. <li>9. It could be that at one point a gene that controls how the neck is formed could have mutated and with each new offspring the mutated gene could have become more prominent [sic] which is a possibility of why they have the characteristics that they have. <li>10. Less diversified or slow to evolve, compared to Neognaths. <li>11. The Palaeognaths have not diversified; there remain only 5 descendants, 4 of which are flightless and 1 which is mainly ground-dwelling. This group has not diversified, not migrated much, and each of the 5 have few (if any) different species (excluding Tinamous). <li>12. It is hard to tell because the oldest Palaeognath fossil found is only 70 million years old. <li>13. Birds in this group barely branched off into different species compared to the Neognaths. A majority of birds in this category split up into groups with long legs and beaks and stayed in the same section of the globe. <li>14. Ancestor split: Neognaths and Palaeognaths. Palaeognaths eventually split into ratites (four orders, no keeled breastbone, flightless), and Tinamous (one order, keeled breastbone, can fly). All orders came to be mostly ground-dwelling.

Question**Response**

III-2: How would you describe the relationship between the Ostriches and the Tinamous, in your own words?

1. They both have feathers.
2. Tinamous are smaller and have retained the power of flight, although they generally walk. They are both threatened by man.
3. Although they are both similar, the Ostriches resemble more to the Palaeognath birds and the Tinamous can fly unlike the Ostriches.
4. Their relationship is perhaps that of a distant cousin. Since they do have some similarities. However a major difference is the Ostrich's lack of a keel bone which is key for flight.
5. The Tinamous are actually descendants of two orders of ratites, which are the ancestors of the Ostriches and the Rheas. However, the Tinamous can fly and Ostriches cannot due to their lack of a keeled breastbone. They do have shared jaw and pelvis anatomy as well.
6. They both walk rather than fly. Tinamous have the ability but prefer the former. They both are products of their habitat in the scope of their size.
7. Both are flightless groups but they are grouped separately because the trait of flightlessness developed separately in the Palaeognaths.
8. Though both are land-walking birds that have their habitat threatened by humans, Tinamous are much smaller, usually only spanning about 17 inches in length, and also have the ability to fly in needed.
9. The overall size of the Ostrich is much greater than the Tinamous but they seem to have the same body shape. Both of their neck shapes are similar except that the Ostrich's is longer. Head shape is similar too.
10. They evolved from the same group, Palaeognaths. Ratites (to which Ostriched belong) evolved from Tinamous.
11. The trait of flightlessness in Ostriches differs from other birds, like Kiwis and Emus. Tinamous are able to fly, are smaller birds that are located in South America, while Ostriches are flightless, located in Africa. There are 47 or so species of Tinamous, only 1 species of Ostriches.
12. Because they have common features they are derived from each other.
13. Very different. The Tinamous is [sic] small and can fly, compared to the Ostrich which is large and flightless. Without the aid of seeing the birds separate in evolution, I would have thought that Tinamous would have been in the Neognath category.
14. Ostriches and Tinamous come from the same super group of birds (Palaeognaths). Tinamous do have a keeled breastbone and can fly, unlike other ratites. Even though Tinamous can fly, they are generally ground-dwelling. Ostriches are also ground-dwelling.

Question	Response
<p>Neognaths and Palaeognaths</p> <p>IV-1: How did these two groups of birds arise, in your own words?</p>	<ol style="list-style-type: none"> <li>1. From adaptive radiation. <li>2. From a common ancestor. The division in these two groups comes from the way their jawbones are developed. <li>3. Both groups have different bone structure. <li>4. Perhaps environmental strain caused these two distinct groups to emerge. The Neognathae is supposed to be more “new jaw” a more modern jaw bone. Same can be said for Palaeognaths. <li>5. These two groups were able to adapt and survive where earlier birds could not. They developed features to keep them alive long enough to keep reproducing and where [sic] able to arise in that matter. <li>6. They diverged based on jaw structure and further diversified from there. <li>7. The basal ancestor of birds speciated by changing the jaw structure to produce a new kind of bird (Palaeognaths). <li>8. The Neognaths appear to have formed as a response to changing environment, where their expansions to connecting land masses caused an adaptation of the jawbone to accommodate different dietary patterns, whether they be different species of prey or plants, while the Palaeognaths remained generally dominant within one area where predators were few, having very little need for evolutionary changes. <li>9. It could be that as these birds traveled into other areas the environment was completely different than what they were used to and the birds who migrated had to evolve in order to survive. Therefore, the birds who never moved stayed the same while the ones who did slowly changed over time to survive in their new environments. <li>10. Neognaths seemed to have evolved according to their environment (land and water). Palaeognaths seemed to have evolved according to their physiological needs, or something to do with food. Maybe their source of primary food changed, thus their jaws adapted. <li>11. Evolutionary traits such as flightlessness, jaw and pelvic anatomy differentiates the orders of birds. Neognathae birds became more prevalent with dominant genes of flight, etc. <li>12. They are descendants of dinosaurs. <li>13. Both of them separated into two distinct categories: Neognath and Palaeognaths due to evolution from <i>Archaeopteryx</i>. <li>14. I’m not sure how they arose, but there are structural differences between the two, specifically with the jaws. Palaeognaths also have specific pelvic anatomy which separates them from Neognaths.

Question**Response**

IV-2: If a scientist found a bird fossil, how would he or she decide which of these two groups the fossil belongs to? Why would he or she use this evidence, and not something else?

1. By their shapes and environment. Because they're different in appearance and they are found mostly either by the shoreline or other environments.
2. Jawbones, because that's the major structural split.
3. The scientist would have to compare the fossil with other fossils to determin[e] which bone structure it is.
4. The scientist would have to closely examine the fossil to see what type of bone structure does the bird have to then classify it. Also molecular mapping would help the scientist figure out where the bird is from. This works since it helps override weaknesses in other forms of evidence.
5. By comparing the jaw and pelvis anatomy of the Palaeognathae against the Neognath group. The scientist would use this evidence and not something else because it explains the location, description, and anatomical differences of the two groups side by side with the dots.
6. The skeletal structure of their jawbones. This would be used because it is the only exclusive derived factor between the two.
7. First the physical traits are looked at to find similarities and then these findings are compared to molecular evidence if possible. The traits chosen for focus must be homologies for the birds to be closely related. Sometimes similarities arise from convergent evolution which is confusing to true phylogenetic classification.
8. The scientist would use the jaw and pelvic anatomies to determine which group to classify the fossil, as they are the shared characteristics that differentiate them specifically.
9. The scientist would look at the shape of the head and (jaw) neck of the fossil because those differ the most from these two groups of birds.
10. Genetic/molecular evidence- seems more accurate, based on DNA. Skeletal structures/physical appearance- seems less accurate as with other species of birds, common structures does [sic] not denote a relationship or common ancestry.
11. Pelvic structure, jaw structure, size, wingspan/skeletal makeup; location of fossil. These two pieces of evidence are the main difference between the bird groups.
12. They would evaluate the fossils and figure out which traits match that of another bird's traits. If the same features are shared then that is what group the bird is put in.
13. Palaeognaths have a shared jaw and pelvis anatomy that helps scientists differentiate them from Neognaths.
14. By studying the jaw and pelvic anatomy. These are the main differences between the two orders.

Question**Response**

IV-3: Do these two groups seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?

1. No. Through molecular evidence.
2. Neognaths are much more numerous, outnumbering the Palaeognaths by approximately 5:1.
3. No, the Neognaths have more descendant[s], they have subgroups and different types within.
4. No, in my opinion it seems only the Neognathes seems to have the greatest number of descendants. This can be due to the Palaeognath(s) never having been that numerous.
5. They do not. The map clearly shows that the Neognath group diverged into many other groups, while the Palaeognath group had five diverging groups which could not compare in amount.
6. The Neognathae have flourished primarily because of environment. They had more niches to fill and were not hunted to extinction quite so often.
7. The Neognaths seem to have diversified more after the initial split and therefore have exponentially higher numbers. The map explained that they had the opportunity to expand after the Cretaceous extinction.
8. The Neognaths appear to have an exponentially greater number of diverse species, all of which are the progression of a number of descendant groups, however the Palaeognaths have five major descendant groups that remain intact, without major evolutionary advancement or diversification of species. The explosion of descendant groups within the Neognaths were a form of adaptive radiation, in which particular circumstances allowed them to diversify without much resistance.
9. No, it was stated that there were more Neognaths in the world then [sic] there are Palaeognathae. I believe it's because the Neognaths structure is more adaptable in different types of environments.
10. No, there are significantly more dots that originated from the Neognaths. The Neognaths experienced rapid diversification in which a significant number of descendants were successful.
11. No- Palaeognaths have very few descendant groups. The main difference in the groups is flying ability which accounts for the geographic location and ability to evolve easier/faster.
12. Most birds today are Neognaths because they are found on both land and water.
13. No, Palaeognaths are drastically smaller with only five separate types of birds living today. Neognaths dominate the [planet] and live in the air, water, and land.
14. No- there are many more descendants of Neognaths. This is at least partially the case because Palaeognathae has such specialized anatomy and lifestyle. The Neognaths are a much more diverse and broad group, thus able to encompass a larger spectrum and amount of species.

Question**Response**

Questions about specific orders

V-1: Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl (Ducks + Geese + Swans)? Why do you think so? (Hint: these groups are found in the bottom left.)

1. Land Fowl and Waterfowl. Because they seem to have smaller characteristics or similarities.
2. Land Fowl and Waterfowl are more closely related, as Flamingos branch off with Grebes and Tropicbirds.
3. Land Fowl and Waterfowl because those two groups stayed together longer and share many characteristics.
4. Land Fowl and Waterfowl seem to be more closely related since their structure seem to be more match. As opposed to the Ostrich.
5. Land Fowl and Waterfowl are more closely related as they are situated more south on the map together than Flamingos and Land Fowl.
6. Land Fowl and Waterfowl; they have similar locations connoting shared characteristics.
7. Land Fowl and Waterfowl are closer because Flamingos are filter feeders.
8. Land Fowl and Waterfowl seem to be more closely related, as their groupings within the evolutionary map stay close throughout the timeline, suggesting common descendant groups and similar adaptive characteristics. Where Flamingos are relatives of the diving Grebes, fowls were an original diversification of the Neognaths within the first 20 million years of their divergence from Palaeognaths.
9. The map states that Land Fowl and Waterfowl are more closely related. Their overall general body structure is very similar except for their legs which were adapted to either H₂O or land.
10. Land Fowl and Waterfowl appear more closely related as their species originated from the same dot titled "Fowl." They remained closely related (after diversifying into land and water) well before Flamingos appeared.
11. Land Fowl and Waterfowl are more closely related; both are types of fowl and originated from the Neognaths further back than Flamingos.
12. Land Fowl and Waterfowl because they are part of the same subgroup within the Neognathae group.
13. Land Fowl and Waterfowl- Flamingos live in vast colonies and differ in body structure compared to fowl. Although Land and Water fowl live in different habitats, besides the factor of webbed feet, they seem similar in body structure. They both also emerge from the same point in early evolution.
14. Land Fowl and Waterfowl. Progressing backward in the visualization, these two came closer together, while Flamingos are at a distance.

Question	Response
<p>V-2: Based on the map, how long ago did the Cuckoos + relatives and Penguins last share a common ancestor? (Hint: these groups are found in the top right.)</p>	<ol style="list-style-type: none"> 1. 40 and 35 My ago. 2. When they were both part of the Neoaves. 3. Neoaves. 4. It seems from 40 – 35 MYA. 5. At around 65 million years ago when the major Neoaves adaptive radiation took place. 6. 35 million years ago is the most recent date. 7. They shared a common ancestor approximately 65 MYA, possibly from before the great extinction. 8. These groups seem to share a common ancestor about 90 million years ago. 9. Around 65 MY ago when they were all Neoaves. 10. Around 65 MYA (give or take 10 MY), in the group called Neoaves. 11. Around 65 million years ago Penguins and Cuckoos were grouped in Neoaves together before an explosion of diversity. 12. It does not say that the two shared any common ancestors? 13. 65 million years ago in the “Neoaves explosion.” 14. Around 65 MYA ~Neoaves.
<p>V-3: How would you describe the relationship between the Seriemas and the extinct Terror Birds, in your own words? (Hint: the Seriemas are found in the top left.)</p>	<ol style="list-style-type: none"> 1. They both look terrorizing. 2. They do not appear to be related in any close way. 3. Both are large carnivorous birds and the Seriemas are about to be extinct. 4. There are similarities. The Terror Birds were large and killed prey in a similar fashion that the Seriemas do. However the Seriemas run from danger and I don’t think the Terror Birds did that. 5. Could not locate Terror Birds. 6. They are both carnivorous birds with claws built for rending prey. 7. The Seriemas are descendants of the Terror Birds. 8. The Terror Birds, or Phorusrhacid, is an early relative of the Seriemas, which is now considered to have included the Terror Birds within its classification. 9. Seriemas might be the smaller version of the Terror Bird. As mention [sic], Seriemas can’t fly very far and from what I know Terror Birds couldn’t fly at all. Therefore Terror Birds ran from danger like the Seriemas, which is another similarity they share. 10. Closest living relative to Terror Birds. 11. Seriemas are the closest relative to Terror Birds before extinction. 12. They were part of the same group. 13. Both birds are carnivores and have a similar way of tearing their prey open with their claws, however the difference of course being size. Seriemas may become extinct like Terror Birds. 14. The Seriemas are the only living group members from the order Cariame [sic]- the Terror Birds are extince members of the same order.

Question	Response
Overall map experience	
VI-1: Do any bird orders seem more advanced than others? Why or why not? If so, which ones?	<ol style="list-style-type: none"> 1. Yes. Due to their differences in adaptation radiation, if they are flightless or not, etc. The shorebirds. 2. The specialized bird orders seem more advanced because of evolutionary traits that take time to develop, such as Penguins and Kingfishers. 3. No, all the birds are different so it's hard to compare them. 4. No, personally I think as I look at each bird that their environment shaped them to fit perfectly. Each bird fits perfectly in one place than in another. 5. Yes they do. The Neognaths multiplied and evolved so much more than the Palaeognaths, which stayed behind and ultimately only produced five species of bird. 6. [blank] 7. Perhaps birds of prey are the most advanced because they developed grasping claws to better catch prey and kill with beaks. Flamingos with their adaptations of long legs and filter feeding are equally as advanced in a different direction. 8. The superior intelligence of the parrot seems to be a major advancement for an order of animal known for their smaller brains, though does not seem to be as superior of a characteristic of their environment as much as something like an ostrich's land speed. 9. The Neognaths seemed more advanced over the Palaeognaths because there are more of them which means they have adapted well over time. 10. The Noegnaths because they diversified rapidly. 11. The order of Gruiformes is most complex, with several species spanning the map that are diverse; it seems they evolved diversely. 12. No, they all seems to share some similar traits. 13. Flamingos since they live in large colonies and are filter feeders. Sandgrouse since they are camouflaged and dwell in[sic] the ground. Owls- great senses for hunting at night. Parrots- one of the most intelligent, dexterous feet, broad, curved bill. 14. It depends on what you think of as advanced. The ones that survive and do not get hunted as often may be considered advanced.

Question	Response
<p>VI-2: Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?</p>	<ol style="list-style-type: none"> 1. Yes, because of their size. Ostriches. 2. The Ostrich family tree because they are less diversified. 3. Most of the birds from the Palaeognath group, such as the Ostriches, because of how muscular they are and the fact that they run to escape danger. 4. The Hoatzin definitely comes across a bit primitive. The physical features of this bird make it seem so. 5. The Palaeognaths seem more similar in that they are larger and non-flight birds. 6. [blank] 7. The line that produced flightless birds seems most similar to dinosaurs since most didn't fly. 8. The bone and body structures of Palaeognaths such as Ostriches and Emus seem to greatly resemble dinosaurs, especially the appearance of their legs and feet. 9. Palaeognaths seem more similar to dino's because of their overall body shape. 10. Terror Birds, simply because they resemble the "most popular" threatening dinosaurs (T-Rex) and raptors. 11. The Seriemas look like velociraptors; some of the larger flightless birds as well. Their posture, size, and beaks all resemble dinosaurs. 12. To me some of them share similar traits to dinosaurs. Ostriches for some reason being the main one. 13. Terror Birds due to their vast size and aggressive nature. Seriemas seem like a smaller version of a Terror Bird. Ostriches/Rheas mainly due to their large size. 14. Not sure.
<p>VI-3: What happened to the original ancestral bird species?</p>	<ol style="list-style-type: none"> 1. They became extinct or evolved and branched out. 2. They evolved into modern species or went extinct. 3. The original ancestral bird had to change over time to adapt and this led to all these different types of birds. 4. From my reading it seems to have gone extinct. 5. They became extinct and what exists of modern birds today derived from the Neognath and Palaeognath groups. 6. [blank] 7. It seems to be extinct. 8. The "original" bird species diversified into two groups about 100 million years ago, where one group had an explosion of diversification, while the other seemed to stay relatively the same. 9. It has died out most likely due to changes in the environment. 10. Rapid diversification/evolution. 11. The original ancestor, <i>Archaeopteryx</i> became extinct. 12. They still exist. 13. They went extinct. 14. The ancestor of the modern birds survived the Cretaceous-Tertiary mass extinction. It is questionable which is the original ancestral bird species. There are bird and bird-like dinosaur ancestors.

Question**Response**

VI-4: What types of evidence do scientists use to decide how to group species of birds into orders? Do all these types of evidence have the same value, or do some seem to be more or less important than others?

1. Fossils and molecular evidence. No, some fossils can't really be dated too far back to compare.
2. Anatomical, genetic, molecular. The genetic proof seems to carry more weight- physical traits can arise from different stimuli.
3. At the beginning it was just bones, but scientists classify these birds for their characteristics.
4. They use Anatomical similarities and differences from living birds. and fossil birds, as well as molecular similarities and differences among living birds. I don't think they have the same value since the molecular seems to be more important to me.
5. Scientists use physical features to group species of birds into orders. As well as capabilities. Some types of evidence seem more important such as flight capability over webbed feet.
6. [blank]
7. Scientists used derived traits of each species to classify them. Molecular evidence is also used and is more important.
8. Physical characteristics are the greatest determiner in which a bird is placed into a group. The value seems to vary, as greater general characteristics, such as long legs, could outweigh values such as the size of the beak.
9. Skeletal structures because it seems that that is where all birds differ the most.
10. Skeletal structure and molecular evidence. Molecular seems to have more value and accuracy. Skeletal seems less reliable.
11. They use size, flight trait and beaks to determine species. Flying ability seems to hold more value.
12. They use fossils to determine traits and then decide on which group to put them in. Studying fossils is the most accurate way of doing it.
13. Seem less important. Types of evidence includes [sic] body structure and how evolution has changed their bodies to adapt to environment.
14. Molecular evidence seems more complicated and more valuable than anatomical evidence.

Question**Response**

VI-5: Why do scientists change their minds about how to classify birds into groups? Can you give an example of this from the map?

1. Because of their variety and relation to ancestors, physical form, and adaptive radiation.
2. When a new fossil or genetic information is discovered. The pelicans reclassified by molecular structure.
3. The Flamingos were part of the Neoaves, but over time they started to be part of the Land Fowl and Waterfowl.
4. New discoveries can be made that may change one bird's initial classification. An example from the map is shore birds and their divisions.
5. Scientists change their minds about how to classify birds into groups because of their evolutionary past. Mousebirds and Woodpeckers were closely grouped before, but the differences in diet, feet structure, and habitat put them apart.
6. [blank]
7. Learning that a homology is an analogous trait and is the result of convergence can reclassify a species. Ex. the development of flightlessness was thought to be one divergence but evidence proved it happened twice.
8. Because of the diversification of many physical characteristics over time, scientists will reclassify some species of birds. For example, scientists originally classified loons and grebes as closely-related groups until recently, where molecular evidence has shown them to be classified differently.
9. They might have found new fossils to compare modern birds with.
10. Possibly because of a lack of sufficient fossil evidence. Ex: Palaeognath fossil yet to find.
11. Seriemas were originally grouped as an ancestor of the Terror Bird, but later reclassified to be closer to falcons, etc.
12. Because evolution is still evolving?
13. [blank]
14. Anatomical vs. gene differences. Molecular similarities among ratites and Tinamous are unclear, so these grew further apart.

Question**Response**

VI-6: Did using the evolutionary map change your understanding about bird evolution? If so, how? (A sentence or two is fine).

1. Yes. It helped me understand the basics of evolution and how they came about to survive today.
2. By grouping similar species and showing the expansion, it was easy to see which birds are related.
3. Yes, it shows you how they have different categories and how the(y) expand over time.
4. It did, it/the dots helped me gauge the actual distance between a bird and its relationship with other birds.
5. Yes it did. I did not know that modern birds derived from two bird groups and primarily one. It is interesting to know that Ostriches and other Palaeognaths are basically unchanged throughout history.
6. Yes, I wasn't aware just how major the discrepancies were between different birds. I also wasn't aware that most birds come from a single group.
7. The map helped me visualize the proportions that different divergences produced. It also helped me realize the differences between bird species and solidified some facts about phylogeny.
8. It did show stark distinctions that I would never have known were there, such as how eagles and owls differ so much from falcons, and allowed for a blatant view of Palaeognaths, which I had no idea were such evolutionary oddities.
9. No.
10. Yes, significantly more complex. Seems to have happened rapidly.
11. The visuals of bird fossils showing their relation to dinosaurs gave me a different perspective.
12. I learned a little about birds but overall it did not change my understanding of birds. Still know very little about the subject.
13. Yes, did not realize that birds were placed in two categories, and watching the dots progress from the center really helped.
14. Yes. I learned there were birds and bird-like creatures that existed with/as dinosaurs. I learned a bit about the complexity of classifying different bird species.

Question**Response**

VI-7: Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?

1. It worked well in the beginning, but then with the different names, it complicated it a little bit. I guess cause it was cramped together un a few moments, but got the base of knowledge.
2. I liked the grouping and photos with the information. A time outline for each stage might be helpful in remembering when certain species split off. I found the entire process easy to follow and enjoyable.
3. They only labeled the beginning “time of the first birds” and present day, they should have the years in between as well.
4. Initially it was confusing however reading helps. ☺
5. I wish I could click on certain bubbles, but they were disabled. Also, a more clear separation for the final map screenshot of present day would make the groupings more clear. I did like how the data starting [sic] to spread as you went through the evolution journey.
6. I found the map useful and learned a lot in a relatively short period. It was challenging to draw conclusions based on comparison but other than that, it was very easily digested.
7. It was easy and intuitive, the activity kept the information interesting and the ability to go back was very helpful. The most surprising aspect was the illustrations. They are both educational and in some cases beautiful ☺
8. The amount of the diversification in the Neognathae was very surprising in comparison to the Palaeognathae, and the placement of orders was initially confusing (i.e., the grouping of penguins so early in the Neognathae explosion), but overall the map seemed to guide me along the progression of the orders fairly well and provide much more information [than] I would have learned otherwise.
9. I was confused halfway through the study, not sure if it was the map or the instructions. During certain points in the timeline the labels on the circles were covered by the mouse arrow and were unreadable, Ex. stop #7, Seriemas.
10. The back and forth arrows helped in terms of keeping track of time; however, providing the estimated timeframe in lower left corner would aid in accuracy. The amount of dots and their distance apart at present day was surprising.
11. Simple layout that may lead to easier absorption of material would be to integrate the two halves of the screen, so that when the left size evolves, pictures/info can be viewed when hovering over the dots, like the names are now.
12. It was confusing to begin with but got easier the more I interacted with it.
13. There were a lot of pictures of birds that were really helpful, however maybe it would be best to also include examples of evolution through skeletal structure. The map really helped, however present day you may want to label categories that show close relation among the birds.
14. I did like the map! It was a little unclear how the groups split. I think the visualization of the species moving away from each other (and getting closer if you move backwards in the visualization) helped understand relationships among the groups.

Directed instructions and questions for novices

The following process was used when directing novices through the second part of the evaluation. Novices were directed to complete tasks and answer questions in this order, though the exact wording they were given varied slightly. Occasionally, they requested clarification or additional explanation of instructions. On other occasions, I asked follow-up questions in order to better understand the meaning or reasoning behind responses. Those follow-up questions are included in the following table of responses. Six people participated in this part of the evaluation. After the third participant had completed their evaluation, I dropped question I-3 from the evaluation.

Part I:

Begin by going to the visualization website at <http://goo.gl/R8vFe>. Read the “Introduction” and “About this map” pages (accessed via the links on the top frame of the screen).

I-1) Click through the animation until you reach the present day. You can click on the linked dots to learn more about the orders. Distance on the map shows genetic distance between orders. In your own words, how do you describe what is being represented on the screen?

I-2) For orders that are close together, what type of similarity is being displayed?

I-3a) Can you find any examples of birds that are anatomically similar but far away from one another on the map?

I-3b) How would you explain this, using the map?

Part II:

Click on the dot on the first screen and read about it. Then move on to the next stop in the timeline. For this part of this evaluation, you should concentrate on the right-hand dot (“Palaeognaths”) and what happens to it over time. Take a few minutes to move the timeline forward and explore this group of birds until you reach the present day. You should read about each dot that is linked to information. Feel free to move both backwards and forward in the timeline. For now, focus your attention on only the lower right corner of the map.

II-1) How would you describe what has happened to this group of birds over time to the present day?

II-2a) How would you describe the relationship between the Ostriches and the Tinamous? Again, you can move back and forth in the map.

II-2b) How closely are they related?

II-3) How would you describe the relationship between the Tinamous and the extinct Moas?

Part III:

For this part of this evaluation, you will be asked questions related to the two groups of birds that appear during the second stop in the timeline (when there are only two dots on the map). You may interact with the map to help you answer the questions.

III-1) How did these two groups of birds arise, in your own words?

III-2) Do these two groups seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?

Part IV:

For this part of this evaluation, you will be asked questions about groups of birds all over the map. To answer each question, you should first find the dot representing the present-day group (or groups) that the question is about, and then work your way “backwards” through time on the map if you need to.

IV-1) These groups are found in the bottom left. Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl (Ducks+Geese+Swans)? Why do you think so?

IV-2) These groups are found in the top right. Based on the map, how long ago did the Cuckoos+relatives and Penguins last share a common ancestor?

Part V:

For the last part of this evaluation, you will be asked some questions about your overall experience using the map. You may interact with the map to help you answer the questions. Please base your answers upon what you learned when looking at this map, rather than your prior understanding of birds.

V-1) Do any bird orders seem more advanced than others? Why or why not? If so, which ones?

V-2) Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?

V-3) What happened to the original ancestral bird species?

V-4) Did using the evolutionary map change your understanding about bird evolution? If so, how?

V-5) Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?

V-6) Do you have any general comments about the interface design?

Results of directed feedback from novices

Table 8: Results of directed feedback from novices. Italics indicate follow-up questions or notes about the participants' actions

Question	Response
General questions	
I-1: Click through the animation until you reach the present day. You can click on the linked dots to learn more about the orders. In your own words, how do you describe what is being represented on the screen?	<p>1. It starts with one species, and through natural selection they branched into groups. <i>Follow-up: How are the groups different?</i> Where they live, survival tactics, based on environment.</p> <p>2. The evolution of birds and how they've evolved to be unique. Over time they've gotten more distinctive in their different areas. <i>Follow-up: How are the groups different?</i> Their capabilities and feather patterns and where they reside.</p> <p>3. It's like a tree without any branches. New species keep forming as new dots form. How far out a dot is represents how far away a group is from the first ancestor, in terms of having the same characteristics.</p> <p>4. The first bird ancestor evolved into different birds, and they became different. Different traits.</p> <p>5. How similar all the species are over time with little clusters. They spread out over time. <i>Follow-up: How are the groups different?</i> They appear related in some way because they're clustered. Maybe by similar characteristics or what they evolved from.</p>

Question	Response
I-2: For orders that are close together, what type of similarity is being displayed?	<ol style="list-style-type: none"> 1. Major anatomical similarities- jaw and bone structure. Anatomical differences that depend on the environment. 2. Their anatomy was the main similarity. 3. The ones that are closer have the same characteristics- big spaces show that they are different in a way. 4. Maybe how they're related? Or the features they share in common. 5. <i>Clicked on orders near one another.</i> I feel like this group is sort of related, because they hunt (<i>points to cluster with Owls, Eagles, etc.</i>) These live mostly near water. (<i>points to cluster with Pelicans, Penguins, etc.</i>)
I-3a: Can you find any examples of birds that are anatomically similar but far away from one another on the map?	<ol style="list-style-type: none"> 1. Cranes are similar to Flamingos. They have long legs and necks. 2. Flamingos and Ostriches. 3. Flamingos and Bustards. They both have longish legs and are from a different branch on the ancestry. <p><i>Note: this question was dropped after the responses of the first three participants.</i></p>
I-3b: How can you explain this, using the map?	<ol style="list-style-type: none"> 1. It seems like they come from a different cluster, but it seems that they're both water-dwelling. I assume that most water-dwelling birds have similar properties. 2. They have long legs and necks. 3. Habitat... to survive, they have to have certain characteristics. Like Flamingos and Cranes might have long legs for similar purposes. <p><i>Note: this question was dropped after the responses of the first three participants.</i></p>
Palaeognaths	
II-1: How would you describe what has happened to this group of birds over time to the present day? Be as specific as you can.	<ol style="list-style-type: none"> 1. The birds stayed within their subgroups. Four are flightless and one isn't. It seems like they haven't branched into as many subgroups as the other group did. It seems like they're relatively unchanged on the timeline. 2. It evolved slowly, and after a certain point... Those birds didn't change much, but their geographic position didn't change much. They went from one group to three and then stayed at five. 3. It seems like it only spread out a little from the first ancestor. It only has five dots... the other dot just blew up and spread all over. 4. It stayed one group for a while, and then became diverse. But it moved away from the center. 5. They were expanding over time and developing different characteristics. For example, Ostriches and Emus kept dinosaur-like traits like feet, and other groups seem more like birds today- small and not predatory. It seems like two groups at the beginning, and then more at the end.
II-2a: How would you describe the relationship between the Ostriches and the Tinamous, in your own words?	<ol style="list-style-type: none"> 1. The main difference is the Ostriches are flightless and the Tinamous aren't. 2. They evolved from the same bird, but over time adapted to different environments. The Tinamou is like a small Ostrich. 3. I'm not sure I see that many similarities. The Tinamou seems like a shorter, fatter version of the Ostrich. If you go back, they come from the same group, and probably the habitat made them adjust. 4. They're related somehow, because they came from the Palaeognath, originally. 5. They have similar habitat though this one (picture of Tinamou in a tree) is more versatile. Both run a lot for a defense mechanism, though Tinamous can fly.

Question	Response
II-2b: How closely are they related?	<p>1. It doesn't seem very close. It seems Ostriches are more unchanged. The further out you go on the map, the newer species you get. Maybe Tinamous are better adapted; they can fly and burrow.</p> <p>2. Pretty close- they're in the same species and came from the same bird.</p> <p>3. Pretty close. Not right next to each other, but just because they don't look alike doesn't mean they aren't related.</p> <p>4. Pretty close. At least compared to the other group (Neognaths). They didn't move as far apart.</p> <p>5. Kind of close- not as far apart as others. Like Tinamous and this one (pointed to Perching Birds). But not the closest within this group.</p>
II-3: How would you describe the relationship between the Tinamous and the extinct Moas?	<p>1. They seem to have the same size and structure, but Tinamous are on a smaller scale. <i>Had a hard time finding the Moas; prompted that they were in the past and that it was necessary to click on the past groups to see them.</i> <i>Follow-up: Why do you say so?</i> Their physical location is different.</p> <p>2. Tinamous evolved from Moas. <i>Follow-up: Why do you say so?</i> They both came from the same dot.</p> <p>3. They have the same body shape, but Moas are taller. <i>Had to explain where Moas were on the map, and subject didn't read the text.</i> <i>Follow-up: Why do you say so?</i> Not sure. <i>Follow-up: If they were on a family tree, how closely would they be related?</i> As close as the Ostrich family- they seem to have the same characteristics.</p> <p>4. It's confusing that Moas don't have their own dot. But It says [Tinamous] are the closest living relative.</p> <p>5. It says they're the closest living relatives.</p>
Neognaths and Palaeognaths	
III-1: How did these two groups of birds arise, in your own words?	<p>1. Their jaw structure is the main difference. <i>Follow-up: How did they get this difference?</i> Based on fossils.</p> <p>2. Those that discovered one group didn't know about the other one, then later they found out there were two.</p> <p>3. Only certain types of groups survived. I guess they separated into two categories. They seem to have different characteristics, like the jaw.</p> <p>4. They evolved from the original bird. It split into two.</p> <p>5. At this point, the two groups have different jaw structure and pelvis anatomy.</p>
III-2: If a scientist found a bird fossil, how would he or she decide which of these two groups the fossil belongs to? Why would he or she use this evidence, and not something else?	<p>1. By their shapes and environment. Because they're different in appearance and they are found mostly either by the shoreline or other environments.</p> <p>2. Whether it is similar to any other bird group fossil.</p> <p>3. If it's a smaller bird, Palaeognaths. They're the smaller of the two groups. Also, you'd examine the jaws, because Neognaths are known for jawbone structure. Neognaths are also more diverse, so it's more likely to be a Neognath because they have more species. But I'm not sure of that. Also their pelvis.</p> <p>4. Their anatomy. The jaw and pelvis.</p> <p>5. The bone structure. But for more assurance, they would try to look at...genetically, which it's most closely related to.</p>

Question	Response
III-3: Do these two groups seem to have the same number of descendant groups that have survived to the present day? Based on what you learned from the map, why is (or isn't) this the case?	<ol style="list-style-type: none"> 1. (answered in Q II-1) 2. No. The left side evolved more quickly and populated the map. Can't say why based on the map. 3. (answered in Q II-1) 4. No. The Neognaths evolved into more species. Palaeognaths didn't branch as fast. 5. No. At some point, one group became really diverse. I think it said their predators became extinct. And there was something about radiation.

Questions about specific orders

IV-1: Based on the map, which of these pairs of groups are more closely related: Flamingos and Land Fowl, or Land Fowl and Waterfowl? Why do you think so? (Hint: these groups are found in the bottom left.)	<ol style="list-style-type: none"> 1. Land Fowl and Waterfowl. Because they started off in the same cluster. 2. Land Fowl and Flamingos. They're closer together. (<i>Was only looking at present-day, and didn't manipulate the map.</i>) 3. Land Fowl and Waterfowl. Back at the beginning, they're overlapping one another, which means they're closely related. The Flamingos overlap with other groups. 4. Land Fowl and Waterfowl. They came from the same group, and are both called Fowl. 5. Land Fowl and Waterfowl. They came from Fowl, but Flamingos came from Neoaves.
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IV-2: Based on the map, how long ago did the Cuckoos + relatives and Penguins last share a common ancestor? (Hint: these groups are found in the top right.)	<ol style="list-style-type: none"> 1. Back in the Neoaves. <p><i>Follow-up: Can you put a year on that? About 65 MYA.</i></p> <ol style="list-style-type: none"> 2. (<i>Was trying to answer this by looking at the present day. Prompted to go back in time if needed, but just answered question using information on the present-day screens.</i>) About 40 (million) years, based on the fossil dates. 3. About 65 MYA. (<i>Looking at the Neoaves adaptive radiation screen.</i>) 4. About 65 MYA, after the adaptive radiation. 5. 90 MY ago. <i>This was based on counting the number of backwards clicks to get to the adaptive radiation screen.</i>
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Overall map experience

V-1: Do any bird orders seem more advanced than others? Why or why not? If so, which ones?	<ol style="list-style-type: none"> 1. It seems like the species on the outside are more advanced. It's based on natural selection- these are the traits that have been passed down to help with survival. 2. No- they all seem to have specific characteristics based on their environments. 3. I guess- if you define advanced as fitting into their habitat... I don't know. Maybe Ostrich leg length is better for certain situations. Really hard to say. It doesn't say where they live, so I'm going off the pictures. 4. It's hard to say. Maybe the ones that aren't endangered. 5. Some of the birds on the Neoaves seem a lot more specialized. Also, the Palaeognaths are all at risk of extinction, so they should probably start evolving some more.
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Question	Response
VI-2: Do any bird orders seem more similar to dinosaurs than others? Why or why not? If so, which ones?	<p>1. Ostriches and Loons. They seem larger and less complicated. It seems like their traits are less practical for today- counterproductive traits. Mainly size, and being flightless. Although Ostriches have survived until today.</p> <p><i>Note: seemed to be looking at proximity to center when talking about these groups being "less complicated."</i></p> <p>2. No. Based on physical features- none of them seem more reptilian.</p> <p>3. Maybe the Kiwi. It seems more dinosaur-like- more compact, more like a reptile.</p> <p>4. The older ones. Palaeognaths and Neognaths.</p> <p>5. Palaeognaths. I feel like they sort of are, but the ancestral birds are small. I think people usually say Ostriches are like dinosaurs, but from the information presented you can't really say that so much.</p>
V-3: What happened to the original ancestral bird species?	<p>1. It seems to have split into two groups, with differences based on jaw structure, pelvis structure, and location.</p> <p>2. It evolved and adapted to different locations it may have moved to.</p> <p>3. One group survived, one went extinct. They're technically around, because all birds are relatives. Look at the true ancestry of birds- there were some that went extinct.</p> <p>4. It split up into two groups. But then it changed- evolved.</p> <p>5. They evolved. Some of the original ones went extinct, but for the most part they expanded.</p>
V-4: Did using the evolutionary map change your understanding about bird evolution? If so, how?	<p>1. It clued me in to specific traits that ended up being passed down to families or clusters of species.</p> <p>2. I guess so. Based on their location, one bird may have evolved more or less than another bird.</p> <p><i>Follow-up: What do you mean? Adapted more. (Listed features like flight or not needing flight).</i></p> <p>3. You could see where everything was coming from.</p> <p>4. I never really thought about it before, so yes. I didn't know about the two groups at the beginning. And the adaptive radiation was when the dinosaurs went extinct.</p> <p>5. I never thought there were several distinct groups. I would have thought they evolved in a more linear way. It's easier to see the branching like a tree, and not as linear.</p>
V-5: Do you have any general comments about your experience with using the map (e.g., was anything confusing or surprising)?	<p>1. It made sense. As time went on, species branched out. Older ancestors stayed close to the center and newer species branched out. This made it easier to understand.</p> <p>2. The Palaeognaths evolved more slowly- not as many birds relocated to that particular area.</p> <p>3. The way it spread out was kind of confusing. If it could explain how things spread in different directions, like how far apart the spaces mean.</p> <p>4. A timeline would be nice, so you could see where you are.</p> <p>5. At first it was sort of challenging, but it got easier. You sort of have to click through it to know where it's going- the overall pattern- and then it's useful.</p>

Question**Response**

V-6: Do you have any general comments about the design of the visualization, or the interface itself?

1. It could be more visually appealing. For example, use little pictures of birds, rather than dots.
2. Pretty straightforward. It was easy to use arrows and see which dots were linked. *Note: was verbally instructed that only outlined dots were linked.*
3. The visuals (pictures) help. I wish everything were clickable. Rollover text helps a lot to keep track of things.
4. Just the timeline. But it was easy to use, once you got the hang of it.
5. It's pretty clear. Seems pretty user-friendly. There's a lot of white space, which is nice. It makes it easier to interact. [At the beginning] it's empty, but as it fills you can really see the contrast.

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Approval of Exempt Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Sonia H. Stephens**

Date: **October 19, 2011**

Dear Researcher:

On 10/19/2011, the IRB approved the following activity as human participant research that is exempt from regulation:

Type of Review: Exempt Determination
Project Title: An Interactive Visualization for Evolution Education
Investigator: Sonia H. Stephens
IRB Number: SBE-11-07888
Funding Agency:
Grant Title:
Research ID: N/A

This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these changes affect the exempt status of the human research, please contact the IRB. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 10/19/2011 12:17:21 PM EDT

IRB Coordinator

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