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Diagramming Evolution: The Case of Darwin's Trees

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Abstract

From his earliest student days through the writing of his last book, Charles Darwin drew diagrams. In developing his evolutionary ideas, his preferred form of diagram was the tree. An examination of several of Darwin's trees—from sketches in a private notebook from the late 1830s through the diagram published in the *Origin*—opens a window onto the role of diagramming in Darwin's scientific practice. In his diagrams, Darwin simultaneously represented both observable patterns in nature and conjectural narratives of evolutionary history. He then brought these natural patterns and narratives into dialogue, allowing him to explore whether the narratives could explain the patterns. But Darwin's diagrams did not reveal their meaning directly to passive readers; they required readers to engage dynamically with them in order to understand the connections they disclosed between patterns and narratives. Moreover, the narratives Darwin depicted in his diagrams did not represent past sequences of events that he claimed had actually occurred; the narratives were conjectural, schematic, and probabilistic. Instead of depicting actual histories in all their particularity, Darwin depicted narratives in his diagrams in order to make general claims about how nature works. The conjunction of these features of Darwin's diagrams is central to how they do their epistemic work.

Keywords

Charles Darwin, diagrams, evolution, historical explanation, narrative, scientific practice

Introduction

Diagramming was central to Charles Darwin's scientific practice. During *HMS Beagle's* first landfall, Darwin diagrammed Quail Island in the Cape Verde archipelago.[1] And in the last decade of his life, he diagrammed the growing tip of a plant following the sun.[2] Darwin also used diagrams extensively in his publications. In one of his earliest theoretical works, Darwin represented the earth as composed of rectangular blocks to illustrate how the Andes were elevated by volcanoes.[3] And in his last book, Darwin diagrammed how a stone sitting in a field would sink into the turf as it was undermined by earthworms.[4]

Darwin also used diagrams to investigate evolutionary processes, in both private notes and publications. In an 1837–1838 notebook, Darwin drew primitive tree diagrams to think through questions raised by his evolutionary speculations.[5] Tree diagrams occur repeatedly in his personal

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[1] CUL-DAR 32.1.16a, Darwin Papers. Cambridge University Library.

[2] CUL-DAR 209.11, Darwin Papers. Cambridge University Library.

[3] Charles Darwin, "On the Connexion of Certain Volcanic Phenomena in South America; and on the Formation of Mountain Chains and Volcanoes, as the Effect of the Same Powers by Which Continents Are Elevated (Read March 7, 1838)," *Transactions of the Geological Society of London (Series 2)* 5, no. 3 (1840): 601–31, figs. 1, 2, 3, and 4.

[4] Charles Darwin, *The Formation of Vegetable Mould, through the Action of Worms, with Observations on Their Habits* (London: John Murray, 1881), figs. 6 and 7.

[5] Charles Darwin, "Notebook B," in *Charles Darwin's Notebooks, 1836–1844*, ed. Paul H. Barrett et al. (Cambridge: Cambridge University Press, 1987), 26, 36. (Citations to Darwin's notebooks are to Darwin's original pagination.)

notes written during the 1840s and 1850s.[6] As he worked on his "Big Species Book" during the 1850s, Darwin designed a sequence of four diagrams for the book.[7] Events forced his hand, and he shelved the elaborate treatise in favor of a brief "abstract." The abstract—published as the *Origin*—included a single illustration, an elaborate fold-out diagram of the evolutionary process.[8] Even after publishing the *Origin*, Darwin continued to use tree diagrams to think about evolution.[9]

I examine three episodes in which Darwin drew evolutionary tree diagrams: the series of three diagrams in his 1837–1838 notebook, a single notebook page from the late 1850s featuring five tree diagrams, and the 1859 diagram from the *Origin*. Several scholars have written able investigations of Darwin's tree diagrams.[10] These have in the main addressed the development of

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6 Darwin, "Notebook B" (ref. 5), 26, 36. CUL-DAR 205.5.90v, CUL-DAR 205.5.127v, CUL-DAR 205.6.51, and CUL-DAR 205.5.183-186, Darwin Papers. Cambridge University Library.

7 CUL-DAR 10.2.26R-S, Darwin Papers. Cambridge University Library.

8 Charles Darwin, *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (London: John Murray, 1859), facing 117.

9 Charles Darwin, "To Charles Lyell," September 23, 1860, Darwin Correspondence Project Database. http://www.darwinproject.ac.uk/entry-2925 (letter no. 2925; accessed 1 May 2017); CUL-DAR80B.118 and CUL-DAR80B.91, Darwin Papers. Cambridge University Library; Charles Darwin, *The Variation of Animals and Plants under Domestication* (London: John Murray, 1868), 136.

10 J. David Archibald, *Aristotle's Ladder, Darwin's Tree: The Evolution of Visual Metaphors for Biological Order* (New York: Columbia University Press, 2014), 80–112, offers the most comprehensive explication of each of the surviving tree diagrams. For other discussions of Darwin's tree diagrams, see, for example, Heather Brink-Roby, "Natural Representation: Diagram and Text in Darwin's On the Origin of Species," *Victorian Studies* 51, no. 2 (2009): 247–73; Juan L. Bouzat,

Darwin's substantive ideas about how evolution works—asking questions about what the different diagrams say about Darwin's thinking about, for example, divergence of character or recapitulation. Several have also explored the rhetoric of Darwin's *Origin* diagram, examining how it helped to persuade readers to accept Darwin's theory. My focus differs. I focus here in diagramming as an element of Darwin's scientific practice. In particular, I examine less what Darwin's diagrams tell us about *what* he thought than what Darwin's diagrammatic practices tell us about *how* he thought. Using diagrams, Darwin simultaneously represented both observable patterns in nature and conjectural narratives of evolutionary history. And by bringing these natural patterns and narratives into dialogue, his diagrams served as epistemic tools, allowing him to explore whether the narratives could explain the patterns.

Experimenting with Diagrams, 1837–1838

On a stormy October night in 1836, Darwin disembarked from *H.M.S. Beagle* after a five-year voyage. Although Darwin had been exposed to evolutionary ideas before the voyage, he had not

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"Darwin's Diagram of Divergence of Taxa as a Causal Model for the Origin of Species," *The Quarterly Review of Biology* 89, no. 1 (2014): 21–38; Robert J. Richards, *The Meaning of Evolution: The Morphological Construction and Ideological Reconstruction of Darwin's Theory* (Chicago: University of Chicago Press, 1992), 106–15; Julia Voss, *Darwin's Pictures: Views of Evolutionary Theory, 1837–1874* (New Haven: Yale University Press, 2010), 61–126; Alan Gross, "Darwin's Diagram: Scientific Visions and Scientific Visuals," in *Ways of Seeing, Ways of Speaking: The Intersection of Rhetoric and Vision in Constructing the Real*, ed. Kristie S. Fleckenstein, Sue Hum, and Linda T. Calendrillo (West Lafayette, IN: Parlor Press, 2007), 53–80; and Theodore W. Pietsch, *Trees of Life: A Visual History of Evolution* (Baltimore: Johns Hopkins University Press, 2013), 85–97.

developed them systematically.[11] In July 1837, without telling anyone, Darwin opened a small, brown notebook in which to explore these ideas.[12] At this stage, his mind was unsettled. The notebook does not unfold a carefully-considered argument. It bounds from crag to crag. A sweeping pronouncement is circumscribed by a counterexample, which is itself tempered by a further difficulty. Early in the notebook, for example, Darwin stated that sexual reproduction is the "highest office," that is, the most important function, of animals. He then immediately pointed out that the

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[11] Darwin's grandfather, Erasmus Darwin, had published a treatise on evolution before Darwin was born. Erasmus Darwin, *The Temple of Nature: Or, The Origin of Society* (1803; London: Jones & Company, 1825). In addition, Darwin had studied in Edinburgh with Robert Grant, a noted evolutionist, and was familiar with the transmutationist theories of Jean-Baptiste Lamarck. Most historians agree that Darwin did not become a convinced evolutionist until after his return from the *Beagle* voyage. See, for example, Frank J. Sulloway, "Darwin's Conversion: The Beagle Voyage and Its Aftermath," *Journal of the History of Biology* 15, no. 3 (1982): 325–96. For a contrasting view, see Paul D. Brinkman, "Charles Darwin's Beagle Voyage, Fossil Vertebrate Succession, and 'The Gradual Birth & Death of Species,'" *Journal of the History of Biology* 43, no. 2 (2010): 363–99.

[12] Darwin, "Notebook B" (ref. 5). My focus here is on Darwin's diagrammatic practices. For a fuller assessment of Notebook B, see, for example, Jon Hodge, "The Notebook Programmes and Projects of Darwin's London Years," in *The Cambridge Companion to Darwin*, ed. Jon Hodge (Cambridge: Cambridge University Press, 2003), 40–68; David Kohn, "Theories to Work by: Rejected Theories, Reproduction, and Darwin's Path to Natural Selection," *Studies in History of Biology* 4 (1980): 67–170; Camille Limoges, *La Sélection Naturelle* (Paris: Presses Universitaires de France, 1970); and Dov Ospovat, *The Development of Darwin's Theory: Natural History, Natural Theology, and Natural Selection, 1838–1859* (Cambridge: Cambridge University Press, 1981).

argument does not apply to hybrids, whose sexual organs are "perfect" but who generally cannot bear offspring. Shortly afterward, he noted that "mothers [are] apparently only born to breed," then immediately countered with the puzzle that "Eunuchs," "cut stallions," and "nuns" do not have longer life spans despite not reproducing. And the notebook overflows with questions: Why are individual organisms' lives so short? Why is sexual reproduction such a "high object"?[13] Why, if offspring vary, are species so constant over large geographical areas?[14] Why, in contrast, is South America home to two different species of ostrich?[15] And on it went.

One of Darwin's questions is of particular interest: "Each species changes. [D]oes it progress?" Clearly, Darwin thought, there cannot be one universal progressive path; if there were, all organisms sharing the same environment would be identical. Perhaps "every successive animal is branching upwards," some becoming "most perfect" and "some of the branches dying out." Accordingly, "Organized beings represent a tree *irregularly branched*."[16] He did not intend to state a definitive conclusion. The notebook continues to brim with statements, contradictions, qualifications, and questions. Rather, the model of a branching tree was a provisional hypothesis.

Darwin proceeded to consider an objection: does the hypothesis not imply that organisms with similar adaptations are closely related? Or, as he deadpanned, "?We need not think that fish & penguins really pass into each other" just because both can swim.[17] Darwin's solution took the form of a hypothetical question: "Would there not be a triple branching in the tree of life owing to three

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[13] Darwin, "Notebook B" (ref. 5), 2.

[14] Darwin, "Notebook B" (ref. 5), 5.

[15] Darwin, "Notebook B" (ref. 5), 13.

[16] Darwin, "Notebook B" (ref. 5), 18–21 (emphasis in original).

[17] Darwin, "Notebook B" (ref. 5), 25.

elements air, land & water, & the endeavour of each typical class to extend his domain into the other domains[?]"[18] Most birds live primarily aerial lifestyles, while some are primarily aquatic or terrestrial in their habits. One finds different groups of mammals and insects, too, living primarily in the air, on land, or in the water. Perhaps the common ancestor of the class Aves may have lived in an aerial environment, but at some point the lineage of birds split, with one of the subsidiary branches eventually adapting to life on land, and another to life in water. Hence, penguins might have developed features similar to those of fish because the branch of the bird lineage that includes penguins adapted to life in water, yet the two groups might not be at all closely related. Darwin drew his first tree diagram to examine the question (figure 1).

[INSERT FIGURE 1]

The three solid lines at the top of the larger image on the left represent the living species of a particular class (for example, birds) that inhabit the air, water, and land, respectively. More abstractly, the solid lines are a snapshot of an observable pattern in nature. Simultaneously, the diagram depicts a hypothesis about evolutionary history—that a lineage of organisms develops like a tree and that in many classes we would expect to see a "triple branching" of the tree as different groups diverged to take advantage of different habitats and ways of living.

How could Darwin represent such a process diagrammatically? If the oldest ancestral forms are extinct, how are they to be depicted? Darwin recognized this problem: "The tree of life should perhaps be called the coral of life, base of branches dead; so that passages cannot be seen."[19] How would he visually represent passages that cannot be seen? Here, Darwin drew from geology, the field

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[18] Darwin, "Notebook B" (ref. 5), 23–24.

[19] Darwin, "Notebook B" (ref. 5), 25.

in which he was first trained.[20] There was a convention in geological illustration to use solid lines to represent what could be seen of a geological structure and dotted lines to represent either what was assumed to be present but was not visible, or what was conjectured to have been present in the past but to have been obliterated by subsequent geological processes.[21] Darwin deployed this convention in his book on coral reefs, which he was writing around the same time. Figure 2 is Darwin's cross-section of Gambier Island in French Polynesia. The horizontal line represents the surface of the sea, the lighter, vertical shading represents the land, and the darker, horizontal shading represents the coral reef.[22] [INSERT FIGURE 2] Because Darwin could not observe the sea floor under the coral reef directly, he represented it using a dotted line.

Darwin repurposed this convention from geological diagramming in his first evolutionary tree diagram (figure 1), using dotted lines to represent organisms that do not now exist, but that he conjectured had existed at some point in the past. Thus, at the bottom of the larger figure on the left is the original parent organism that lived deep in the past. The upward dotted line represents successive generations of its offspring. The dotted line then splits into three, representing the

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[20] See, for example, Sandra Herbert, *Charles Darwin, Geologist* (Ithaca, NY: Cornell University Press, 2005).

[21] See, for example, Martin J. S. Rudwick, "The Emergence of a Visual Language for Geological Science," *History of Science* 14 (1976): 149–95, on 170–71. The use of dotted lines to depict conjectures about forms that no longer exist may go back even further, to Agostino Scilla's 17th-century fossil illustrations. See Paula Findlen, "Projecting Nature: Agostino Scilla's Fossil Illustrations," *Endeavour* 42, no. 2 (2018) (this issue).

[22] Charles Darwin, *The Structure and Distribution of Coral Reefs* (London: Smith Elder and Co., 1842), 48, figure 2.

splitting of the original lineage. One of the three resulting branches remained adapted to the air, and the others adapted to land and water, respectively. As we approach the present, the dotted lines become solid, depicting the three different extant forms, inhabiting different environments. The diagram thus embodies a conjectural historical narrative—a visual representation of a hypothesis about how a particular lineage evolved from a single ancestor into three related forms inhabiting different environments.

The diagram is, simultaneously, a snapshot of an observable pattern in nature (different taxa having terrestrial, aquatic, and aerial forms) and a conjectured and schematic history of the evolution of a lineage of organisms through time. More, the diagram draws a connection between the pattern and the history, suggesting as a provisional hypothesis that the history explains the pattern. That the hypothesis is provisional is consistent with the general tone of the notebook. The notebook did not articulately argue for a theory. It asserted and denied, made blanket statements and qualified them. Most of all, it asked questions. Similarly, the diagram is not a visual summary of the propositional contents of a firmly-held theory. It is a tool for thinking about whether his hypothesized evolutionary history could account for a pattern we see in nature.

Another pattern visible in nature is that living orders of fish range from the simplest, most rudimentary forms to the most advanced and elaborate. We could almost organize extant groups of fish on a single line ranging from the simplest to the most complex. On the other hand, there are no very simple living birds, and there are gaps separating the extant groups. If all birds descended from a single common progenitor, why do we not see a similar linear arrangement of birds from the simplest to the most elaborated? Indeed, at the time Darwin was drawing this diagram, many English naturalists believed that a linear arrangement was impossible and that the proper way to represent the affinities of birds is to arrange them in circles within circles: the class Aves containing five circles representing the different orders of birds, each order containing five circles representing the different families in that order, and so on. Figure 3—Nicholas Vigors's diagram of the Aves—illustrates such a circular pattern of affinities.[23]

[INSERT FIGURE 3]

Because we view taxonomy through an evolutionary lens, geometrically regular diagrams like Vigors's seem quaint. In Darwin's day, however, many believed that such circular diagrams captured the underlying order of nature. William Sharp Maclaey, for example, suggested that the geometrical regularity of taxonomy meant that "the variation of animal structures may, in the end, come within the province of the mathematician."[24] And William Swainson believed Macleay's system exhibits a "universal law in natural arrangement."[25]

At the time, Darwin accepted, at least provisionally, the circular pattern of bird affinities.[26] Darwin used his second diagram to inquire into the causes of the pattern—specifically, to ask whether he could develop a conjectural historical narrative that could account for both the linear pattern of fish affinities on the one hand and the circular pattern of bird affinities on the other. He

[23] Nicholas Aylward Vigors, "Observations on the Natural Affinities That Connect the Orders and Families of Birds, Read December 3, 1823," *Transactions of the Linnean Society of London* 14, no. 3 (1825): 395–517, on 509.

[24] William Sharp Macleay, *Horae Entomologicae: Or Essays on the Annulose Animals* (London: S. Bagster, 1819), II:395.

[25] William Swainson, *Zoological Illustrations, or, Original Figures and Descriptions of New, Rare, or Interesting Animals* (London: Printed by R. and A. Taylor for Baldwin, Cradock, and Joy; and W. Wood, 1820), 92.

[26] Darwin, "Notebook B" (ref. 5), 45–46.

wrote, “Is it thus fish can be traced right down to simple organization—birds, not[?]”[27] and immediately followed by drawing his second tree diagram (figure 4).

[INSERT FIGURE 4]

On the right, Darwin showed fish. Here, both simple and complex forms exist, and Darwin used solid lines to represent them. A branching evolutionary process, Darwin’s diagram suggests, could indeed explain the branching linear pattern of fish affinities. The birds (depicted on the left) present more difficulties. Many species of complex birds exist, represented by solid lines. The simple precursors intermediate between living forms that Darwin conjectured must once have existed are represented by dotted lines. How could this account for the circular pattern of affinities depicted by Vigors? “We may fancy,” Darwin wrote, “that in perfection, the bottom of branches deaden, so that in … birds, it would only appear like circles...—but in lower classes perhaps a more linear arrangement.”[28] He meant that in “lower” groups like fish, the intermediate species remain extant, so the connections between the different species can be rendered as a solid line. In more “perfect” organisms like birds, the intermediate forms have gone extinct, leaving gaps between the existing species. In order to understand the apparent circular arrangement, we must project Vigors’s two-dimensional diagram into three dimensions. We begin with the common ancestor of all birds, proceed upward through the various extinct birds from which the living groups derived, and end at the top with Vigors’s circular arrangement of living birds. Darwin never drew a projection such a three-dimensional diagram. For the convenience of the reader, I include such a projection in figure 5, visualizing a three-dimensional diagram for the order Insessores (the top circle in Vigors’s diagram). [INSERT FIGURE 5] Darwin never drew such a projection, but he did imagine a three-

[27] Darwin, “Notebook B” (ref. 5), 26.

[28] Darwin, “Notebook B” (ref. 5), 27.

dimensional diagram of the conjectured history, revealing a potential cause of Vigors's two-dimensional pattern. As Darwin put the point in a later notebook, "The tree of life must be erect not pressed on paper, to study the corresponding points."[29]

As with Darwin's first diagram, his second simultaneously depicts both an observable natural pattern (actually, two patterns: the linear affinities of living fish and the circular affinities of living birds) and a conjectured history of how those patterns might be explained. The solid lines represent a snapshot of the affinities between extant bird species on the one hand and fish on the other. The diagram as a whole also represents a conjectured history of the evolution of bird and fish lineages over time. And, as with the first diagram, by placing these two elements into juxtaposition, the diagram allowed Darwin to ask whether his conjectured evolutionary history might explain the observed pattern. Note again, too, Darwin's tone. He did not express his hypothesis with any sense of certainty, merely suggesting that "we may fancy" that his conjectured history might explain the observed pattern.

Some months later, Darwin drew his third tree diagram (figure 6).[30] [INSERT FIGURE 6] In several respects, this diagram departs from his first two diagrams. Darwin had gained confidence in the capacity of his theory to make sense of observed patterns. Earlier in the notebook, he had followed an assertion with its negation, or a qualification. And he was constantly asking questions.

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[29] Charles Darwin, "Notebook D," in *Charles Darwin's Notebooks, 1836–1844*, ed. Paul H. Barrett et al. (Cambridge: Cambridge University Press, 1987), 59. See also Charles Darwin, "Notebook C," in *Charles Darwin's Notebooks, 1836–1844*, ed. Paul H. Barrett et al. (Cambridge: Cambridge University Press, 1987), 155 ("There is same difficulty in arranging animals in paper as drying plant, all brought in one plane.").

[30] Darwin, "Notebook B" (ref. 5), 36.

He launched into the third diagram more forcefully, writing "I think," and then sketching the diagram. And he scribbled in the margin of the diagram that "Case must be" that the number of living species remains constant over evolutionary time. Moreover, the diagram had become more general. In the first diagram, he had asked questions about specific classes of animals having terrestrial, aquatic and aerial forms, and in the second, he had explored patterns of affinities in birds and fish. In the third diagram, the specific classes of organisms were replaced by symbols representing notional taxa (the numeral 1 representing the common ancestor, and the letters A, B, C, and D representing the current descendant species). Darwin thus used his third diagram to investigate evolutionary processes in general, rather than in particular cases.

But in another way, Darwin's third diagram is continuous with the first two. The diagram represents an observed pattern in nature. The living world is not just a jumble of organisms each of which is just slightly different from every other. Rather, they fall into discrete groups, represented in the diagram by the three species in genus A, four species in genus B, three species in genus C, and three species in genus D. And some genera are more distant from each other than others, with an "immense gap of relation" between A and B, only the "finest gradation" between B and C, and "rather greater distinction" between B and D.[31] The diagram simultaneously depicts a conjectural narrative of an evolutionary history. The numeral 1 represents a hypothesized ancestral species that no longer exists. The lines that end without cross-hatches represent species that Darwin conjectured had gone extinct. And the thirteen species in the genera he labeled with the letters A, B, C, and D are still living.

Again, Darwin used the diagram to relate a pattern observable in nature with a conjectural historical narrative. Living beings, considered in their affinities to each other, cluster in groups.

[31] Darwin, "Notebook B" (ref. 5), 36.

Darwin suggested that one would expect to see this pattern if his conjectured evolutionary history had actually happened: "Thus genera would be formed.—bearing relation to ancient types." Moreover, the more extensive the groups of organisms being compared, the greater the differences one would expect to find between them: "the *greater the groups* the *greater the gaps* ... between them.—for instance there would be great gap between birds & mammalia, Still greater between Vertebrate and Articulata [annelids and arthropods]. still greater between animals & Plants." Yet because all organisms are "coming from one stock & obeying one law," and all seek to fill the three environments of land, air, and water, one would expect to find certain points of similarity even between the most distantly related organisms. Darwin thus suggested that the patterns of affinity we see in the living world, obscure as they might at first seem, are precisely what we would expect to find if his conjectured evolutionary history had happened. Still, even this third diagram does not depict a fully fleshed-out theory. He concluded: "Heaven know whether this agrees with Nature: *Cuidado*."[32]

Diagramming the Theory, 1840–1858

In his 1837–1838 notebook, Darwin was trying out evolutionary ideas, convinced that he was onto something, but not entirely certain of his ground. By the early 1840s, he had gained confidence, writing two manuscript sketches of his theory to be published if he should die unexpectedly.[33] Throughout the 1840s and 1850s, he continued to develop his theory, and he continued

[32] Darwin, "Notebook B" (ref. 5), 42–44 ("*Cuidado*" is Spanish for "be careful").

[33] These manuscripts have since been published as Charles Darwin, *The Foundations of the Origin of Species. Two Essays Written in 1842 and 1844*, ed. Francis Darwin (Cambridge: Cambridge University Press, 1909).

diagramming. Here, I consider a single page of diagrams from this period (figure 7).[34] Perhaps even more than Darwin's earlier diagrams, this page showcases the dynamic, searching quality of Darwin's diagrammatic practices. Scribbled on the back of an advertising broadside for a local printer and stationery merchant, five diagrams crowd the page—interspersed with, and sometimes overwritten by, textual annotations.

[INSERT FIGURE 7]

As in his earlier diagrams, Darwin explored how a pattern in nature might be explained by a conjectural evolutionary history. In this case, the natural pattern was not ecological or taxonomic, but embryological. The study of embryology had flowered following Karl Ernst von Baer's 1828 treatise,[35] which had been introduced to the Anglophone world 1837 by Martin Barry and brought to

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[34] CUL-DAR205.6.51, Darwin Papers. Cambridge University Library. The page is undated. I consider the most likely dating to be between 1856 and 1859. It seems clearly to predate the 1859 publication of the Origin. One of the diagrams includes ideas about the lineage of domestic pigeon breeds that I do not believe Darwin would have had the information even to conjecture prior to his pigeon-breeding experiments of 1855–1858. For more on Darwin and pigeon breeding, see James A. Secord, "Nature's Fancy: Charles Darwin and the Breeding of Pigeons," *Isis* 72, no. 2 (1981): 163–86; and Mary M. Bartley, "Darwin and Domestication: Studies on Inheritance," *Journal of the History of Biology* 25, no. 2 (1992): 307–33. Although Archibald, Aristotle's Ladder (ref. 10), 92, dates the page to "possibly" between 1852 and 1855, he has indicated (2017, personal communication) that he now considers the later dating more likely.

[35] Karl Ernst von Baer, *Über Entwickelungsgeschichte der Thiere: Beobachtung und Reflexion*, vol. 1 (Königsberg: Bornträger, 1828).

an even wider audience in William Carpenter's treatise on physiology, which first appeared in 1839 and went through multiple subsequent editions.[36]

Baer had identified two fundamental patterns of embryological development. Barry framed them as "unity of structure" and "unity of plan." The principle of unity of structure holds that "*all the varieties of structure in the animal kingdom, are but modifications of, essentially, one and the same fundamental form*."[37] Each animal embryo begins as a simple, homogeneous structure having the same form as every other animal embryo. This first pattern is synchronic: a snapshot of the germ taken at the beginning of development will be identical across animal groups. The principle of unity of plan holds that the path followed by animal embryos as they develop is "universally the same."[38] This second pattern brings in a temporal dimension. The pattern is an identity in the process of development over time, from the moment of conception to the moment of birth. Figure 8 is a diagram Barry created to illustrate this "fundamental unity" of structure and plan.[39]

[INSERT FIGURE 8]

The diagram depicts the embryological development of fish, reptiles, birds, and mammals. Point A represents the common "germ," which on the principle of unity of structure is identical across the four groups. Points B, C, D, and E represent fish, reptiles, birds, and mammals, respectively, at birth. Their distance on the horizontal axis from point A represents the degree of

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36 Martin Barry, "On the Unity of Structure in the Animal Kingdom," *The Edinburgh New Philosophical Journal* 22 (1837): 116–41, 345–64; William B. Carpenter, *Principles of General and Comparative Physiology* (London: John Churchill, 1839), 170.

37 Barry, "On the Unity of Structure" (ref. 36), 126–27 (emphasis in original).

38 Barry, "On the Unity of Structure" (ref. 36), 126.

39 Barry, "On the Unity of Structure" (ref. 36), 134, fig. 11.

"elaboration" of the various animals during development, with fish changing the least from the common germ to birth, and mammals the most. Although the four groups are thus not identical at birth, the solid curved lines connecting Point A with each of Points B, C, D, and E are identical in curvature, depicting "identity in the manner of development," or unity of plan.

In Darwin's page of diagrams (figure 7) he struggled with whether his conjectured evolutionary history could account for Barry's unities. The four diagrams in the center of the page show him working through in different ways the same basic idea. In figure 9, I have made Darwin's diagram from the middle left of figure 7 more legible. [INSERT FIGURE 9] Darwin's diagram represents both of the patterns identified by Barry, and a narrative of the history conjectured by Darwin to account for them. The "common embryo" at the bottom of Darwin's tree depicts an undifferentiated germ, representing Barry's first, synchronic pattern of unity of structure. Darwin's diagram represents the second, temporal, pattern by showing that the embryo, as it develops, undergoes an "alteration in some way," gradually developing into either a carnivore on the one hand or an herbivore (represented by pachyderms and ruminants) on the other.

Darwin's diagram simultaneously depicts a conjectural evolutionary history. Although it begins with an embryo and traces that embryo's gradual development, the diagram also includes adult organisms as intermediate stages, referring to the "common parent" of the carnivores and the "common parent" of the pachyderms and ruminants.[40] Similarly, the diagram below and to the right of the one on which we have been focusing is substantially identical, except that it depicts only the

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[40] Darwin's division of ungulates into pachyderms and ruminants has since been superseded. The pachyderms included, among others, elephants and hippopotamuses. It is now considered that hippopotamuses are more closely related to ruminants than either are to elephants, and the pachyderm designation has therefore been rejected as referring to a polyphyletic group.

evolutionary history. At the base of its rightmost tree sits an "Eocene Pachyderm Ruminant," designating the common ancestor alive during the Eocene epoch of the two groups. Darwin thus used diagramming to bring a conjectured evolutionary history into dialogue both with Barry's synchronic pattern of unity of structure and with Barry's temporal pattern of unity of plan.

Darwin's attempt to marry Barry's natural patterns with Darwin's narrative—to use the conjectured evolutionary history to explain the observed patterns in embryological structure and development—is also apparent in several of the notations scribbled around, and over, the diagram. To the right, Darwin wrote, "This is the explanation of *longer* greater similarity of Embryo of Pig and Cow." The similarity of pig and cow embryos extending late into development (an instance of Barry's observed natural pattern) is, Darwin hypothesized, explained by the lineages of pigs and cows only very recently having diverged (an episode in Darwin's conjectured evolutionary history). On the other hand, lineages of organisms that diverged early in evolutionary history would have embryos that diverge in structure earlier in development. At the bottom of the page, Darwin wrote, "Generally as Selection is slow & much extinction is required, the most diverse form will have branched off soonest."[41] Thus, the diagrams simultaneously represent the undifferentiated germ shared by the different animal groups, the similar pattern of embryological development across groups, and the evolutionary history that Darwin conjectured could explain those two patterns.

Diagramming for the Public, 1859

In 1859, Darwin published the *Origin*. Darwin ensured that his books were profusely illustrated. His monograph on barnacles, published shortly before the *Origin,* boasted forty-seven plates. His orchid

[41] CUL-DAR 205.6.51 (ref. 34) (emphasis in original).

book, published shortly after the *Origin,* included thirty-three engravings.[42] And Darwin attended closely to the details of the images in his books, from the creation of drawings and photographs to the production of engravings and plates.[43] Nevertheless, he included only one illustration in the *Origin,* a fold-out lithograph of a tree diagram (figure 10). Darwin believed the diagram to be essential. He told his mentor Charles Lyell that the *Origin* would be "perplexing and unintelligible" without the diagram.[44] He told his publisher John Murray that the diagram was "indispensable" and "earnestly beg[ged]" that Murray have the plate carefully inspected. If it failed to print clearly, "I assure you that parts of my book will be as unintelligible as Hebrew.—"[45]

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[42] Charles Darwin, *Living Cirripedia, A Monograph on the Sub-Class Cirripedia, with Figures of All the Species*, 2 vols. (London: The Ray Society, 1851); Charles Darwin, *A Monograph on the Fossil Lepadidæ, or Pedunculated Cirripedes of Great Britain* (London: Palaeontographical Society, 1851); Charles Darwin, *A Monograph on the Fossil Balanidae and Verrucidae of Great Britain* (London: Palaeontographical Society, 1854); Charles Darwin, *On the Various Contrivances by Which British and Foreign Orchids Are Fertilised by Insects* (London: John Murray, 1862).

[43] See, for example, Jonathan Smith, *Charles Darwin and Victorian Visual Culture* (Cambridge: Cambridge University Press, 2006); Phillip Prodger, *Darwin's Camera: Art and Photography in the Theory of Evolution* (Oxford: Oxford University Press, 2009).

[44] Charles Darwin, "To Charles Lyell," September 2, 1859, Darwin Correspondence Project Database. http://www.darwinproject.ac.uk/entry-2486 (letter no. 2486; accessed 1 May 2017).

[45] Charles Darwin, "To John Murray," May 31, 1859, Darwin Correspondence Project Database. http://www.darwinproject.ac.uk/entry-2465 (letter no. 2465; accessed 1 May 2017); Charles Darwin, "To John Murray," December 5, 1860, Darwin Correspondence Project Database. http://www.darwinproject.ac.uk/entry-3010 (letter no. 3010; accessed 1 May 2017).

[INSERT FIGURE 10]

The diagram is complex. Indeed, Darwin's initial exegesis of the diagram stretches to eleven printed pages.[46] To understand the diagram, consult the detail in figure 11.

[INSERT FIGURE 11]

- The vertical axis represents time: past at the bottom, present at the top. The space between any two contiguous horizontal lines (labelled from I to XIV) represents 1,000 generations.
- The horizontal axis represents character differences: the farther two organisms are apart horizontally, the more different they are in habits, constitution, and structure.
- The capital letters G through L, running along the bottom of the diagram, represent five ancestral species in a single genus.
- The five dotted lines running between species I and the first horizontal line (labeled Roman numeral I and representing the lapse of 1,000 generations) are the various offspring of species I. Four of the lines terminate at or before the thousandth generation, indicating that these lineages have gone extinct. One of the lineages, however, reaches z^1, which is sufficiently different from species I (that is, distant from I on the horizontal axis) as to represent a distinct variety of species I.
- The offspring of variety z^1 continue to branch out. This lineage survives, varies and evolves, with most branches of the lineage going extinct, but others continuing to survive and evolve.

[46] Darwin, *Origin* (ref. 8), 116–26.

- Eventually, at the uppermost horizontal line (labeled Roman numeral XIV and representing the lapse of 14,000 generations), species I has given rise to six daughter species. These species fall into two discrete genera, one comprising n^{14}, r^{14}, and w^{14}, and the other comprising y^{14}, y^{14}, and z^{14}.[47]

Darwin returned to the diagram frequently in the *Origin,* using it to explore a wide range of phenomena. I will focus my attention here on two such uses.

One of the functions of the third notebook diagram had been to explore why organisms tend to cluster into discrete groups rather than simply forming a large mass of more or less similar organisms. Darwin used the published diagram to explore the same phenomenon. Since each of the lines labelled I to XIV on the diagram represents 1,000 generations, each of the individual dots proceeding upward from the various nodes in the diagram represents something like 50 generations. Thus, after 50 generations, the offspring from species I are very near horizontally to I, signifying that they are almost indistinguishable in habits, constitution, and structure from I. And we can observe the same phenomenon by examining any two contiguous dots anywhere in the diagram. After 14,000 generations, however, not only are species n^{14} through z^{14} very different in character from I; they are also very different from each other and fall into two discrete genera.

As with his earlier diagrams, Darwin brought the natural patterns and conjectured history into dialogue. As he worked his way through his exegesis of the diagram, Darwin noted that the variations that would arise in offspring would be "extremely slight" and "of the most diversified nature." Of these variations, only those "which are in some way profitable will be preserved or naturally selected." And because "competition will generally be most severe between those forms

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[47] Darwin, *Origin* (ref. 8), 116–17. The pathologically alert reader may have noticed that two of the species at level XIV have the same designation: y^{14}. This is surely unintentional.

which are most nearly related to each other in habits, constitution, and structure," the forms most like their parents and each other will be most likely to go extinct. He concluded: "[T]his will generally lead to the most different or divergent variations (represented by the outer dotted lines) being preserved and accumulated by natural selection."[48] The expected result of his conjectured history, in other words, is precisely the natural pattern we observe—discrete groups of organisms that are relatively well-differentiated in habits, constitution, and structure both from each other and from the ancestral species from which they are descended.

As we have seen, in his initial exegesis of the diagram, Darwin described it as showing how, after 14,000 generations, a single species (I) diverged into two new genera, each comprising three species. Darwin then made a curious suggestion. Instead of the space between any two contiguous horizontal lines representing 1,000 generations, "it would have been better if each had represented ten thousand generations."[49] Indeed, he later suggested that the reader suppose that "each may represent a million or a hundred million generations."[50] If we rescale the vertical dimension of the diagram in our imaginations by supposing that the distance between two contiguous horizontal lines represents a hundred million generations rather than 1,000, we can use the diagram to explore much longer ranges of geologic time. Darwin also suggested that we imaginatively rescale the horizontal dimension of the diagram, by supposing that the amount of character difference represented by any particular horizontal distance on the diagram "to be very great."[51]

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[48] Darwin, *Origin* (ref. 8), 117–21.

[49] Darwin, *Origin* (ref. 8), 117.

[50] Darwin, *Origin* (ref. 8), 124.

[51] Darwin, *Origin* (ref. 8), 125.

By inviting his readers to dynamically, and multiply, rescale the diagram in their imaginations, Darwin's readers could see how his theory could explain the evolution not just of new species but also of "distinct families, or even orders, according to the amount of divergent modification supposed to be represented in the diagram."[52] More fundamentally, he wanted his readers to appreciate a basic pattern of the living world observable at every level of taxonomic organization. Darwin's third tree diagram (figure 6) had shown how his conjectural evolutionary history could account for the fact that living species group into genera, with great empty gaps between them. By 1859, Darwin had concluded that this pattern repeats up and down the tree of life: "It is a truly wonderful fact—the wonder of which we are apt to overlook from familiarity—that all animals and all plants throughout all time and space should be related to each other in group subordinate to group, in the manner which we everywhere behold." We can observe this pattern, Darwin wrote, at the levels of species, genera, families, orders, and classes, as well as in taxonomic groups intermediate between them. "The several subordinate groups in any class cannot be ranked in a single file, but seem rather to be clustered round points, and these round other points, and so on in almost endless cycles." This wonderful fact "is explained through inheritance and the complex action of natural selection, entailing extinction and divergence of character, as we have seen illustrated in the diagram."[53]

From our vantage point, the branching visual form of the diagram, and the repeating self-similar patterns it exhibits at every possible scale, immediately suggest fractal geometry. The mathematics of fractals had not yet been created in Darwin's day—and in any case, he was fairly innumerate. But it is apparent that Darwin believed that a relatively simple set of operations—vary,

[52] Darwin, *Origin* (ref. 8), 125

[53] Darwin, *Origin* (ref. 8), 128–29.

struggle, reproduce—applied rigorously and recursively will generate complex but regular patterns that are invariant regardless of scale.

In another passage, Darwin suggested that his readers reimagine his diagram in a different way to explore a different issue—the characteristic pattern of geological succession. Many nineteenth-century naturalists had noted that extinct species for which fossil remains had been found tend to be intermediate in character between living groups.[54] If we were to examine the fossils of early whales, for example, we would find that it averaged out, the different features of the various living Cetaceans and is therefore intermediate between them. In Darwin's day, it was not obvious why this should be so. Darwin invited his readers to use his diagram to suggest an answer.

On his original interpretation, the visible pattern in nature was represented by the top line of the diagram only. It depicted living, and therefore observable, forms, while the lower lines represented organisms that are unobservable because now dead. As Darwin began his discussion of geological succession, he asked his readers to "turn to the diagram"[55] and to reimagine "each horizontal line" as not representing time, but instead "a section of the successive strata of the earth's crust including extinct remains."[56] So interpreted, the diagram depicts a very different observable pattern: each superscripted letter represents a fossil we can see in a museum today, and its position in the diagram coincides with the geological stratum in which it was found. Again, Darwin suggested that the observable pattern—fossil forms tending to be intermediate in character between later

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[54] See, for example, Richard Owen, *A History of British Fossil Mammals, and Birds* (London: John van Voorst, 1846), xxi–xxii; William Buckland, *Geology and Mineralogy Considered with Reference to Natural Theology* (G. Routledge & Company, 1836), I:113–14; Darwin, *Origin* (ref. 8), 329.

[55] Darwin, *Origin* (ref. 8), 331.

[56] Darwin, *Origin* (ref. 8), 124.

forms—is exactly the pattern we would expect based on his conjectured evolutionary history: "Thus, on the theory of descent with modification, the main facts with respect to the mutual affinities of the extinct forms of life to each other and to living forms, seem to me explained in a satisfactory manner."[57]

Darwin's use of diagrams in the *Origin* is an evolution of his diagrammatic practices in his notebooks. In the notebooks, he had used diagrams to think through questions for himself, while in the *Origin,* he was seeking to explain his theory to his readers and convince them of its truth. But the fundamental mode was identical: take an observed pattern in nature and explore whether a conjectured evolutionary history can explain the pattern. Even Darwin's tone of voice is comparable. In his notebook diagrams, Darwin's tone was exploratory. By the time of the *Origin,* we can suppose he was at least convinced of the basic truth of his theory. Yet he introduced his diagram by inviting readers to use it, as he had, to *think with*: "The accompanying diagram will aid us in understanding this rather perplexing subject."[58] And he began his use of the diagram to analyze geological succession with: "As the subject is somewhat complex, I must request the reader to turn to the diagram…."[59] Note, in both cases, Darwin's use of the word "us." Thus did he invite his readers to think with him using the diagram.[60]

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[57] Darwin, *Origin* (ref. 8), 333.

[58] Darwin, *Origin* (ref. 8), 116.

[59] Darwin, *Origin* (ref. 8), 331.

[60] Darwin's invitation to his readers to use his diagram to think with him is a vivid instance of the sense in which diagramming is a social practice. As stated in the introduction to this special issue: "By reproducing and sharing diagrams, users collectively constitute their own subjective practices of representation that enable and constrain the use of diagrams as reasoning tools." Greg Priest,

Diagramming Patterns, Diagramming Narratives

If Darwin's diagrams are tools that he used—and that he invited his readers to use—to investigate evolutionary processes, what more can we say about how those tools functioned? We have already seen the beginnings of an answer: Darwin used diagrams to represent both a pattern that we can observe in nature and a conjectural narrative of an evolutionary history, and then brought the pattern and the history into dialogue to explore whether the history could explain the pattern. But let us dig a little deeper.

Diagramming was central to the practice of many early nineteenth-century naturalists. Although even a cursory survey is impracticable here, John Herschel can serve as an exemplar: he was widely renowned as a practicing naturalist (predominantly astronomy), was the premiere British philosopher of science of the period, and used diagrams in his scientific work, as well as discussing diagrams in his philosophical writings. In his essay on how to calculate the orbits of binary stars, for example, Herschel's method was, as he put it, "essentially graphical." Herschel first gathered together all of the observations he could find on the changing locations of the two stars in the system. If the observations had all been exact, they would "necessarily admit of a regular curve being drawn through them, whose nature would, of course, be determined by the laws of elliptic motion" and which would have "a peculiarly graceful and flowing outline." Because errors in the observations were inevitable, however, it would be impossible to draw a regular curve encompassing every observation. Instead, Herschel drew "by the mere judgment of the eye, and with a free but

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Silvia De Toffoli, and Paula Findlen, "Introduction to the Special Issue: Tools of Reason: The Practice of Scientific Diagramming from Antiquity to the Present," *Endeavour* 42, no. 2 (2018) (this issue).

careful hand, not through, but among them, a curve presenting as few and slight departures from them as possible, consistently with this character of large and graceful sinuosity, which must be maintained at all hazards." Although (indeed, because) such a diagram does not encompass every data point, Herschel considered that it represents the real situation better than the data themselves: "[B]y substituting the curve for the points, we have made a nearer approach to nature."[61]

On Herschel's account, such a substitution of regular, ordered diagrammatic curves for aggregations of particular observed data is appropriate not only for astronomy; it is useful across vast fields of science. A critical step in any scientific investigation is the establishment of laws, by which Herschel meant regular, invariant patterns in nature: "In the discovery of these [laws] much trouble may be saved, and much clearer insight gained by … connecting a series of dots, by a continuous outline."[62] Indeed, diagramming is not merely a useful tool. The regular curve that reveals an invariant pattern in nature is, according to Herschel, the very model of a "sound induction":

> The general proposition is more than a sum of the particulars. Our dots are filled in and connected by an ideal outline which we pursue even beyond their limits,—assign it a name, and speak of it as *a thing*. In all our propositions this *new thing* is referred to,

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[61] John F. W. Herschel, "On the Investigation of the Orbits of Revolving Double Stars: Being a Supplement to a Paper Entitled 'Micrometrical Measures of 364 Double Stars &c, &c,'" *Memoirs of the Royal Astronomical Society* 5 (1833): 171–222, on 178–79.

[62] John F. W. Herschel, "Whewell on the Inductive Sciences," in *Essays from the Edinburgh and Quarterly Reviews* (1841; London: Longman, Brown, Green, Longmans, & Roberts, 1857), 142–256, on 249. See also [John F.W. Herschel], "Quetelet on Probabilities," *The Edinburgh Review* 92, no. 185 (July 1850): 1–57, on 49.

> the elements of which it is formed forgotten; and thus we arrive at an inductive formula; a general, perhaps a universal proposition.[63]

For Herschel, thus, the fundamental function of diagramming as a scientific practice is to find and to characterize the regular patterns of nature.[64] On Herschel's account, a diagram succeeds by giving us a snapshot both physical and mental, a *coup de l'oeil* that allows us to perceive in an instant the fundamental order that characterizes a natural system: "Their course, graphically projected, speaks not only to the eye, but immediately to the mind."[65] Thus does diagramming contribute to natural history's goal of "exemplifying the simplicity of nature as it emerges slowly from an entangled mass of particulars in which, at first, neither order nor connection can be traced."[66]

Herschel drew astronomical diagrams. But Herschel's conception of diagramming can be applied as well to the living world. We could, in theory, compile every observation that has ever been made of any bird into an encyclopedic collection, but it would likely prove impossible to discern any pattern of similarities and differences of different groups of birds directly from such a mass of data. Vigors's circles within circles (figure 3) are a Herschellian "ideal outline" of patterns of

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[63] Herschel, "Whewell on the Inductive Sciences" (ref. 62), 246 (emphasis in original). See also 172-173.

[64] For a fuller exploration of Herschel's diagrammatic practices, see Thomas L. Hankins, "A 'Large and Graceful Sinuosity': John Herschel's Graphical Method," *Isis* 97, no. 4 (2006): 605–33. I would like to thank an anonymous reviewer for this journal for bringing Hankins's article and Herschel's binary star orbit diagrams to my attention.

[65] John F. W. Herschel, "Terrestrial Magnetism" 1840. In *Essays* (ref. 62), 63–141, at 82.

[66] John F. W. Herschel, *A Preliminary Discourse on the Study of Natural Philosophy* (London: Longman, Rees, Orme, Brown and Green, 1830), 263–64.

affinity that would not be readily apparent from the raw data. We can imagine a collection of many tens of thousands of embryos of different animals at different stages of development, but it would be difficult to see commonalities of embryological development across groups. Barry's embryological diagram (figure 8) represents a single, universal, common germ and a single, universal path of development. Despite their differing subjects Herschel, Vigors, and Barry used diagrams for the same fundamental purpose: to represent regular patterns in nature.[67]

Diagramming served a different purpose for Darwin. It was not that he denied the existence of patterns in the living world. Indeed, as we have seen, his diagrams represented those patterns. Figure 1 shows the common tendency of different animals to have forms adapted to aquatic, aerial and terrestrial habitats. Figure 4 depicts a linear model of the affinities of fish and a circular model of the affinities of birds. Figure 6 represents the common tendency of living beings to form discrete and well-differentiated groups. Figures 7 and 9 show the unity of structure and plan of embryology. And figure 10 expresses a variety of patterns, from the nesting of groups of organisms within larger groups up and down the taxonomic scale to patterns of geological succession. But depicting a natural pattern was only part of what Darwin sought to accomplish through diagramming. Darwin also used diagramming to bring those observed patterns into dialogue with conjectured narratives of evolutionary history to see whether those narratives could explain the patterns. In order do this, Darwin's diagrams had to depict not only the patterns, but also the narratives.

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[67] My analysis of Vigors and Barry barely scratches the surface of diagrammatic practices in representing patterns in the living world in the early nineteenth century. For a much more extensive discussion, see Mary P. Winsor, "Considering Affinity: An Ethereal Conversation," 3 pts., *Endeavour* 39, no. 1 (2015): 69–79; 39, no. 2 (2015): 116–26; 39, no. 3 (2015):179–87.

Before turning to how Darwin depicted narratives in his diagrams, we need first to examine narrative in its more familiar form. Historical narratives are typically composed of words, as a linguistic "account of the unfolding of a series of events, along with an effort to explain how and why these processes and events came to be."[68] Consider the following condensed example: Henry VIII was married to Catherine of Aragon. Concerned that Catherine might not provide him with a male heir and besotted with the young Anne Boleyn, Henry sought to have the Pope annul his marriage to Catherine. The Pope refused, but Henry nonetheless proceeded to marry Anne, in the process rejecting the Pope's authority and initiating the English Reformation. We understand such a narrative in two different, but complementary ways: as a sequence of separate, causally related events, and as a single, narrative whole. William Gallie emphasized the former mode; we understand a narrative by "following" it as a causal sequence.[69] Henry's frustrations at what he saw as Catherine's failure to bear a son, and his infatuation with Anne, caused him to seek an annulment, the Pope's refusal of which caused him to reject papal authority, and so on. It is not that we can deduce or predict each event from what happened before; narratives always involve "some surprises." But, for us to be willing and able to follow the narrative, we must be satisfied with the

[68] Daniel Little, *New Contributions to the Philosophy of History* (Dordrecht: Springer Netherlands, 2010), 29; see also Paul A. Roth, "Philosophy of History," in *Routledge Companion to the Philosophy of Social Science*, ed. Alex Rosenberg and Lee McIntyre (New York: Routledge, 2017), 397–407, on 399 (to same effect).

[69] W. B. Gallie, *Philosophy and the Historical Understanding* (New York: Schocken Books, 1968), 22–50.

narrative plausibility of the causal sequence—the surprises "should never offend our sense of what is possible."[70]

Louis Mink proposed an alternative view: we understand a narrative not by following separate events through a causal sequence, but by seeing the narrative as an integrated whole, by showing how each separate event "belongs to a configuration of events like a part to a jigsaw puzzle." On Mink's conception, we see the whole narrative of Henry, his wives, the Pope, and the English Reformation in a single, synoptic view, as part of a coherent configuration, with each individuated event having meaning only by virtue of its place in the configuration. Mink illustrated his point with a metaphor: "To comprehend temporal succession means to think of it in both directions at once, and then time is no longer the river which bears us along but the river in aerial view, upstream and downstream seen in a single survey."[71] Mink considered that his configurational mode was the singular proper way to conceive of understanding a narrative. On my view, Gallie's and Mink's conceptions are not alternatives, but complements. As when we alternately conceive of light as a wave and as a particle, the fact that the two models of narrative understanding cannot simultaneously be entertained does not require us to reject one of them. As Paul Roth notes, both

[70] Gallie, *Philosophy and the Historical Understanding* (ref. 69), 23–24. See also M. Norton Wise, "On the Stories Told by Indicator Diagrams and Carnot Diagrams," *Endeavour* 42, no. 2 (2018) (this issue); M. Norton Wise, "On the Narrative Form of Simulations," *Studies in History and Philosophy of Science Part A* 62 (2017): 74–85, on 77–78; and John Beatty, "What Are Narratives Good For?," *Studies in History and Philosophy of Biological and Biomedical Sciences* 58 (2016): 33–40.

[71] Louis O. Mink, "History and Fiction as Modes of Comprehension," *New Literary History* 1, no. 3 (1970), 541–58, on 551, 554–55.

conceptualizations are fruitful: "[A]s a history, a narrative is a sequence of events, but, as a narrative, it is a single unit, the semantic equivalent of an atomic statement."[72]

These notions of followability and configurational understanding are useful in examining Darwin's narratives. Consider first his evolutionary narratives expressed in words. The *Origin* teems with narratives of the historical process by which some trait or behavior might have evolved—as when he explored how a light-sensitive membrane may have developed into the vertebrate eye, how the simple hives of bumblebees may have evolved into the elaborate geometry of honeybee combs, and how ants gathering pupae of other ants for food may have gradually given rise to a class of ant slaves.[73] In the *Descent of Man*, Darwin even offered a narrative of how human moral codes evolved out of the instincts of social animals.[74] Take the case of the evolution of castes of ant slaves as an example. Darwin noted that "it is possible" that pupae stolen for food might be unintentionally reared to adulthood. If that were to happen, such ants "would" then follow their instincts and do whatever work they could. "If their presence proved useful" to their captors, this habit of capturing pupae for food "might by natural selection be strengthened and rendered permanent." Thus, he

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[72] Paul A. Roth, "How Narratives Explain," *Social Research* 56, no. 2 (1989): 449–78, on 456. See also Wise, "On the Stories Told" (ref. 70) and "On the Narrative Form of Simulations" (ref. 70), 81–82.

[73] Darwin, *Origin* (ref. 8), 186–89, 224–35, 219–24.

[74] For an account of Darwin's narrative of the evolution of morality, see Greg Priest, "Charles Darwin's Theory of Moral Sentiments: What Darwin's Ethics Really Owes to Adam Smith," *Journal of the History of Ideas* 78, no. 4 (2017): 571–93, at 581–91.

concluded, "I can see no difficulty in natural selection" explaining the evolution of slave-making ants.[75]

As with our compressed narrative of Henry VIII, we understand Darwin's narrative by following it in causal sequence. The individual events might not have happened the way they did, and the end result would have been very different. Had the ants eaten all of the stolen pupae, the causal sequence would have been interrupted, and no slave caste would ever have been created. But it is narratively plausible that some pupae might have been overlooked, and so too with the subsequent contingencies. At the same time, any one of the events has meaning only in the context of the whole narrative configuration. We only care, for purposes of Darwin's narrative, that not every pupa was eaten because that fact is central to the ultimate outcome—the existence of a caste of slave ants.

Although Gallie's and Mink's conceptions are helpful in considering Darwin's linguistic narratives, there is a peculiarity of Darwin's narratives that are not captured in either of their formulations. Most historical narratives are narratives of events that are claimed to have happened more or less exactly in the way narrated. The Henry VIII narrative claims that the Pope really did refuse Henry's request for an annulment and that Henry really was willing to defy the Pope, even to the point of creating an alternative structure of religious authority. Darwin's narratives very rarely work this way. Rather, they are conjectural suggestions of how events might have transpired. Darwin began his narrative of the evolution of slave-making ants, for example, by stating that he would not "pretend to conjecture" how such a behavior evolved. In the next sentence, and continuing for about a page, he did exactly that. He did not claim that his narrative was a true account of a sequence of actual events. Rather, it was an account of a sequence of events that might plausibly

[75] Darwin, *Origin* (ref. 8), 223–24.

have occurred, and that, if they had occurred, would account for the evolution of a caste of slave ants. This feature of Darwin's evolutionary narratives will be relevant to my analysis of the narratives depicted in Darwin's diagrams, and I will return to it.

Having considered Darwin's linguistic narratives, let us return to how he depicted narratives in his diagrams. As we have seen, each of the diagrams we have examined depicted an observed pattern in nature, but each also depicted a conjectural narrative of an evolutionary history that might account for the observed pattern. Darwin's first tree diagram (figure 1) depicted the hypothesized branching of a lineage into forms that gradually adapted to aquatic, terrestrial and aerial habitats. His second tree diagram (figure 4) conjectured a history in which more "advanced" animals (birds) suffered more frequent extinctions than less advanced ones (fish). His third tree diagram (figure 6) represented lineages undergoing divergence of character and extinction. His page of embryology diagrams (figures 7 and 9) depicted a hypothesized history of the evolution of mammals. And the tree diagram from the *Origin* (figures 10 and 11) depicted a comprehensive narrative of evolutionary development, divergence, and extinction.

We follow the narratives embedded in Darwin's diagrams in the same way that we follow his linguistic narrative of the evolution of castes of slave ants. We trace each lineage from an initial ancestor at the bottom of the diagram to the living species at the top, going through a sequence of causally related stages. Some lineages end in extinction, and others proceed toward the present. From any particular moment in the evolution of a lineage as visually depicted in one of Darwin's diagrams, we cannot deduce or predict what will happen at the next moment. That lineage may go extinct, or it may split into two or more new lineages, or it may continue largely unchanged. There are, as Gallie led us to expect of historical narratives generally, "surprises," but each of those surprises is narratively plausible in its diagrammatic context. By following a group of lineages from the bottom to the top of the page in the published diagram from the *Origin* (figures 10 and 11), for example, we see how we can, step by step, plausibly proceed from a small group of closely related species in a single genus to larger groups of genera, with the species within each genus bearing close similarity to their near relatives but being quite distinct from relatives with which they share more distant common ancestors.

Mink's conception of configurational understanding of the narrative as a whole also helps us to understand Darwin's diagrams. We know the pattern that a particular diagram is designed to investigate before we trace through its causal sequence. Different classes of animals have terrestrial, aquatic and aerial forms, and fossil organisms tend to be intermediate between living groups. The diagram offers us a synoptic, bird's-eye view of both the pattern and the history that Darwin credited with giving rise to it. A synoptic, or configurational, understanding of a diagram thus emphasizes the intimate connection between the observed pattern and the conjectural history represented in the diagram.

As with his linguistic narratives, because the narratives depicted in Darwin's diagrams are not meant to represent actual sequences of historical events that are claimed to have occurred more or less as stated in the narrative, understanding the narratives embedded in Darwin's diagrams requires us to go beyond the analytical tools of following and configurational understanding. Recall that Darwin's linguistic narrative of the evolution of slave castes of ants was entirely conjectural. So, too, are many of the narratives depicted in Darwin's diagrams. Before drawing his diagram investigating patterns of bird and fish affinities (figure 4), Darwin asked himself "Is it thus[?]" that the pattern may be explained and introducing his conjectured explanation with the words "we may fancy." After his notebook diagram of divergence and extinction (figure 6), he wrote "Heaven know whether this agrees with Nature: *Cuidado*."

Even where the narratives depicted in Darwin's diagrams are not entirely conjectural, they are in other ways profoundly unlike more typical narratives like that of Henry VIII. In the first place, the narratives depicted in Darwin's diagrams are typically schematic, in that they do not represent particular events traced out in their singularity. Darwin's third notebook tree representing animals branching into groups (figure 6) is representative: it does not depict any particular animals (the groups are represented by capital letters), and it does not tell us what variations arose in which lineages, or why some lineages survived and others went extinct. And even where the diagrams are not conjectural, they are generally probabilistic. Even his most elaborated diagram—from the *Origin* (figures 10 and 11)—represents the kind of events that, in general, tend to happen, rather than particular events that are asserted to have actually happened. Darwin's extended exegesis of the published diagram teems with signposts to this effect: Darwin's diagram depicts a large genus because "on an average" large genera are more variable; the variations depicted are "supposed" to be minor and to occur at different times; the horizontal lines "may" represent the passage of 1,000 generations; organisms will "tend to vary," will "tend to" pass on those variations to their offspring, and those variations will "generally" be preserved in the lineage.[76]

Due to their conjectural, schematic and probabilistic character, the narratives depicted in Darwin's diagrams are thus dissimilar in important ways from more traditional narratives. They are not sequences of causally related events that Darwin claimed had actually happened. Rather, they are abstract representations of the structural characteristics of sequences of causally-related events that we should generally expect to happen. We can see this structural aspect of Darwin's diagrams by imaginatively deforming them. If we change the episodes in a narrative, we no longer have the same narrative. If Henry had accepted the Pope's ruling and remained married to Catherine, the English Reformation never would have happened, or would have happened in a very different way. Consider, in contrast, changing the narrative depicted in Darwin's published tree diagram (figure 10).

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[76] Darwin, *Origin* (ref. 8), 117–18.

Extend one line here and cut off another line there; add a superscripted letter here and delete a superscripted letter there. Stretch the whole diagram out horizontally and vertically by some arbitrary amount. The fundamental structure and import of the diagram would not change. In this respect, Darwin's diagrams represent the fundamental structure of evolutionary patterns and the histories conjectured to be responsible for them as having, in a loose sense, a fractal character.

Moreover, understanding the narratives Darwin depicted in his diagrams demands a fundamentally more active engagement by the reader than does understanding more typical linguistic narratives. In the first place, Darwin's diagrams are far less transparent. In a linguistic narrative, the connection between the events, even if it is conjectural, is readily legible. But when one first looks at Darwin's diagrams, they convey little or no meaning. The reader must not just read Darwin's accompanying textual apparatus; they must then use that apparatus to interpret the visual elements of the diagram. The reader must then dynamically engage with the diagram, traveling along it in the mind to achieve an understanding that is immanent in the diagram but that is only revealed in response to such an imaginative act.

Indeed, Darwin envisioned that users of his published diagram would engage with it in an even more dynamic fashion than this. He expected the users of his diagram to focus on different aspects of the diagram to understand different phenomena. One attends to the diagram in one way to understand why lineages are expected to diverge in character over time and to different aspects to understand why species tend to group into distinct genera. Darwin even expected his readers successively to reinterpret the diagram, giving visual elements new meanings each time, and then imaginatively to reengage with the diagram. Recall how he invited readers to dynamically rescale his diagram in order to understand how the groups-within-groups pattern would be repeated at different taxonomic levels. Recall also how he insisted that his readers should reinterpret the diagram as representing fossils in geological strata in order to understand why extinct organisms tend to be intermediate between living groups. Darwin expected the users of his diagrams to engage in acts of "manipulative imagination" on the diagram. Darwin's diagrams do not communicate knowledge directly to a passive recipient; rather, the user must interpret the diagram, modify it in the mind, and reinterpret it, in an active, iterative process.[77] Darwin is thus paradigmatic of the fundamentally dynamic quality of scientific diagramming. A stated in the introduction to this special issue: "Diagrams can serve as more than static images from which to extract information. Diagrams can be mentally manipulated to generate, explore, and test hypotheses. This manipulability is central to their ability to generate knowledge."[78]

Darwin's Trees as Tools of Reason

The introduction to this special issue invites us to consider the use of diagrams as "tools of reason" and diagramming as "an epistemic practice."[79] In light of our investigation of how Darwin's tree diagrams function, what can we say about their use as reasoning tools? How did diagramming constitute an epistemic practice for Darwin? The core of the answer to this question is that diagramming provided Darwin with a visual language in which he could represent both the patterns visible in the natural world and the sequence of historical events that he conjectured might have given rise to them. He could thus bring natural patterns and historical sequences into dialogue and

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[77] The term "manipulative imagination" was coined in the context of knot diagrams by Silvia De Toffoli and Valeria Giardino, "Forms and Roles of Diagrams in Knot Theory," *Erkenntnis* 79, no. 4 (2014): 829–42; see also Silvia De Toffoli, "'Chasing' the Diagram: The Use of Visualizations in Algebraic Reasoning," *Review of Symbolic Logic* 10, no. 1 (2017), 158–86.

[78] Priest, De Toffoli, and Findlen, "Introduction to the Special Issue" (ref. 60).

[79] Priest, De Toffoli, and Findlen, "Introduction to the Special Issue" (ref. 60).

so more easily investigate their causal relationships. Diagrams like those of Vigors, Barry, and Herschel are particularly well suited to representing regular and invariant patterns, which we customarily consider to be paradigmatic of scientific knowledge. Linguistic narratives are particularly well suited to representing an unfolding of a series of events and explaining how and why they happened, which we customarily consider to be paradigmatic of historical knowledge. Darwin was seeking to understand the potential contribution of individual historical trajectories to the making of patterns in the living world. He was seeking to do science in a way that was resolutely historical, or history in a way that was resolutely scientific. This is the context in which we can best understand Darwin's oft-quoted dictum that "when we regard every production of nature as one which has had a history … how far more interesting, I speak from experience, will the study of natural history become!" It was in service of this effort of combining science and history into a single integrated mode of inquiry that Darwin deployed a mode of diagramming that was as well suited to the depiction of narratives as it was to the depiction of patterns.

Although Darwin generally refused to defend particular historical narratives of the evolution of particular traits or lineages, he did believe that the general historical trajectories disclosed by his conjectural narratives were competent to explain the general features of natural patterns, and he believed that his tree diagrams gave him insight into the nature of the relationship between the narratives and the patterns. Recall the patterns that Darwin represented in his diagrams—the existence in many classes of aerial, aquatic and terrestrial forms, the organization of species into groups within groups, the similarities in embryological development across animal groups, and the intermediate character of extinct organisms. None of these patterns had obvious explanations, and there was no reason to imagine that they were connected. Yet Darwin proposed for each of these patterns a variant of the same conjectured history. A single model of evolutionary change could account for widely different patterns that have no other obvious connection. Perhaps he would not have considered himself justified in grounding truth claims in any one of these arguments standing alone, but the wide explanatory reach of the model of evolutionary change embedded in Darwin's diagrams was powerful evidence, in his view, of the truth of those ideas:

> The principle of natural selection may be ... tested,—and this seems to me the only fair and legitimate manner of considering the whole question,—by trying whether it explains several large and independent classes of facts; such as the geological succession of organic beings, their distribution in past and present times, and their mutual affinities and homologies. If the principle of natural selection does explain these and other large bodies of facts, it ought to be received.[80]

He put the point even more clearly in a letter to a colleague who was skeptical of his theory: "I believe in Nat. Selection, not because, I can prove in any single case that it has changed one species into another, but because it groups & explains well (as it seems to me) a host of facts in classification, embryology, morphology, rudimentary organs, geological succession & Distribution.—"[81] As we have seen, this is exactly the kind of explanatory reach that Darwin used his diagrams to develop and explore.

There is, it must be admitted, an apologetic quality to Darwin's defense of the explanatory role of his conjectural narratives. Darwin implied that it would have been better if the narratives were both more detailed and more certain, but that such precision is not possible. In this regard, Darwin uncharacteristically sold himself short. Darwin's diagrams do explanatory work that more detailed and more certain narratives of evolutionary change could not have done as well. They are, as

[80] Darwin, *The Variation of Animals and Plants under Domestication* (ref. 9), 9.

[81] Charles Darwin, "To Cuthbert Collingwood," March 14, 1861, Darwin Correspondence Project Database. http://www.darwinproject.ac.uk/entry-3088/ (letter no. 3088; accessed 9 May 2017)).

Jessica Carter puts it in her contribution to this special issue, sources of "epistemic gain."[82] I have already discussed two respects in which this is the case. First, by diagramming, Darwin could simultaneously and in a common idiom represent both observed patterns in nature and conjectural historical narratives that he considered might account for those patterns. This use of diagramming to depict narratives as well as patterns is central to diagramming's epistemic function for Darwin. Second, Darwin's diagrams invited and rewarded the use of a manipulative imagination that allowed new and different phenomena to be explored through the diagrams.

Finally, the narratives depicted in Darwin's diagrams are better suited to his explanatory purposes than precise narratives of actual evolutionary trajectories would have been. Darwin depicted narratives in his diagrams not to represent actual episodes of evolutionary change that he claimed had occurred, but to represent the general structural features we should commonly expect to see in cases of evolutionary change. For that purpose, Darwin's diagrams are more legible. By permitting, even encouraging, the representation of the abstract, the schematic, and the conjectural, Darwin's mode of diagramming allowed him better to achieve his goal of representing the general structural character of evolutionary change than would any number of records of the particular details of individual evolutionary trajectories. It is in part by effacing the particular that Darwin's diagrams are able to communicate the basic structure of evolutionary change. As we have seen, for Herschel, Barry and Vigors, as for so many of Darwin's other contemporaries, a curve of "large and graceful sinuosity"[83] embodying a simple regularity in nature was the very model of a sound induction. As Darwin's diagrammatic practices reveal, he was reaching after a different model of

[82] Jessica Carter, "Graph-Algebras: Faithful Representations and Mediating Objects in Mathematics," *Endeavour* 42, no. 2 (2018) (this issue).

[83] Herschel, "On the Investigation of the Orbits" (ref. 61), 179.

induction, and a different method of generating scientific knowledge. For Darwin, historical narrative was a fundamental element in the making of scientific knowledge, and diagramming was central to how Darwin employed narrative in his scientific practice.

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Captions for Images
Diagramming Evolution

Figure 1: First tree diagram from Charles Darwin’s 1837–1838 notebook. The first dot at the bottom of the larger figure depicts the common ancestor of a class (for example, Aves, or birds). The dotted line proceeding upward from the common ancestor represents its successive offspring, forming a single lineage. The lineage branches into three, with one lineage remaining adapted to life in the air, while one of the other lineages gradually adapts to a primarily terrestrial lifestyle and the other to a primarily aquatic lifestyle. The three solid lines represent the currently living bird lineages adapted to the three different habitats. CUL-DAR121.26. Darwin Papers. Cambridge University Library. Reproduced by kind permission of the Syndics of Cambridge University Library.

Figure 2: Charles Darwin’s diagrammatic section of Gambier Island in French Polynesia. The horizontal line depicts the level of the ocean, the lighter, vertical shading depicts the island, and the darker, horizontal shading depicts the encircling coral reef. From *The Structure and Distribution of Coral Reefs* (London: Smith Elder and Co., 1842), 48 (Figure 2). Image courtesy Stanford Libraries.

Figure 3: Nicholas Aylward Vigors’s circular diagram of the affinities of the class Aves (birds). Each of the five orders making up the class (clockwise from the top, Insessores, Rasores, etc.) is inscribed in a circle comprising five families. Although not depicted in this figure, Vigors drew another diagram showing those five families, each inscribed in a circle comprising five genera. We can further imagine the class Aves itself inscribed in a circle, making one of five classes making up the phylum Vertebrata. These circles within circles proceed up and down the taxonomic hierarchy. From “Observations on the Natural Affinities that Connect the Orders and Families of Birds, Read December 3, 1823,” *Transactions of the Linnean Society of London* 14, no. 3 (1825): 395–517, on 509. Courtesy of the Department of Special Collections, Stanford University Library.

Figure 4: Second tree diagram from Charles Darwin’s 1837–1838 notebook. The figure on the right depicts fish using solid lines because there are presently-living forms going from the very simplest to the most complex. The figure on the left depicts birds, with the dotted line representing earlier, less complex, forms that are no longer extant, and the solid lines representing more complex, currently extant, forms. CUL-DAR121.26. Darwin Papers. Cambridge University Library. Reproduced by kind permission of the Syndics of Cambridge University Library.

Figure 5: Three-dimensional projection of a detail of figure 3, showing how Darwin imagined his conjectural history of the evolution of birds could account for a circular pattern of affinities like that proposed by Vigors. By the author.

Figure 6: Third tree diagram from Charles Darwin’s 1837–1838 notebook. The number 1 represents the common ancestor of the group. The letters A, B, C, and D represent currently-living descendants of the common ancestor, exhibiting various differing

degrees of similarity one to another. The lines without cross-hatches show lineages that have gone extinct. CUL-DAR121.36. Darwin Papers. Cambridge University Library. Reproduced by kind permission of the Syndics of Cambridge University Library.

Figure 7: Page of Charles Darwin's notes from the 1850s, including five tree diagrams. The diagrams depict various aspects of embryological development and suggest possible evolutionary relationships among different lineages, including mammals and domesticated pigeons. CUL-DAR205.6.51. Darwin Papers. Cambridge University Library. Reproduced by kind permission of the Syndics of Cambridge University Library.

Figure 8: Martin Barry's diagram of the embryological development of fish, reptiles, birds and mammals. The embryos of all four groups are identical, and are all designated by the letter A, representing Barry's principle of unity of structure. Letters B, C, D, and E represent fish, reptiles, birds, and mammals at birth. Although they have differentiated to different degrees, the solid lines from A to each of B, C, D, and E are identical in curvature, reflecting Barry's principle of unity of plan. From "On the Unity of Structure in the Animal Kingdom," *The Edinburgh New Philosophical Journal* 22 (1837), 116-141, 345-364, on 134 (figure 11).

Figure 9: Rendering of Charles Darwin's diagram on middle left of figure 7. The diagram depicts the process of embryological development from an embryo that takes a similar form in different groups through the development and birth of individual organisms including (on the left) dogs, cats, and hyenas. The diagram simultaneously depicts narratives of conjectured evolutionary histories of the same groups. By the author.

Figure 10: Charles Darwin's published fold-out tree diagram. The interpretations of the diagram are spelled out in the text. From *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (London: John Murray, 1859), facing 117.

Figure 11: Detail of Charles Darwin's published fold-out tree diagram shown in figure 10. The interpretations of the diagram are spelled out in the text. From *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (London: John Murray, 1859), facing 117.