Lessons from Embryos: Haeckel's Embryo Drawings, Evolution, and Secondary Biology Textbooks

by

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ABSTRACT

In 1997, developmental biologist Michael Richardson compared his research team's embryo photographs to Ernst Haeckel's 1874 embryo drawings and called Haeckel's work "noncredible." *Science* soon published "Haeckel's Embryos: Fraud Rediscovered," and Richardson's comments further reinvigorated criticism of Haeckel by others with articles in *The American Biology Teacher*, "Haeckel's Embryos and Evolution: Setting the Record Straight" and the *New York Times,* "Biology Text Illustrations more Fiction than Fact." Meanwhile, others emphatically stated that the goal of comparative embryology was not to resurrect Haeckel's work.

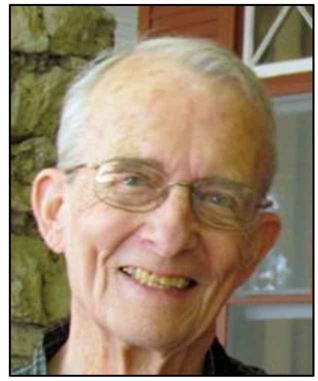
At the center of the controversy was Haeckel's no-longer-accepted idea of recapitulation. Haeckel believed that the development of an embryo revealed the adult stages of the organism's ancestors. Haeckel represented this idea with drawings of vertebrate embryos at similar developmental stages. This is Haeckel's embryo grid, the most common of all illustrations in biology textbooks. Yet, Haeckel's embryo grids are much more complex than any textbook explanation.

I examined 240 high school biology textbooks, from 1907 to 2010, for embryo grids. I coded and categorized the grids according to accompanying discussion of (a) embryonic similarities (b) recapitulation, (c) common ancestors, and (d) evolution. The textbooks show changing narratives. Embryo grids gained prominence in the 1940s, and the trend continued until criticisms of Haeckel reemerged in the late 1990s, resulting in (a) grids with fewer organisms and developmental stages or (b) no grid at all. Discussion about embryos and evolution dropped significantly.

Human embryos were noticeably absent from grids until the 1960s, when BSCS texts spurred human embryo use again. This trend continued until the early 2000s, when humans were removed from grids and discussion about human evolution dropped. In the late 1990s, photomicrographs replaced embryo drawings, but the resulting grids, with inconsistent developmental stages and embryo alignments, simply added confusion.

Currently, the narrative centers on descriptive comparisons with little inference or predictive value. In trying to use embryo grids that will appease evolutionists and non-evolutionists, the grids' narratives are now quite different from Haeckel's original intent. We see a marked evolution from the grids' earliest to current use, with obvious questions about what the future will bring.

DEDICATION



My sincerest appreciation goes to my friend, mentor, and former advisor at the University of Iowa, Dr. Darrell G. Phillips who passed away in September 2013. At an educational conference at Cornell University in 1964, Jean Piaget said, “A ready-made truth is only a half-truth.” Darrell guided me to recognize the true meaning of Piaget’s quote—that the discovery of knowledge is not always clean and orderly. Sometimes true discoveries are messy, loud, and roundabout. I am forever in debt to Darrell for teaching me many things of which schools have, as yet, no inkling.

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Lessons from Embryos: Haeckel's Drawings, Evolution, and Secondary Biology Textbooks

Ernst Heinrich Philipp August Haeckel (1834–1919) was a well-known German comparative embryologist, scientific illustrator, and public-speaking figure during the late nineteenth and early twentieth centuries. Haeckel is one of a handful of scientists who helped move the world of science, at that time reserved for specialists, to the world of the non-specialist in the late 1800s (Breidbach, 2006b; Burrow, 2000). More specifically, ideas about evolution might have stayed long sequestered in the scientific community if it were not for the actions of scientists like Haeckel and Thomas Henry Huxley (1825–1895) who engaged the public with new scientific ideas (Schwartz, 1999).

Haeckel generated a broad appeal across all social classes, due in part to his numerous books and vivid natural images from foreign lands (Allen, 1975, p. 6). Haeckel was also his own best publicist, stirring up interest in evolution, embryology, and comparative anatomy with his speaking tours. Haeckel biographer Robert J. Richards claims that Haeckel, even with stiff competition from the likes of Huxley and biologist/ anthropologist Herbert Spencer (1820–1903), became the foremost champion of Darwinism not only in his home country of Germany, but throughout the world. Richards argues that during the late 1800s and early 1900s, more people learned of evolution through Haeckel than any through other person (Richards, 2008, p. 2).

Embryo comparison charts, or what became known as Haeckel's embryo drawings (see Figure 1) often accompanied Haeckel's books and speeches. The embryos appeared in a grid-like fashion and each embryo in the grid held two properties—the type of organisms that it was and the developmental stage that it was in. The embryo comparison grid allowed Haeckel to structure "real data" in a way that was orderly and ordered. I will refer to Haeckel’s embryo drawings as embryo grids due to their unique arrangement of embryos in columns and rows. In Haeckel’s embryo grids, the different organisms line up next to each other in columns while the developmental stages of the organisms appear in rows. Each row has different organisms in it but they are all at the same stage in embryonic development.

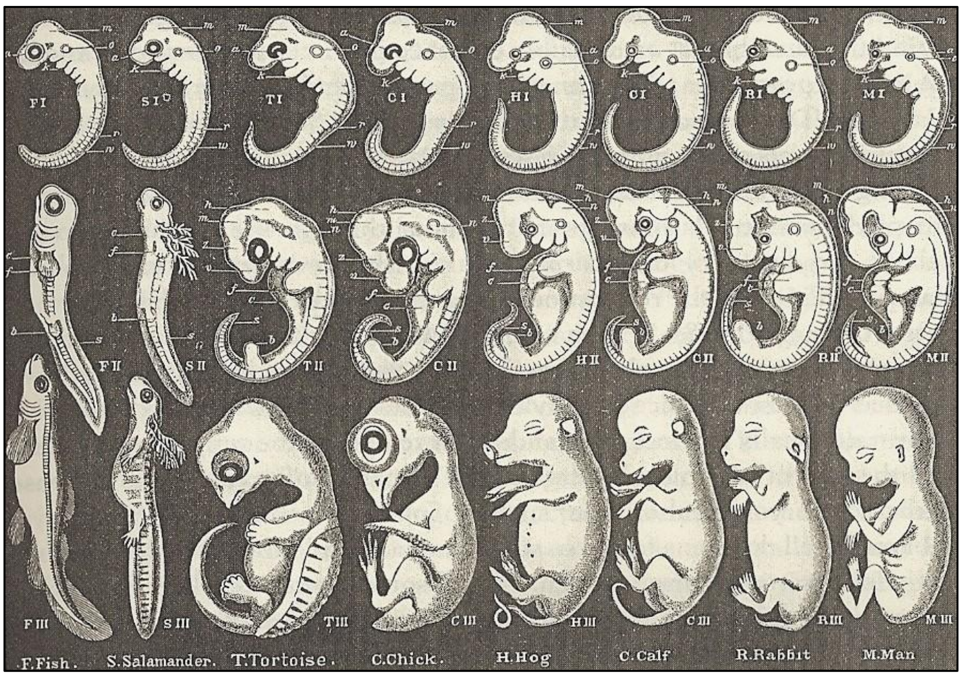


Figure 1. Haeckel’s embryos from *Anthropogenie* (1874). This embryo representation soon appeared in college and high school texts in the late 1800s and early 1900s. From *Anthropogenie* (p. 256). By E. Haeckel, 1874, Leipzig: Engelmann.

Haeckel believed that his comparison of different vertebrate embryos was paramount for the understanding of evolution. By integrating two processes—development of an embryo (ontogeny) and the embryo’s evolution from its ancestors (phylogeny)—Haeckel formulated the Biogenetic Law in the 1860s. That law stated that the evolution of an organism was traceable by following the organism’s embryonic development. For example, human embryos have pharyngeal pouches, or “gill slits,” just as fish do. As the human embryo develops, the gill slits are lost and the embryo develops a tail and four appendages. The human embryo now takes on the appearance of an adult reptile. The tail is absorbed and the embryo now looks like a primate. These anatomical similarities helped Haeckel justify his claims that embryos recapitulated their evolutionary history during development.

By the end of the nineteenth century, as Haeckel's embryo drawings became responsible for making similarities of embryos common knowledge (Hopwood, 2006, p. 286), several leading embryologists accused Haeckel of doctoring his drawings to make embryos fit his law. Haeckel rejected the criticism, declaring that his intent was not to mislead, but to accentuate the similarities between embryos and make them more obvious for a broad audience. Haeckel's attempts at defending his work failed and by the early 1900s, his Biogenetic Law fell out of favor with most experimental embryologists who found it (a) too full of exceptions and (b) too weak to drive new developmental research. Even though Haeckel's ideas about embryos and ancestral histories fell by the scientific wayside many years ago, his detailed and authoritative embryo drawings remain conspicuous in many of today's biology textbooks, presumably to help students understand something about evolution and man.

It seems as if Ernst Haeckel and his embryo drawings are a bit like that big, bouncy, weighted clown that no matter how hard you try to knock down, always bounces right back up. That appears to be a suitable analogy for how Haeckel's work remains intertwined with biology textbooks. In my examination of biology textbooks, there is no other diagram that has proven so prevalent and resilient. In fact, most people who have taken a high school biology class, whether in the class of 1911 or the class of 2010, have likely seen Haeckel's embryo drawings in biology textbooks. This is odd when one considers how Haeckel has long been the subject of special condemnation for his idea of the Biogenetic Law and recapitulation.

The fact that Haeckel's embryos have remained in biology textbooks is well-documented (Bowler, 2007; Gould, 1977; Richards, 2008). What now requires examination is the context in which authors place Haeckel's drawings. Do the drawings explain common ancestry? Recapitulation? Social Darwinism? Are they intended to show that humans are just like any other animal, or are humans somehow different? What are Haeckel's embryos really trying to explain to students? Critics of evolution are quick to spot a Haeckel-like embryo illustration and proclaim that the textbook is "still using Haeckel's fraudulent drawings to provide evidence for evolution" (Wells, 1999; 2000) Is it really this simple or is there more to the story than just the embryo picture? The purpose of this research is to dig deep into the visual culture of textbooks to examine not only Haeckel's embryos, but also the changing narratives that accompany the embryo illustration.

While my preliminary examination of texts indicates that Haeckel's embryo grids are mainly found in chapters about evolution, a review of studies on evolution and secondary education reveals no discussion of Haeckel's embryos. Gerald Skoog, a Texas Tech science education professor, is highly recognized for his work on evolution and science textbooks. In 1979, Skoog published a chronological and quantitative study of evolution in 93 high school biology texts (published 1900 to 1977) that continues to serves as a benchmark in textbook and evolution education. Skoog's study, however, was limited in scope. Skoog used a word count of paragraphs to establish the extent to which text authors wrote about evolution. He concluded that in the 1970s, a whole host of individuals involved with textbook publication, including publishers, authors, educators, textbook review boards, and politicians, were sensitive to the efforts of antievolutionists to suppress, if not to totally remove, evolution from textbooks (Skoog, 1979, p. 636). Skoog's description of textbooks written before 1970 offered no analysis of why certain decades showed increases or decreases in evolution topics.

Dorothy Rosenthal (1985), a now-retired science educator at Long Beach State University, expanded upon Skoog's work in the 1980s by measuring the percentage of a text devoted to evolution rather than using a word count. This methodology removed increasing textbook length as a confounding variable. Rosenthal determined that biology textbooks published in 1968 and 1969 represent the zenith for evolution discussion, averaging 13.7 per cent of the total texts. By the late 1970s and early 1980s, the attention to evolution declined to 9.9 per cent.

David Moody (1996) acknowledged the importance of Rosenthal's study, but noted that what might be more important is the extent to which evolution is presented as a central, organizing principle to biology. His methodology to determine how evolution serves as a unifying theme throughout a text is complicated, and involves early versions of concept mapping technology. Moody determined the frequency of the term "evolution" by counting chapters in which the term occurred. Also important was where the term first appeared (what Moody refers to as sequence)—was evolution discussed in the first chapter or further back in the text? The third factor that Moody examined was proximity value. Here, he noted how closely evolution tied in with several other keys words. Proximity values were higher if evolution and a proximity term like "natural selection" occurred close together, such as in the same paragraph.

Because of the time required to code just one text, Moody's sample size was small, with only eight texts. Included in his sample were Raymond Oram's 1986 and 1994 editions of *Biology: Living Systems*, James Otto and Albert Towle's 1985 and Towle's 1993 versions of *Modern Biology*, 1985 and 1990 editions of *BSCS Blue Version* and 1982 and 1992 editions of *BSCS Green Version*. Moody selected *Biology: Living Systems* and *Modern Biology* due to their wide classroom use. The Biological Sciences Curriculum Study (BSCS) texts were chosen due to the publishers' commitment to an expanded coverage of evolution (Moody, 1996, p. 402).

Moody found that in the 1986 edition of *Biology: Living Systems*, discussion of evolution occurred about midway through the book and the concept appeared in only two chapters. The 1994 edition of *Biology: Living Systems* was revised to the extent that the text's use of evolution exhibited high proximity to other key evolution terms (i.e., evolution was explained in more depth and breadth) instead of introducing the term only once or twice in several chapters. The lead author made an effort to weave the important concept into other areas rather than just in a chapter titled, "Evolution."

Results for *Modern Biology*, the popular text originally written by Truman J. Moon, mirrored that of *Biology: Living Systems.* The 1985 edition of *Modern Biology* saw a relatively minor role for the concept of evolution, with the term "natural selection" used in only one chapter. The 1993 version revealed an increase in the use of the term "evolution" across several chapters. Natural selection now appeared in fourteen chapters.

The BSCS blue and green texts published in the 1980s placed evolution prominently in the beginning of the texts but Moody showed that after the first few chapters, the emphasis on evolution tailed off. The 1990 BSCS *Blue Version* though, revealed significant changes. The term “evolution” expanded into eighteen chapters, rather than six chapters in the 1985 edition. Evolution showed greater proximity to other terms such as natural selection, mutation, gene, and so forth. The 1982 BSCS *Green Version* exhibited a great deal of attention to the concept, “population,” but the 1992 edition, following the pattern already seen in the other texts, placed more emphasis on the terms “evolution” and “natural selection.”

Moody’s examination of 1980s texts supports other research findings that the 1980s was a period in which previous gains about placing human evolution and human reproduction in textbooks were lost. The 1990s, however, saw a reversal of this decline and Moody speculates that education reform movements in the late 1980s drove publishers to dust off human evolution and reproduction and place them back into textbooks. In my examination of embryo grids, the number of human embryos in the grid and discussion of human evolution, increased during the 1980s and the 1990s.

Skoog’s (2005) recent research involves the degree of emphasis on human evolution in more than 100 texts published throughout the twentieth century. Like Moody, Skoog identifies the 1960s and the BSCS movement as pivotal in textbook discussion of human evolution. Prior to the 1960s biology texts provided little discussion about human evolution. I would add that 1960s texts are key in the return of human embryos to Haeckel’s embryo grids and human evolution was much discussed with these grids.

Skoog also found that in the early 1980s, textbooks dropped discussion of human evolution entirely or whittled the discussion down to a few paragraphs. This change however, did not last long. In the 1990s, textbooks again gave more coverage to human evolution. Skoog believes the return of human evolution is due to the inclusion of human evolution in many state biology standards.

Ronald Ladouceur's dissertation and subsequent publication of his work in *The History of Biology* (2008) reexamines twentieth century biology texts, including *Exploring Biology* by Ella Thea Smith. Ladouceur defends some of the texts that Skoog criticized for a lack of evolution emphasis, including *Exploring Biology* and *Modern Biology*. He questions Skoog's defense of BSCS for providing the impetus for other publishers to add more coverage of evolution in their texts, by pointing out that Smith, the first author to discuss the modern synthesis in a high school biology text in 1959, incorporated evolution with the modern synthesis and genetics before the BSCS series entered the market in 1963. In Ladouceur's view, it is erroneous to commend BSCS texts as exceptional and leave *Exploring Biology* unacknowledged and forgotten. I agree that Smith appeared ahead of her time with the incorporation of the modern synthesis in *Exploring Biology*, but if you compare *Exploring Biology* to BSCS in terms of embryo grids and evolution, BSCS texts were indeed exceptional. BSCS texts afforded more discussion to embryology and evolution compared to any text published in the early 1960s, including *Exploring Biology*.

A recent key critic of Haeckel's embryo drawings is Jonathan Wells of the Discovery Institute, based in Seattle, Washington. In the late 1990s, Wells wrote a critique of Haeckel's illustrations in the *American Biology Teacher*, followed by his examination of ten high school biology textbooks for their use of Haeckel's comparative embryo drawings. This work was not published in a peer-reviewed journal but Wells' text rankings can easily be found on the internet. Almost all of Wells' texts received an "F" grade because with his categorization method, any use of Haeckel's drawings and the mentioning of the term "gill slits" were deemed misleading, and therefore deserving of an "F."

My study is a point of departure from evolution education studies in that it will focus on a comprehensive study of Haeckel's drawings in American biology textbooks. The purpose of my study involves quantitatively and qualitatively analyzing a large selection of Haeckel's embryo grids in public high school biology texts, guided by several main questions:

- When did Haeckel's embryos first appear in secondary biology texts, and are there periods when Haeckel's embryos drop out of textbooks? If so, how tangled up have Haeckel's embryos become as a consequence of socio-political and pedagogical influences on the teaching of evolution in high school biology textbooks?
- What organisms (e.g., monkeys) appear in Haeckel's grid that were not part of his original grid (i.e., fish, salamander, tortoise, chick, pig, calf, rabbit, and human) and when do certain organisms appear and disappear?
- When and how are human embryos depicted in Haeckel's embryo pictures? When human embryos do occur, is there any mention of human evolution?
- Are there different roles that textbook authors give Haeckel's drawings in the support of evolution? For example, do authors use the embryos to show support for recapitulation or do grids provide a visual of how embryos look like each other, implying a possible common ancestry?
- The nature of science became an important component of biology education in the late twentieth century. Is there any point in biology textbook history that Haeckel's embryos serve as an example of the ever-changing nature of science?
- Recently, opponents of evolution have seized Haeckel's so-called fraudulent embryo drawings to "provide evidence" that all of evolution must also be fraudulent. In textbooks that continue to use Haeckel's embryos, has this accusation been recognized and addressed?

- Given the various ways that Haeckel's diagrams appear in texts, how can embryo grids help show that science is not static, or that Haeckel's work remains relevant to evolution and embryology?

Like its originator, Haeckel's embryo drawings draw praise from some and vilification from others. This contentiousness has a long history, not only in terms of infighting by biologists, but also in the world of textbook publishing. Interpreting patterns of Haeckel's embryo drawings in textbooks requires an historical examination on several fronts. This dissertation consists, in part, of a background discussion, divided into three main sections. I first examine the growth of comparative embryology as evidence for evolution, Haeckel's contributions to the field of comparative embryology, including the Biogenetic Law and recapitulation, and how embryologists attacked and abandoned Haeckel's ideas the late 1800s.

Second, I trace Haeckel's influence to the U.S. as authors incorporated his embryo drawings into their biology texts. Here, I examine biology textbook writing in terms of key authors and publishers. In addition to examining a wide scope of authors and texts, I will also examine four major biology textbook writers in detail: George W. Hunter, Truman J. Moon, Ella Thea Smith, and BSCS' multiple authors.

Third, the background discussion will focus on the presence or absence of evolution in texts during most of the twentieth century. Research identifies several events that have influenced how evolution is presented to students, including the Scopes trial of 1925, changes in curriculum goals in the 1960s, and repeated influences by creationists, and more recently intelligent design followers to eliminate evolution from classroom teaching. For texts that abandoned discussion of evolution, it would seem likely that Haeckel's embryo grids also disappeared from these texts. However, what about the large number of texts that not only continued discussing evolution, but also continued to place embryo drawings in what has now become a contestable space? Have textbook authors and publishers used Haeckel's drawings to serve as evidence for recapitulation, much as Haeckel intended for them to do? If yes, this is doubly strange since the idea of recapitulation, and the embryo images themselves, have long been discredited. If no, then what are these embryos really trying to explain to students? This overarching question is at the center of my study involving Haeckel and embryos.

BACKGROUND DISCUSSION

Section I: The Road to Haeckel's Embryos

Haeckel's embryo drawings and I go back a long time—certainly longer than when I started this investigation. I know firsthand that textbook diagrams and pictures can maintain a type of permanence in one's memory. I realized this while doing an earlier study on textbooks and development when I happened upon a 1968 edition of BSCS's *Green Version* biology textbook, the same text that my high school biology class used (see Figure 2). Turning the page to a large Haeckel embryo drawing, I recalled a class discussion about human evolution, gill slits, tails, and monkeys.

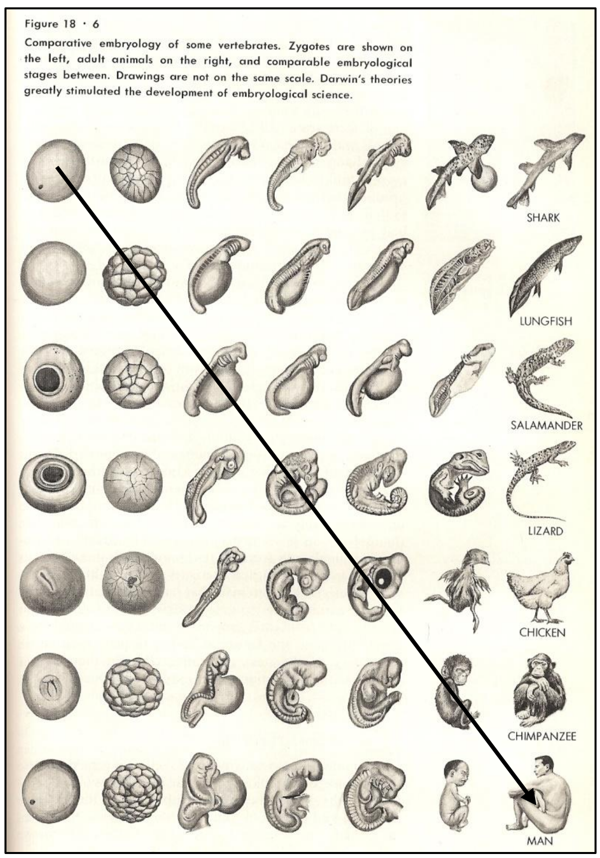


Figure 2. Haeckel's embryos in the *BSCS Green Version*. Following Haeckel's idea of recapitulation, a diagonal line (drawn by author and not part of the original drawing) from the egg in the top left corner to the man in the bottom right corner, shows the recapitulated path that Haeckel believed human embryos went through to reach adult status. From *An Ecological Approach* (p. 670). By BSCS, 1968, Chicago: Rand-McNally.

Little did I know that Haeckel's embryos would carry with me over the years and serve as a basis for this study. Unlike with many biology textbook illustrations, which change from generation to generation, I can say with a fair degree of certainty that my grandmother studied Haeckel's embryos, my mother and father studied Haeckel's embryos, I studied Haeckel's embryos, and my younger brother studied Haeckel's embryos. I am intrigued about how and why these embryos have remained so persistent in biology education when most other teaching illustrations have fallen by the wayside. I am also curious to see if, while the drawings have remained somewhat similar over the years, the discussion about the embryo grids has changed over time.

In order to examine Haeckel's embryo drawings, I will provide background information on the historical nature of comparative embryology, Ernst Haeckel and his Biogenetic Law, and Haeckel's long list of critics. Much has been published about biology in the late 1800s (see William Coleman's *Biology in the Nineteenth Century,* Ernst Mayr's *The Growth of Biological Thought*, Lynn K. Nyhart's *Biology Takes Form,* and E. S. Russell's *Form and Function*). The purpose of my background discussion is not to rehash in its entirety what has already been written, but to provide the reader with the context in which Haeckel worked and the controversies that arose with his Biogenetic Law and the idea of recapitulation.

Early comparative embryology.

Throughout much of the early and mid-1800s, morphology dominated the field of embryology. The ability to study tiny embryos in detail was due to several factors, including better and more powerful microscopes, improved staining techniques, and the acceptance of embryology by German universities as a serious field of study within the disciplines of anatomy and zoology (Gilbert, 2014; Nyhart, 1995). With university funding, more students attended university and studied under noted embryologists such as Christian Pander (1794–1865), Heinrich Rathke (1793–1860), and Karl Ernst von Baer (1792–1876). Among these three embryologists, Pander identified the chick blastoderm in 1817, Rathke described gill slits in vertebrate embryos in 1825, and von Baer discovered that mammals develop from fertilized eggs in 1828. Building on the work of Pander, von Baer later observed that embryonic germs layers give rise to the same organs in different organisms (the germ layer concept).

The work of these three men along with others, marks the birth of comparative embryology (Russell, 1916). The scene was now set for a substantial period of microscopic examination of embryos and their structural features. The arrival of Darwin's theory of evolution in the late 1850s, though, meant a new focus. After the publication of Darwin's *On the Origin of the Species,* embryonic structures were targeted as homologies to help trace ancestral lineage. This was the type of scientific environment that Darwin and Haeckel immersed themselves in—a scientific world of observing, drawing, and comparing. The world of experimental embryology, in which embryos were diced, sliced, and subjected to different experimental conditions was still a ways off.

Darwin.

Ernst Haeckel's work took on a new direction with the 1859 publication of Charles Darwin's *On the Origin of Species*. As Europe entered a great age of reading, the time was right for the popularization of Darwin's work and his ideas about evolution. Increased literacy rates resulted in the mass production of books and magazines, many of which touted science as a prestigious form of study (Kelly, 1981). *On the Origin of*

Species also arrived as the European industrial revolution took hold and with it, science and industry now became a large part of many people's lives. Promoting Darwinism in this era was easier than before 1860 when the impact of science on everyday life was small (p. 144).

Darwin used von Baer's data on embryonic stages and Johannes Müller's summary of von Baer's laws (1842) to support his own idea that embryo similarities provided strong evidence for the concept of descent with modification (Gilbert, 2003; Horder, 2010;). That is, embryos were similar in some respects because all organisms had common lineages. Embryonic differences were due to adaptations explained by natural selection. Darwin was, however, tentative about the idea of recapitulation where embryos supposedly showed evidence of ancestry by passing through ancestral forms during their development (Hopwood, 2009; Richards, 2008).

In *Origin,* Darwin challenged readers to examine how slight changes to embryos over a long time span could produce different forms of life. At the time, this was indeed challenging because the mechanism for inheritance of traits was yet undiscovered. Some *Origin* readers, like Ilya Metchnikoff, Ernst Haeckel, and Carl Gegenbaur, were able to take up Darwin's challenge because they were already working at the forefront of descriptive embryology. Darwin's theory now opened the door for evolutionary morphologists and embryos to reconstruct ancestral histories.

Haeckel's early work.

Robert J. Richards documents the life of Ernst Haeckel, born in 1834, in his book, *The Tragic Sense of Life: Ernst Haeckel and the Struggle over Evolutionary Thought* (2008). Growing up, Haeckel was influenced by several influential thinkers including

Johann Wolfgang von Goethe (1749–1832), Alexander von Humboldt (1769–1859), and Charles Darwin (1809–1882). Haeckel also read botanist Matthias Schleiden's *Der Pflanze und ihr Leben* (1848), which inspired him to study botany at the University of Jena. His parent's plans for Haeckel, however, did not include becoming a botanist. With their insistence, Haeckel studied medicine at the University of Wurzburg where he worked with the renowned pathologist Rudolph Virchow (1821–1902). He continued his studies at the University of Berlin, working with Johannes Müller who helped steer Haeckel's interests towards marine science. Haeckel graduated from Berlin in 1857 with a dissertation written on river crabs. To appease his parents, Haeckel passed the state medical examinations in 1858, but after one year of medical practice, he changed direction and pursued research in marine biology.

The sea drew Haeckel to its shores and deep oceans. As an accomplished drawer, Haeckel published several self-illustrated monographs on the then, little-known marine organisms. Haeckel actually discovered many marine life forms, especially radiolarians, on his adventurous field study trips. When Darwin published *Origin*, Haeckel was already established as a professor at Jena. Between the work of Haeckel and fellow biologist Carl Gegenbaur (1826–1903), Jena became a powerhouse in the study of comparative anatomy and embryology.

Haeckel came away from reading Darwin's *Origin* with the certainty that he could help spread the serious ideas in Darwin's book to German scientists and interested laypeople. One of Haeckel's earliest public speeches concerning Darwinian evolution was heard at the 1864 annual conference of the Association of German Scientists and Physicians at Stettin, Germany. Darwin's message was founded, Haeckel stated, on the idea of progress, both the progress of human evolution and the progress of nature. Other scientists also realized the great importance of Darwin's work and followed Haeckel's lecture method of popularization. As a result, few theories before or after Darwin reached the public so fast (Kelly, 1981, p. 23).

Haeckel's first major publication was an 1866 two-volume book titled *Generelle Morphologie der Organismen* (*General Morphology of Organisms*), dedicated to preeminent leaders in evolutionary biology, Johann Goethe, Jean-Baptiste Lamarck, and Darwin. Over 1,200 pages long, Haeckel seemed to write about anything and everything, including his views on morphology, the genealogy of mankind, embryology, and the denial of a deity (Brown, 2002; Heie, 2008). Haeckel's famous evolutionary trees initially appeared in *Generelle Morphologie* and made Haeckel one of the first biologists to use comparative anatomy to draw phylogenetic trees for the entire animal kingdom. Haeckel's "trees of life" helped usher in the intertwining of comparative embryology to evolutionary morphology. (Richardson & Jeffery, 2002, p. 247).

Robert Richards makes clear that Haeckel got his hands dirty experimenting with embryos—he did not just sit at his desk, copying other people's drawings of embryos. Early in his career, Haeckel dissected many of the marine organisms that he gathered during his collection trips. He also studied the embryology of ten different genera of siphonophore (e.g., jellyfish) eggs (Richards, 2013, p. 238) and performed several early embryology experiments by manipulating the light, salinity and temperature of marine environments in which he placed embryos. Haeckel also divided early embryos in half to see if separated cells would continue to develop independently. Reminiscent of the findings of Hans Driesch who would perform similar experiments twenty years later than

Haeckel, some of the cells stopped growing, but many continued developing although they were usually smaller than normal embryos (Richards, 2008). Haeckel's experiments with embryos showed that during early development, embryonic cells are totipotent—that is, they have the capacity to develop into all parts of an organism.

Haeckel's biogenetic law and recapitulation.

In the mid-nineteenth century, scientists held the underlying agreement that science was best explained with the aid of scientific laws. Darwin devoted an entire chapter of *Origin* to the "laws of variation" and he wrote that natural selection was simply a law of nature (Richards, 2008, p. 120). In Chapter 13 of *Origin*, Darwin identified comparative embryology and the study of vestigial structures as important evidences for evolution. Because of Darwin's discussion of embryology, embryos were soon to take on a new purpose, with Ernst Haeckel in particular, leading the charge. Haeckel would soon focus much of the rest of his career on expanding Darwin's examinations and thoughts about embryos. As historian Lynn Nyhart (1995) concludes in her study of morphology and German universities during the 1800s, Haeckel's "main concern was not to expound Darwin's own theory, but to retell Darwin's theory in terms that were peculiarly Haeckelian" (p. 479).

Much like most evolutionary theorists in the late nineteenth century, Haeckel embraced Lamarckian evolution, where organisms transmitted characteristics acquired during their life to their offspring. Haeckel looked in particular to embryos for empirical answers, and eventually evolutionary laws. He knew that fossils could only take you so far when comparing ancestral histories; embryological data on the other hand, was abundant and Haeckel grabbed the opportunity to put embryos to work. Embryos quickly became the centerpiece for Haeckel's Biogenetic Law, traced back to 1866 with the publication of Haeckel's *Generelle Morphologie.* There is, however, no actual use of the words "biogenetic law" in *Generelle Morphologie.* Haeckel discussed ontogeny, phylogeny, and patterns of recapitulation, but his use of the term and description of his Biogenetic Law (das biogenetische Grundgesetz) did not appear until 1872 in a two-volume book that Haeckel wrote about sponges (Churchill, 2007, p. 43).

The Biogenetic Law was based on the idea that the successive (and many believed, progressive) unfolding of new species followed the same laws or rules that governed embryonic development. Just as young embryos developed into predictable later-stage embryos, so too did primitive species develop into more advanced species. Haeckel made clear that his law did not include teleology or divine intervention. To Haeckel, the first organisms on Earth arose through some type of physical and chemical process. This process behaved the same as in the nonliving world and therefore to Haeckel, the study of life and evolution was a mechanical science (Gliboff, 2008). Although Haeckel believed that physical and chemical laws tied evolution and development together, he left little writing behind that makes clear what those physical or chemical laws were (Raff, 1983, p. 13).

Haeckel claimed that his Biogenetic Law operated by three rules or principles. The first rule addressed the concept of correspondence. Here, each embryonic stage corresponded to an adult stage of an ancestral life form. In a human for instance, the zygote corresponded to the adult stage of a protozoan. The zygote developed into a blastula, which corresponded to a colonial protist, and the period in which humans presented pharyngeal arches corresponded to the gill slits of the adult fish. The second rule was terminal addition, where new species resulted from the addition of another stage of development. Haeckel believed that all young embryos looked alike because of some type of physical constraint. This constraint disappeared during late development, resulting in a linear rather than a branched phylogeny, a major departure from Darwinian evolution. The Biogenetic Law's third rule dealt with the idea of truncation. Haeckel realized that by adding more and more structures at the end of development, gestation periods would be enormously long. In order for gestation length to remain constant, each preceding stage in development could be shortened or accelerated. Truncation thus helped explain why certain phylogenic stages in animals were not the same, or in some cases unobservable (Gould, 2002, p. 353).

Haeckel's Biogenetic Law operated on a species level by the process of recapitulation. To Haeckel, recapitulation was a phenomenon or event whereby a particular organism passed through the adult stages of lower organisms during embryogenesis. New structures or organs were added sequentially and terminally until an organism's final birth form was achieved. Haeckel used his famous lithographic plates, comparing embryos of different phyla, to illustrate his idea of recapitulation. His first comparative embryo drawings appeared in *Natürliche Schöpfungsgeschichte* (*The Natural History of Creation*) in 1868 (see Figure 3).

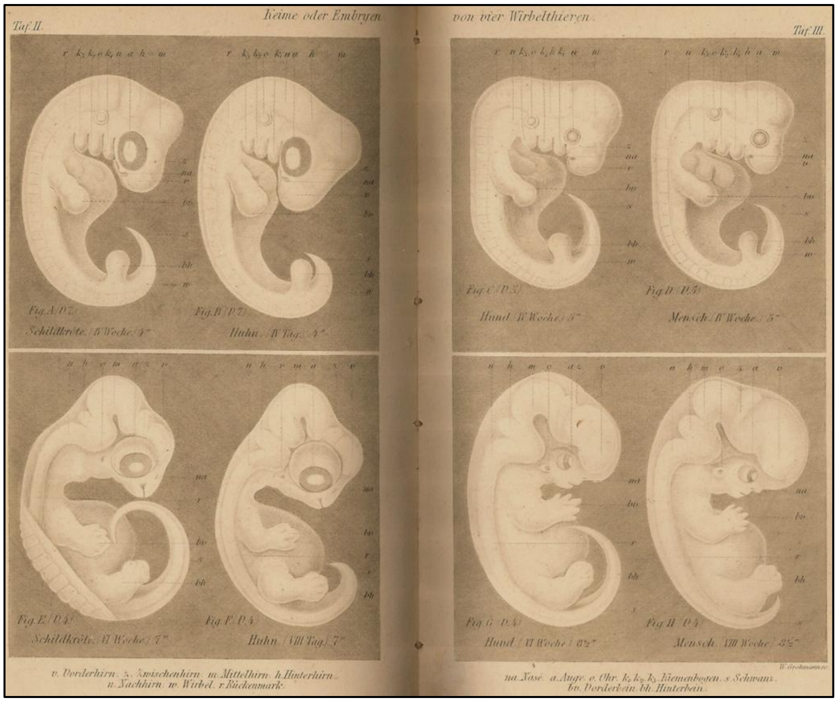


Figure 3. Early Haeckel embryos. Haeckel compares four-week-old turtle and dog embryos (top left), five-week-old dog and human embryos (top right), seven-week-old turtle and dog embryos (bottom left), and eight-and-a-half-week-old dog and human embryos (bottom right). From *Natürliche Schöpfungsgeschichte* (plate II). By E. Haeckel, 1868, Berlin: Reimer.

Haeckel's work and his enthusiasm for his work made the Biogenetic Law popular and successful during the late 1800s and early 1900s. It also resulted in an enormous stimulation of public interest in comparative embryology (Mayr, 1982, p. 117). Figure 4 shows how Haeckel's auditorium stage often looked to his listeners. Haeckel's public lectures incorporated his embryo illustrations to provide narrative evidence for recapitulation and evolution. These same embryo diagrams also made their way to natural history museums around the world. The enlarged visuals would certainly have played a part in Haeckel's belief that evolution could be discussed with everyone in an intellectual manner. Between Haeckel's lectures, speeches, and books, historian Lynn Nyhart believes that after 1866, it became impossible for German zoologists to respond to Darwinism without responding to Haeckel (Nyhart, 1995, p. 137).

Figure 4. Elaborate display that accompanied Ernst Haeckel's public speaking tours. Note embryo grids in the mid-left of the picture. From *The Art and Science of Ernst Haeckel* by O. Breidbach, 2006a, New York: Prestel.

With Darwin's theory came a renewed interest in tracing what all organisms had in common, namely the first multicellular organism from which all other animals evolved. In his 1872 monograph on calcareous sponges, Haeckel used his experience studying embryos to announce that the key to identifying the first common ancestor, what he called the "Urform," was to look at the gastrula, an early stage of embryonic development in animals represented by a hollow sphere of double-layered cells. Haeckel was convinced that the first multicellular organism ancestor, which he called a "gastrea," was in fact, a gastrula of some sort. (Bowler, 1996, pp. 85–86).

Early recapitulation ideas and arguments.

Haeckel was not the first to toy with the idea that embryos recapitulated and revealed their evolutionary history through embryonic development. Science historian Jane

Oppenheimer (1959) points out that between 1797 and 1866 (the year that Haeckel published *Generelle Morphologie*), at least 72 different biologists had already put forth their own conceptualizations about recapitulation. Stephen J. Gould's *Ontogeny and Phylogeny*, John Needham's *A History of Embryology*, and E. S. Russell's *Form and Function* offer rich descriptions of recapitulation and I direct you to these publications for recapitulation's long and complex history. I will provide a condensed chronology of the unfolding of recapitulation that Haeckel no doubt examined before establishing his own ideas about embryos and their ancestral histories.

According to John Needham (1959), Aristotle (384 BCE–322 BCE) foreshadowed the idea of recapitulation by explaining that embryos begin to differ at the point when souls enter the embryo. Until this soul-inspired differentiation occurred, however, all embryos had the same general appearance and began life similarly to plant development, taking up nourishment from the placenta, rather than soil.

The idea of recapitulation as we know it today took a firmer hold with the work of German zoologist Carl Friedrich Kielmeyer (1765–1844). Kielmeyer left few written records of his work, but he did write about the parallelism of the earth's history, patterns in organism morphology, and stages of embryonic development. He was one of the first zoologists to suggest the idea of recapitulation in the late 1790s (Meyer, 1935, p. 382) and his work appears important enough for Haeckel to have read it (Coleman, 1973, p. 343).

Kielmeyer's observations of living organisms led him to suggest the possibility of creatures arising from other creatures in a process similar to that of insect metamorphosis. To Kielmeyer, if the history of the earth exhibited sequential change (fossils were his main line of evidence here), why would the same pattern of transformations not hold true for plants and animals? According to Russell (1916), Kielmeyer wrote that the human embryo begins as a vegetative life, then enters a lower animal stage where the embryo moves but has no sensation, and finally enters a stage much like that of other animals that feel and move.

German naturalist Lorenz Oken (1779–1851), in *Die Zeugung* (1805) and in *Lehrbuch der Naturphilosophie* (1811), stated that human embryos pass through stages similar to those that worms, crustaceans, and insects pass through before finally reaching the mammalian morphology. During this time, Lorenz Oken's ideas of embryos passing through adult stages of lower organisms were widespread among German zoologists (Russell, 1916, p. 69), including anatomist Johann Friedrich Meckel.

Meckel-Serres Law.

Meckel (1781–1833) was intrigued with abnormal anatomy. This interest led him to catalogue and draw embryonic malformations from aborted and miscarried embryos and fetuses. From his examination of embryos, Meckel believed that early-stage human embryos resembled lower forms of life as if to show, "here is how I got to where I am now." Meckel reasoned that malformed embryos resulted from arrested development, where embryos simply stopped developing, resulting in a lower form of life. Meckel investigated more than human embryos and monstrosities though. In the early 1800s he studied various vertebrate embryos and noted how the heart and circulatory systems of mammals went through stages of development that paralleled earlier stages in frogs, salamanders, and lizards (Richards, 1992, p. 50).

French scientist Antoine Étienne Serres (1786–1868) trained as a medical anatomist with interests in normal and pathological human anatomy and embryology. As an anatomist, Serres studied the formation of organs such as the kidney. In noting that the human kidney seemed to go through “stages” from primitive form to progressive forms, Serres concluded that such organization could be extrapolated to the organism as a whole. That is, the human embryo developed by going through organizational states of ancestral development: fish, reptiles, birds, and mammals, in that order.

Although Meckel and Serres never worked together, both anatomists examined embryos at a time when people thought that all organisms belonged on a linear scale of progressive development. That idea, the *Scala Naturae* theory or the Great Chain of Being, placed organisms like worms low on the scale and organisms like humans, higher on the scale. The only things higher than humans were angels and God. The idea of common ancestry did not operate under the *Scala Naturae* theory. Instead, one assumed that a higher power positioned all organisms properly on the great chain. Guided by this framework, recapitulation principles of Meckel and Serres, later known as the Meckel-Serres Law, centered on the idea that organisms higher on the great chain went through earlier phylogenetic stages during development. The Meckel-Serres Law became widely known in Europe in the late 1820s. While Haeckel could not accept the linear arrangement of animals, he did agree with Meckel and Serres that developmental stages of an organism followed adult ancestral forms.

Fritz Müller.

While Haeckel is the person most often associated with the idea of recapitulation, he was not the originator of the idea. That discovery most likely belongs to Fritz Müller

(1821–1897), who attempted to provide a mechanism linking ontogeny with evolution by publishing his description of recapitulation in 1861 (Amundson, 2005, p. 113; Raff, 1983, p. 10). Müller trained in Germany, later immigrated to Brazil, and was hired by the Brazilian government in 1852 as a field biologist and teacher. After reading the *Origin* and communicating with Darwin and Haeckel, Müller believed more than ever that examining individual development held clues to how current species evolved (Breidbach, 2006b, Russell, 1916). He was certain that embryo development mirrored the historical development of the species and he used the larvae of shrimp to serve as his evidence.

According to de Beer (1958), Müller saw two ways in which the development of embryos progressed. First, an organism developed, passing through its normal ontogenetic stages, but then characters were added at the end of development (what Müller called overstepping), or second, the organism diverged more and more from the ontogenetic stages without adding on structures at the end of its development (progressive deviation). Müller expounded upon his recapitulation ideas in his 1864 book, *Für Darwin.* Haeckel read *Für Darwin* in 1865 and adopted some of Müller's ideas to strengthen his own ideas of recapitulation (Richards, 2008, p. 100).

von Baer.

Karl Ernst von Baer belongs to a small group of scientists known as the founders of modern embryology and some historians identify von Baer as *the* father of embryology (Nyhart, 2009, p. 203). As a scientist with a great deal of knowledge about embryo morphology, von Baer disagreed with the idea of recapitulation that Meckel and Serres constructed to explain similarities in embryonic development across the animal kingdom. He denounced the Meckel-Serres Law in 1828 with the publication *Űber*

Entwickelungsgeschichte der Thiere. Biobachtun und Reflexion (On the Developmental History of the Animals. Observations and Reflections). Von Baer had his own opinions on embryos and ancestors and they did not include a linear ranking of low-grade to high-grade organisms. He invested a great deal of time examining chick embryos and von Baer was convinced that chicks showed all the features of being a vertebrate at a very early stage. Prior to this early stage, von Baer was certain that the chick did not recapitulate by going through any polyp, worm, or mollusk stages.

Von Baer's ideas were influenced by two principles that he held dear. First, goal directedness was an inseparable part of nature, and second, embryogenesis was a goal-directed process (Nyhart, 1995, p. 119). Von Baer's work as a comparative anatomist and embryologist led him to the idea that, instead of a single linear scale, there existed four ideal plans of body organization, based on radically different developmental patterns (Churchill, 1991, p. 11): the radiates (e.g., starfish and sea urchins), the mollusks (e.g., clams and octopi), the articulates (e.g., insects and crabs), and the vertebrates.

Von Baer held a teleological view of nature and remained at odds with Darwin and evolution. He also did not agree with Haeckel's Biogenetic Law or recapitulation, giving the reason that the human embryo starts out as a human embryo right at fertilization, and not as some ancient ancestor (Richards, 2008, pp.149–150). Von Baer also insisted that there were many differences and divergences during development while others like Haeckel, guided by Darwin's evolution theory, downplayed differences and emphasized the similarities between different mammalian embryos. Most embryologists during the latter half of the nineteenth century agreed with von Baer that embryos of different species often looked alike, but they questioned what that observation meant.

In 1828, von Baer challenged the idea of recapitulation with six arguments, which taken together, are referred to as von Baer's law of embryology. A more contemporary examination of von Baer's laws, first by Russell (1916) and then by Scott Gilbert (2014) condenses von Baer's six arguments into four. The first two arguments focus on the general pattern of the appearance of traits; the third and fourth arguments are concerned with the development of a single embryo and its taxonomic position. Science historian Frederick Churchill (1991) states that von Baer's first two laws support von Baer's rejection of preformationism, while the second two laws dismiss recapitulation (p. 11).

- Argument One: *General features of a large group of related organisms appear early in embryo development. The large group divides into smaller groups as specialized features appear later in embryogenesis.* In other words, all developing vertebrates look like each other just before neural tube development. Gilbert notes that most embryos are similar in appearance right after gastrulation and up to the point where the neural tube forms. At this point, all vertebrate embryos have gill arches, a notochord, a spinal cord, and primitive kidneys.

- Argument Two: *There is a particular order in which specialized characters appear. That is, from the most general forms the less general characters or structures are developed.* Gilbert uses the skin as a general character. All vertebrate embryos start with the same sort of skin but with time, specialization of the skin occurs. For example, the skin of fish and reptiles develops into scales, the skin of birds develops into feathers, and areas of mammalian skin develop into claws, nails or hair.

- Argument Three: *An embryo does not pass through the adult stages of lower organisms, but becomes less and less like them with development.* The gill slits of fish and pharyngeal arches of humans is an example. The arch becomes an actual gill in fish while in reptiles the arch becomes part of the reptilian skull and becomes the middle ear bones in mammals.

- Argument Four: *The embryos of higher forms never resemble any other adult animal form, although embryos may resemble other embryos.*

Overall, von Baer saw embryology as the study of differentiation, right from the get-go. The embryo has the potential to differentiate into any species of its type, and because of this, the embryo cannot represent the adult stage of any organism, present or past (Gould, 1977, p. 63). Von Baer's concept of development did not make the Meckel-Serres Law immediately go away, but von Baer certainly helped raise many questions about recapitulation's usefulness. These same questions reappeared with Haeckel's later-established Biogenetic Law and von Baer's work remains relevant to current embryologists. Recent research backs up von Baer's claim that there does appear to be a time during which most vertebrate embryos have similar physical structures (phylotypic stage). It is also during this time that gene expression appears to be the most similar between vertebrate groups (Irie & Kuratani, 2011).

According to Ernst Mayr (1982), von Baer's laws were never widely adopted because along with being descriptive and sterile, von Baer's arguments railed against evolution (p. 475). To von Baer, a divine intervention set the process of embryogenesis into action and Darwin's theory of common descent was simply unacceptable.

Recapitulation in the U.S.

Americans reacted slowly to Darwin's *Origin of the Species.* Historian Ronald Numbers asserts that as long as the scientific community remained skeptical about Darwin, theologians felt safe to question evolution and ask their congregations how an idea about monkeys turning into men could ever be taken seriously (Numbers, 1998). By the mid-1870s, however, many American naturalists began speaking up and showing their collective support for biological evolution (p. 2).

Unlike Darwin's theory, recapitulation did not just originate in Europe. American paleontologists Edward Drinker Cope (1840–1897) and Alpheus Hyatt (1838–1902) also published their own version of recapitulation, although it was quite similar to Haeckel's idea. Followers of recapitulation always grappled with the problem of longer and longer ontogenies as organisms acquired more and more characteristics. Cope believed that the gestation periods could remain unchanged (or only slightly longer), if the speed of individual development was increased. By shortening or accelerating the time required for an embryo to go through its ancestral stages, enough time would be left at the end of embryogenesis to add on newly acquired structures. This is Cope's well-known law of acceleration. Likewise, evolution could also be affected by a slowing down of development (law of retardation). To Cope, the extinction of a species could be explained by this type of slow, continued contraction and atrophy of its structures.

According to Gould (1977), paleontologist Alpheus Hyatt's views on recapitulation were similar to those of Cope. Both scientists developed laws of acceleration independent from one another in 1866. They differed however, in that Hyatt did not believe that two forces or mechanisms were responsible for progress and extinction. Hyatt believed that the law of acceleration could account for both processes (p. 92). At the same time that Cope and Hyatt wrote about laws of acceleration, Haeckel was in Europe writing his own ideas about evolution and recapitulation.

One of Haeckel's loudest American adversaries was Louis Agassiz (1807–1873). Agassiz believed that new species appeared according to God's divine plan and that plan placed humans squarely at the top of the "most advanced" species. The plan, according to Agassiz, was evident even during early embryogenesis. According to Gould (2000), Agassiz disliked Haeckel for several reasons, foremost Haeckel's anti-religion rants and his copying of other scientists' work without giving credit where credit was due.

Agassiz did not agree with Haeckel's position on recapitulation, but the American scientist did believe that ontogeny retraced the history of divine creation (Richards, 2008, p. 156). Agassiz wrote in 1856 that rather than organs appearing according to ancestral lineage, eggs were all identical and organs developed in sequence of importance. The most important organs appeared first, such as the brain and sensory organs. Later the limbs and teeth appeared that indicated the genus and species (Müller, 1869, p. 99). To Agassiz, a creator planned embryogenesis and it did not include the passage of an embryo through other animal grades.

Although historians point to Agassiz as one of America's first true scientists, Ernst Mayr is not so gracious in his descriptions of Agassiz. According to Mayr (1959), Agassiz failed. He failed to welcome the unifying theory of evolution, he failed to grow with science, and he failed to go about his failures quietly. Agassiz was always quite vocal about his opposition to Darwin's theory, to the extent that he is often blamed for American scientists' slow acceptance of evolution in the late 1800s and early 1900s (Irmscher, 2013).

The decline of Haeckel and recapitulation.

Haeckel always had big ideas and perhaps his biggest idea, supported by recapitulation, was that all living things were connected. Haeckel's dynamic ideas were exceptionally popular, but his critics told him that popularity did not make his ideas necessarily right. The Biogenetic Law, along with its promise that recapitulation would help reconstruct the evolutionary history of species through embryological research, eventually fell out of favor. The demise of the Biogenetic Law in the inner circle of scientists came at a time when embryology was transitioning to a less descriptive and more experimental phase (Hopwood, 2009; Nyhart, 1995); one with more rigor and less Haeckelian speculation.

Metchnikoff.

Russian biologist Ilya Metchnikoff (1845–1916) is known for his work with phagocytes and immunology, but he was also a serious embryologist. Like Haeckel, he saw the value of studying embryos to determine phylogenetic relationships and he embraced recapitulation as a way to understand the evolution of organisms. Haeckel and Metchnikoff, however, each had his own idea about what constituted the earliest multicellular organism. Haeckel studied amphioxus, a fish-like marine vertebrate to investigate vertebrate origins. In 1872, he proposed the *Gastrea* Theory, in which Haeckel identified what he thought to be the first multicellular organism. Haeckel felt that this primitive organism, which he named *gastrea*, arose from an invagination of a primordial gastrula.

From 1873 to 1878, Metchnikoff published a series of papers on sponges and hydroids (an example of a hydroid is the well-studied *Hydra*) in which he described how these organisms did not fit the pattern of gastrulation that most embryologists were familiar with. Sponges do not fold to form a dual-layered embryo, but have individual cells that migrate to the interior of the embryo to form a dual layer (see Figure 5). Metchnikoff disagreed with Haeckel's *Gastrea* theory, assuming that the earliest multicellular ancestor arose from sponges. He called his earliest multicellular organism a *parenchymella*. Because Metchnikoff worked with "older" organisms on the evolutionary tree, he claimed that his *parenchymella* was older than Haeckel's *gastrea* and that the introgression of cells was a more ancient mechanism of gastrulation. Over time, Metchnikoff, who believed that recapitulation was a viable embryonic process, came to disagree with Haeckel's version of recapitulation, citing that it had too many exceptions and contradictions (Gilbert, 2003; Tauber, 2013).

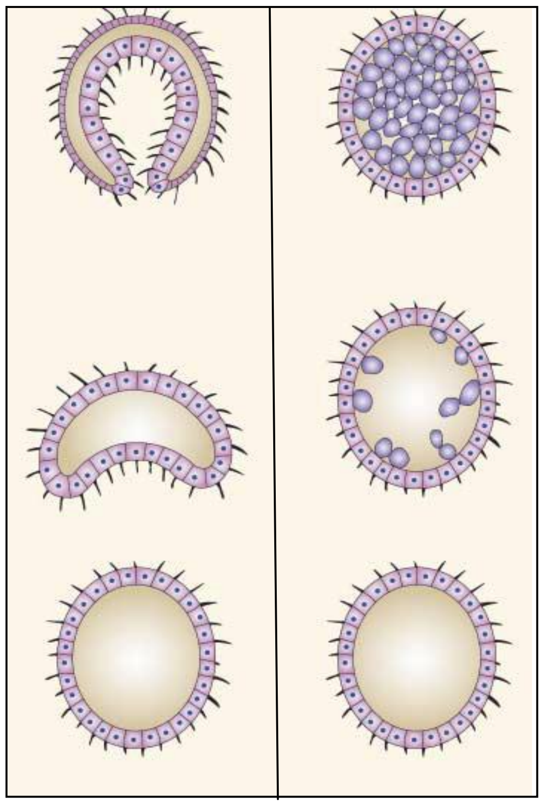


Figure 5. Haeckel's *gastrea* (left) and Metchnikoff's *parenchymella* (right). Metchnikoff's gastrulation mechanism involved introgression, whereby cells proliferate from the inner blastula wall into the hollow blastocoel, resulting in a solid gastrula stage. From *Invertebrate Zoology* 5th ed. (p. 65). By R. D. Barnes, 1987, Philadelphia: Saunders.

Hurst, Sedgwick, and Cunningham.

In the late 1800s, British biologists C. Herbert Hurst (1856–1898), Adam Sedgwick (1854–1913), and Joseph Thomas Cunningham (1859–1935) joined with other European scientists to critically review recapitulation and even to question von Baer's rules. Hurst stated what would become a recurring theme from the late 1800s: "A bird does not develop into a fish and then into a reptile and then into a bird" (Hurst, 1893a, p. 199). Hurst agreed that recapitulation had started out as a promising process for biologists to follow, given that the paleontological record was incomplete, but with increased examination of Haeckel's work, he felt that recapitulation was simply leading good biologists down an absurd path (Hurst, 1893b).

From his study of embryos, Sedgwick, like Metchnikoff found too many exceptions to Haeckel's idea of recapitulation. Sedgwick wrote, "In the vast majority of ontogenies there are no phylogenetic traces, nor by the consideration that a number of organs, such as teeth and hand-claws in birds, limbs in snakes, and gill-clefts in fishes have recently disappeared without leaving a trace in ontogeny" (Sedgwick, 1894, p. 41).

In 1897, Cunningham, then professor of natural history at the University of Edinburgh, declared recapitulation an example of "hasty" science, where a few observations were stretched to make a scientific process universally true (Cunningham, 1897, p. 483). Cunningham argued that if embryos recapitulated, why hadn't embryologists discovered the complete evolutionary history of organisms with ease?

Garstang.

Walter Garstang (1868–1949) trained at Oxford just as experimental embryology started to overshadow the importance of evolutionary embryology. Garstang vehemently opposed Haeckel's Biogenetic Law and he became the chief protagonist in the ultimate rejection of Haeckel's idea of recapitulation (Hardy, 1951, p. 566). In 1922, Garstang made the case before Linnaean Society members that ontogeny created phylogeny through modifications in development and not the other way around. It was during this address that Garstang famously said, "ontogeny does not recapitulate phylogeny: it creates it" (Garstang, 1922, p. 81). What Garstang meant was that knowing an organism's individual development could lead to predictions about the organism's evolutionary pathway (Gilbert, 1997).

Garstang may have written his recapitulation critique in response to Thomas Hunt Morgan's 1916 book, *A Critique of the Theory of Evolution*, in which Morgan called for the discarding of Haeckel's Biogenetic Law in its entirety. Morgan protested that recapitulation was not a viable mechanism for evolution because of the uncertainties generated by the many exceptions to it (Rasmussen, 1991, p. 61). Morgan believed that changes in heredity were due to mutations and not evolutionary history. In effect, he made it known that geneticists, and not embryologists, would soon be the go-to scientists when it came to answering questions about evolution. Nicholas Holland, professor of marine biology at Scripps Institution of Oceanography, believes that Garstang wrote his 1922 critical examination of the biogenetic law to "reestablish embryology as a valid approach for studying evolution" (Holland, 2011, p. 256). In rebuttal to Morgan, Garstang acknowledged that mutations were important in genetics and evolution, but like other embryologists at this time, he questioned placing such high emphasis on genes in the process of evolution.

Garstang's areas of expertise included larval biology and fisheries science (Hall, 2000). Larval stages (what Darwin referred to as "active embryos") had always posed a problem to Haeckel. Crustaceans, echinoderms, annelids, mollusks, insects, and even frogs have larval forms in their life cycles. Were larvae part of an organism's phylogenic record? Initially, Haeckel would argue "no," that evolution occurred in adults and not in larvae or embryos (Hall, 2000). Haeckel was adamant that new structures were added at the end of ontogeny, not at the beginning, which would include larval stages. As more and more larval forms were identified, significant challenges arose to Haeckel's Biogenetic Law. Haeckel finally had to acknowledge that larval forms were a part of an organism's evolutionary history, but this made the process of recapitulation take even more awkward turns (Churchill, 2007).

Garstang's work with marine invertebrate larvae helped show that adaptive modifications take place in larval stages rather than adult stages (Armon, 2010, p. 184). He believed that larvae were the key to finding the earliest invertebrate ancestor to vertebrates. Garstang compared the larvae of echinoderms to the larvae of early chordate embryos and postulated that an early echinoderm larva, one with a lateral nerve tract that had shifted to the back of the organism, was the first vertebrate. This evolutionary scenario, however, has gone the way of Haeckel's *Gastrea* theory, as Garstang's early vertebrate hypothesis is not supported by recent developmental genetics findings (Holland, 2011, p. 247).

In the 1930s, with the modern synthesis underway, debates about recapitulation continued to surface, but by the end of the 1930s most scientists saw support for recapitulation fading (Churchill, 1998). Embryologist Waldo Shumway (1932) sums up the changing role of embryos at the time, "It is the function of the embryo to become an adult without looking backward on ancestral history. It is the business of the embryologist to describe the phenomena which he observes without undue attention to what can be interpreted at most as reminiscences of evolution" (p. 98). Shumway was convinced that new findings from modern genetics and experimental embryology would convince “recapitulation holdouts” to finally surrender.

Several other scientists in the early 1930s published articles declaring that recapitulation had overstayed its welcome, including A. W. Meyer (1935) of Stanford University. Meyer is perhaps best known for his book *The Rise of Embryology* (1939). Several years prior to this publication, Meyer wrote an historical review of the idea of recapitulation for *The Quarterly Review of Biology.* Along with Meyer, embryologist Gavin de Beer offered arguments against recapitulation.

de Beer.

Brian Hall (2000) identifies British evolutionary biologist Gavin Ryland de Beer (1889–1972) as one of the greatest descriptive embryologists of the 1900s. Like Garstang, de Beer attended Oxford and was a student of Julian Huxley, a key participant in the founding of the modern evolutionary synthesis. Huxley’s influence is easy to see, as de Beer later became one of the first embryologists to integrate genetics with evolutionary embryology (de Beer, 1954, p. 20). De Beer speculated in the early 1930s that perhaps the activity of genes was responsible for timing changes in embryonic development (Armon, 2010, p. 184).

With his heavy involvement in the field of experimental embryology, de Beer declared recapitulation outworn and dull in 1930. While dullness is not a quality that should cause outright rejection of a theory, de Beer found faults with recapitulation and like other biologists around him, criticized Haeckel’s Biogenetic Law for not driving new embryological research. To de Beer, Haeckel’s embryo work was an impediment to new hypotheses and scientific progress.

In 1930, de Beer published *Embryology and Evolution* (later editions in 1940, 1954, and 1958 were retitled *Embryos and Ancestors*) in which he revisited Haeckel's concept of heterochrony and recapitulation. Heterochrony is a process where characters already present in an embryo undergo some type of change in their developmental timing, resulting in a speeding up or slowing down of growth. De Beer described eight morphogenetic models, all involving changes in timing of developmental events, to account for evolutionary change. He intended for the models to demonstrate that Garstang's catch phrase "ontogeny causes phylogeny" was more accurate than Haeckel's "phylogeny causes ontogeny" (Oppenheimer, 1959, p. 272).

Gould argues in *Ontogeny and Phylogeny* that of de Beer's eight models, only four are models of heterochrony and those models can be reduced to just two: acceleration and retardation. Gould also agrees with de Beer's argument that it was not the many exceptions and counterexamples of recapitulation that caused recapitulation's decline. While the Biogenetic Law had problems with predictive and explanatory power, Gould and Rasmussen (1991) argue that the law's biggest shortcoming was its unfeasibility as a practical research tool in the areas of genetics and heredity.

Gruenberg.

Many biologists dismissed the Biogenetic Law before 1900, but critiques external to those of scientists in the "inner circle" of research took longer to appear. One such external critic was textbook writer Benjamin C. Gruenberg (1875–1965). Historian Philip Pauly identifies Gruenberg as a key biology textbook author in New York City during the Progressive Era. Gruenberg was a Russian Jewish immigrant who taught at several New York City public high schools before working as educational director for the U.S. Public

Health Service. While teaching, Gruenberg completed a PhD at Columbia with T. H. Morgan in 1911 (Pauly, 2000) and wrote several editions of his popular high school biology text, *Elementary Biology*.

Gruenberg wrote *The Story of Evolution* in 1929 for a general audience, evolutionists and anti-evolutionists alike. He states in the preface, “Are you an evolutionist? Are you an anti-evolutionist? It really does not matter. What matters is the quality of thinking you do to justify your position” (Gruenberg, 1929, preface). The publication date makes one wonder if Gruenberg wasn’t writing in response to the outcome of the Scopes Trial in 1925. *The Story of Evolution* has a textbook feel to it and many of the book’s diagrams are from Gruenberg’s high school biology book. Figure 6 is a Haeckel-like embryo drawing that appears in *The Story of Evolution*. Gruenberg uses this illustration, including a human embryo to discuss gill slits and Eustachian tubes. He reasoned that vertebrate embryos all show “wrinkles” behind the head and on the side of the neck due to common ancestry and not, as Gruenberg states, “due to a theory of special creation.”

Gruenberg discussed the Biogenetic Law in *The Story of Evolution*, but did not identify Haeckel as the law’s originator. He credited von Baer for laying the foundations of comparative embryology in 1828 and described how the Biogenetic Law was “overworked” to the extent that it became an impediment to research and understanding of evolution (p. 131). Gruenberg repeated Garstang’s earlier claim that a human being is never in the course of its development a fish or an amphibian. I found that what Gruenberg wrote about recapitulation for a general audience also made its way into his high school textbooks.

Among scientists and science writers, the 1930s truly seem to mark the end of recapitulation. However, as you will see, the news about recapitulation's demise did not make its way to everyone, including several biology textbook writers.

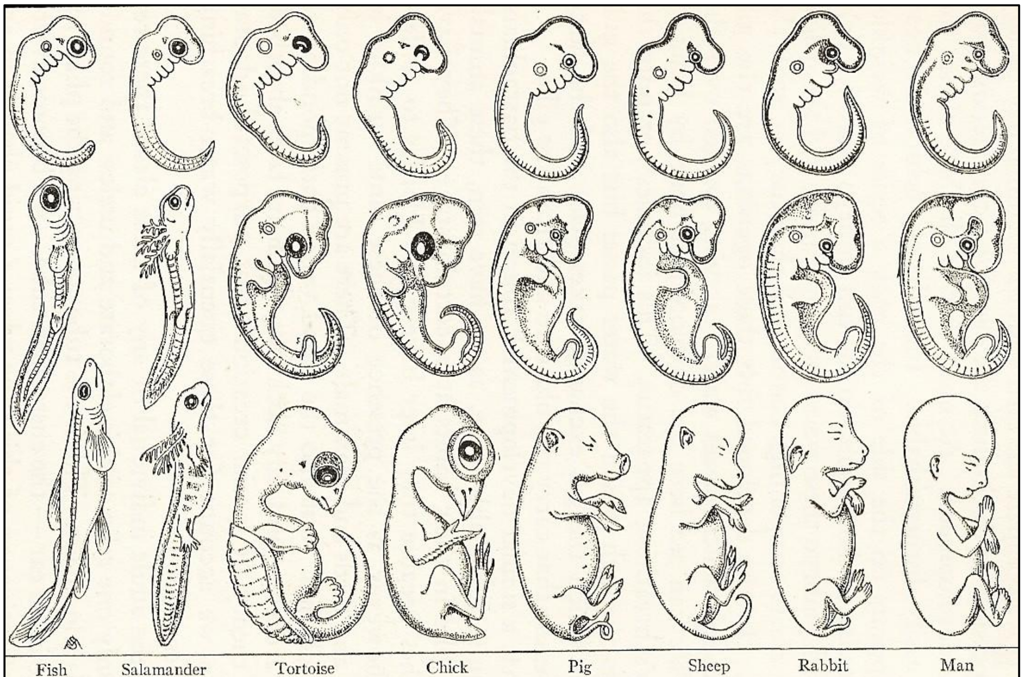


FIG. 35. PARALLELISM IN DEVELOPMENT OF BACKBONED ANIMALS

The three rows of embryos represent distinct stages of development. In the first row the stages of the different species are very much alike; in each succeeding stage they are more distinctive. From Gruenberg, Elementary Biology, published by Ginn & Company.

Figure 6. Haeckel's embryo grid in Gruenberg's 1929 *The Story of Evolution*. This same diagram appeared in Gruenberg's high school biology text, *Elementary Biology*. From *The Story of Evolution* (p. 130). By B. C. Gruenberg, 1929, New York: Garden City Publishing.

Section II: The Importance of Scientific Illustrations

Science attempts to explain how nature works by means of theories. Theories, though, are sometimes hard to understand because of their abstractness. To help with interpretation, a certain degree of "concreteness" is lent to science by the use of pictures, drawings, graphs, and more recently, computer animation and modeling. Most pictures remain just that—pictures. Some illustrations however, become scientific models. In order to be a two-dimensional scientific model, a drawing explores a theory that is already in place. Science models may also serve as instruments for examining phenomenon and mechanisms for which theories cannot yet give good explanations (Morgan and Morrison, 1999). Current research on visual representations and cognition indicate that visuals are usually grasped quickly and intuitively, without explanation. (Doumont, 2002). This intuitive type of visual processing and retention is linked to the idea that scientific representations reduce information to manageable dimensions for readers (Lynch, 1990, p. 181).

Darwin and Haeckel were aware of the need to explain evolution in an understandable way, but in the 1860s and 1870s preparing illustrations for publication was expensive. Nonetheless, both of the scientists did draw illustrations that were copied by others and held up as scientific models for evolution.

Darwin's trees.

Darwin's *On the Origin of Species* is 593 pages long. The text is often dense and there is only one diagram (see Figure 7), but what an important diagram it is. The single illustration is that of an early tree of life representation and with it, Darwin intended to show that all organisms were classifiable, and that all organisms evolved from a single common ancestor (Hall, 2010, p. 148).

Darwin was not the first publish a tree of life diagram. Arguably that distinction goes to naturalist and philosopher Charles Bonnet (1720–1793) who is believed to be the first to apply the tree metaphor to organisms, nearly one hundred years before Darwin did (Pietsch, 2012). Although Darwin's tree does not have a central trunk like many of Haeckel's later tree of life diagrams, Darwin's tree begins with horizontally arranged species, which he identified with capital letters, A through L. The vertical axis is numbered I through XIV and the numbers represent thousands of generations. The species ascend to the top of the page with some species branching off to show evolution from a common ancestor. Some of the species, for example, C and D, show no branching and eventually go extinct.

Darwin’s tree of life presented evolution (and its timescale) in a visual, hierarchical, and understandable way. He made clear that his tree would probably not include every single organism, but that the model served as a general guide (Doolittle & Bapteste, 2007). Trees of life soon became important to evolutionists because they presented a much easier way to display relationships among organisms. Harvard biologist Charles Nunn (2011) believes that “one of the most significant breakthroughs in biology was the realization that lineages in organisms can be represented with a branching tree (p. 20).

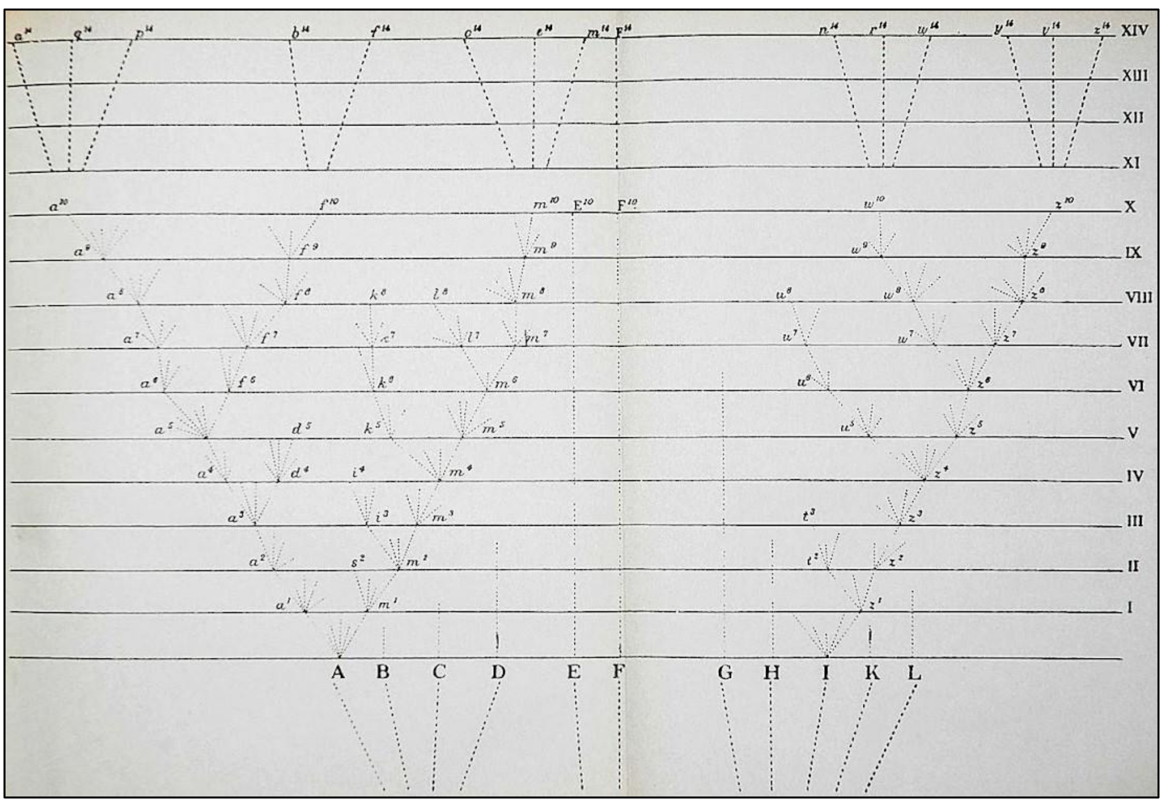


Figure 7. Darwin’s tree of life. From *On the Origin of the Species* (p. 131). By C. Darwin, 1859, London: Murray.

Cultural historian Constance Sommerey of Maastricht University argues that the public success of Darwinism is often attributed to the assumption that evolution "makes for a good story." Sommerey and others argue the direct opposite. They believe that evolution defies narrativization because it does not have a divine purpose and natural selection and species, as they were conceptualized by Darwin, are devoid of agency" or the capacity for species to make choices" (Abbott, 2003, p. 144; Sommerey, 2011). Nor do species in *Origin* act as narrative entities. Darwin's tree of life attempted to make up for this deficiency.

Haeckel's trees.

Haeckel's bold and magnificent trees of life soon followed that of Darwin's. Haeckel's first tree of life appeared in 1866 in *Generelle Morphologie* and his first embryo grid drawing, the focus of this study, was published in 1874 in *Anthropogenie*. It is Haeckel's trees that first made Europeans and Americans familiar with family tree diagrams (Clark, 2008, p. 135).

Haeckel's trees and embryos follow an easily recognizable pattern—that of progressive linearity. While Haeckel's evolutionary trees did branch, there is a recognizable directedness (from lower organisms to higher organisms) in both of his most well known diagrams. Humans depicted in Haeckel's drawings, whether at the top of the tree or at the end of his embryo grid, challenged readers to see on the one hand that humans are animals (and thus connected to nature), but on the other hand, humans are *unique* animals.

Haeckel's trees represented the evolution of the animal kingdom *and* individual development because to Haeckel, the animal kingdom and the organisms in it were in some sense both individuals. That is, the animal kingdom itself was an individual (Nyhart, 1995, p. 133). Nothing could make this more obvious than Haeckel's tree of life drawings, shown in Figure 8.

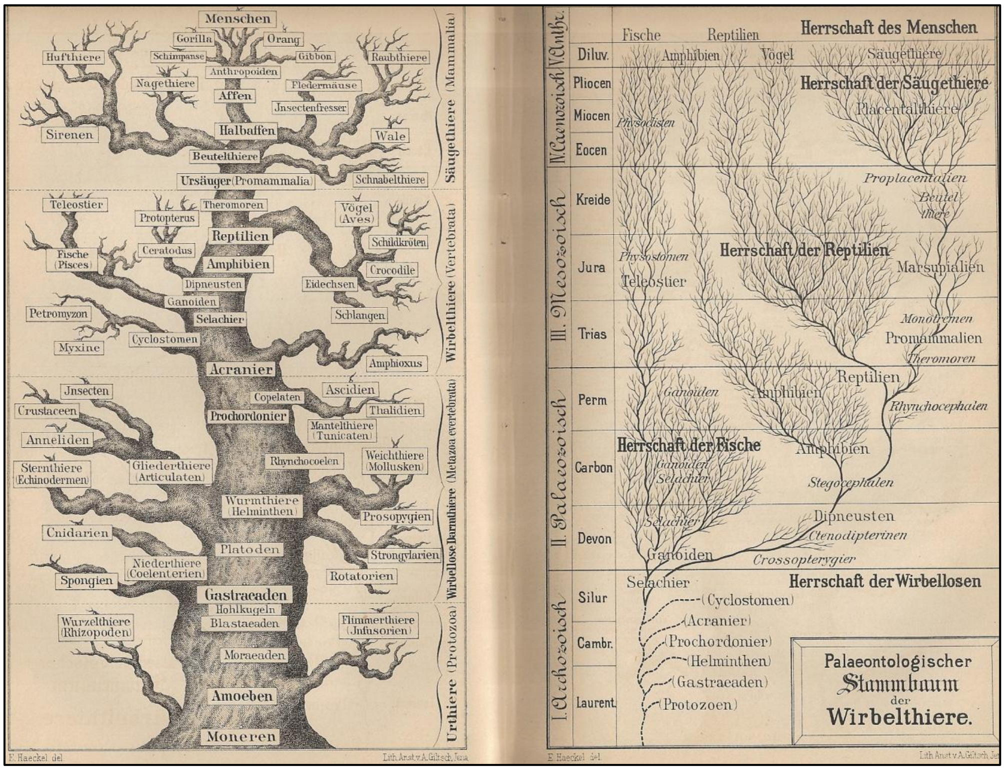


Figure 8. Haeckel's trees of life from *Anthropogenie*. The Moneren, found at the bottom of the "great oak tree" was Haeckel's idea of single-celled organisms that he called "Moners." From *Anthropogenie* Vol. II (Plate 15 and 16). By E. Haeckel, 1891, Leipzig: Engelmann.

Sommerey (2011) argues that Haeckel succeeded in propagating evolution because recapitulation, and especially Haeckel's embryo drawings, provides a narrative that is lacking in *Origin.* The narrative of recapitulating embryos may be one of the reasons that Haeckel's grid remains resilient—it provides an easily recognizable story.

Haeckel's embryo drawings.

Haeckel was an artist as well as a scientist and his communicative method of choice always involved strong visual components (Heie, 2008). Haeckel's use of symmetry and color gave him a unique visual style that was intimately connected with scientific practice (Halpern & Rogers, 2013, p. 465). Philosopher David Ludwig (2013) believes that Haeckel used accurate data for his embryo drawings, but the data was organized in a way that made sense for Haeckel's theoretical framework. In this manner, Haeckel designed his drawings to mediate between a general theory and concrete data (p. 145).

There is little doubt that Haeckel's talents as an artist helped embolden his ideas about embryos and evolution to the public. During the 1800s, enlarged illustrations and wax model embryos were of great importance to embryology lectures because of the tiny size of embryos. You could not hold up a jar full of tiny embryos to an audience and expect them to see the fine morphology of such small organisms. And so, Haeckel drew. His embryo drawings were often a compilation of actual embryos and drawings of embryos done by other embryologists, most notably Theodor Bischoff (1807–1882) and Albert Kölliker (1817–1905) (Richards, 2008).

Haeckel's tireless campaign for Darwinism included his first book written for a general audience, *Natürliche Schöpfungsgeschichte* (Natural History of Creation) published in 1868. This 688-page book consists of twenty reworked lectures that Haeckel delivered at the University of Jena in 1865 to 1866 (Heie, 2008). To further capture interest of the lay reading public, *Natürliche Schöpfungsgeschichte* houses Haeckel's first embryo grid illustration. The grid shows four-week-old dog and human embryos that were nearly identical in appearance, six-week-old dog and human embryos, a six-week-old turtle embryo, and an eight-day-old chicken embryo. By placing different embryos side-by-side, Haeckel hoped to illustrate recapitulation and give a sense of order to evolution (Halpern & Rogers, 2013, p. 465).

Natürliche Schöpfungsgeschichte became the chief source of the public's knowledge of Darwinism and embryos (Richards, 2008, p. 455), but there soon appeared problems. Karl Ludwig Rütimeyer (1825–1895), an anatomist at Basel University, Switzerland was the first to seriously criticize Haeckel's drawings in *Natürliche Schöpfungsgeschichte*. The technology of printing pictures in the late 1800s is quite different compared to today's available technologies. To make copies of drawings in the 1800s, one had to start with copper plate etchings or woodcuts. Woodcuts require that the illustration first be drawn on fine-grained pieces of wood and then handed off to cutters who used sharp knives to cut away any part of the wood not part of the illustration. The finished woodblocks were brushed with ink, pressed on paper, and the paper run through a printing press.

It was one of Haeckel's woodcuts that brought him criticism and charges of "playing loose." Rütimeyer noticed that in one of Haeckel's drawings, the young dog, chick, and turtle embryos appeared remarkably similar, and for good reason, as Haeckel later admitted that the same woodcut was used for the three different embryos (see Figure 9). Haeckel drew the embryos at the earliest stages of development, sometimes referred to as the "sandal" stage when embryos take on the shape of a sole of a sandal. Rütimeyer and others also criticized Haeckel for not giving credit to the original illustrators of the embryo pictures that Haeckel had copied. All might have been forgotten if Wilhelm His (1831–1904), a colleague of Rütimeyer, had not entered the picture. His was professionally better known than Rütimeyer and he was one of Haeckel's most outspoken opponents (Richards, 2008, p. 280). His had long argued that Haeckel's Biogenetic Law and recapitulation stretched the limits of using embryos to support evolution and he believed that Haeckel embellished his embryo drawings to make the embryos appear more similar than they actually were.

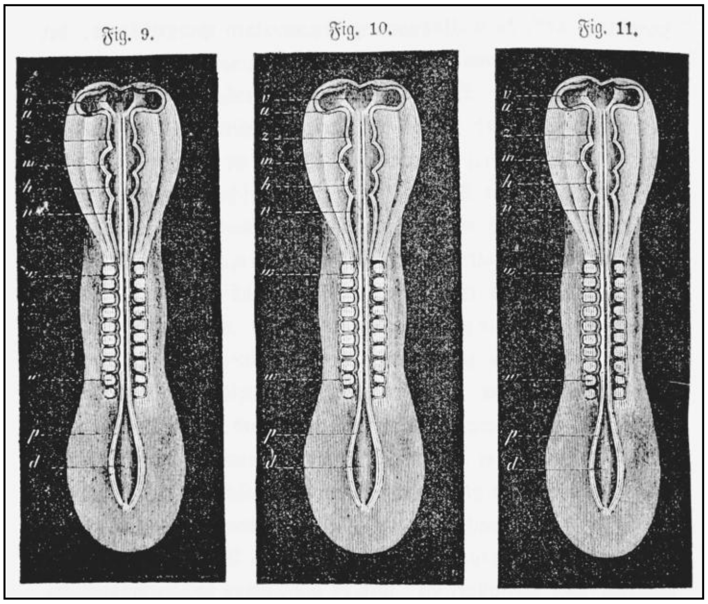


Figure 9. Early embryos of dog, chick, and turtle appearing remarkably similar. From *Natürliche Schöpfungsgeschichte* (p. 248). By E. Haeckel, 1868, Berlin: Reimer.

Rütimeyer published his criticism of Haeckel in a professional journal, *Archiv für Anthropologie* and this probably gave His even more confidence to attack Haeckel. His argued that Haeckel took too much liberty with his drawings, sometimes making heads too large or tails too long. In the case of Haeckel's human embryo drawing, His argued that Haeckel made the human tail longer to make it more apelike (Richards, 2008, p. 240).

Whether Haeckel intentionally drew embryos to fit his image of what embryonic development should look like, we should not ignore that Haeckel was doing novel work. Unlike other comparative embryologists at the time, Haeckel drew embryos the same size and oriented them in the same direction. These techniques gave Haeckel's drawings a certain style or schematic representation of embryos, and helped make morphological comparisons easier. Perhaps *too* easy, some critics would contend. Richards believes that the rather schematic appearance of Haeckel's embryos is because Haeckel originally wanted the sketches used as large wall charts, which Haeckel often used in his public lectures. Haeckel knew that embryology was difficult to understand and an overemphasis on detail was of limited appeal for his public audiences. Thus, Haeckel's embryo diagrams do not have the detail that Haeckel gave to his radiolarian and medusa monographs (Richards, 2008, p. 234). We should also not forget that Haeckel drew his embryos partly for the sake of anatomy and partly to help visualize recapitulation, a supposed universal law already established by the likes of Meckel, Serres, and Müller.

How did Haeckel respond to attacks by His and Rütimeyer? First, he acknowledged that he had adapted his drawings from the work of other well-known biologists—a practice that was common during the late 1800s. Haeckel pointed out to His that all "thinking morphologists produce comparably contrived illustrations" (Richards, 2008, p. 302). Second, Haeckel explained that yes, he may have copied diagrams without giving credit, but he subsequently altered these diagrams slightly to make them more schematic in nature. That is, Haeckel drew what he considered essential features while not drawing in features that he considered inessential for the purpose of comparing embryos. Even with numerous attacks against him though, Haeckel's *Natürliche Schöpfungsgeschichte* resulted in 12 editions (1868–1920) and numerous translations, including English.

Anthropogenie.

Criticism of Haeckel intensified after he published his next book, *Anthropogenie* (The Evolution of Man) in 1874 (Heie, 2008). In this book, Haeckel used comparative embryology to reconstruct the phylogenetic tree of man. Also in *Anthropogenie* is a double embryo diagram (called double because the picture was spread over two pages) with Haeckel's classic grid of eight vertebrates: fish, salamander, turtle, chick, pig, cow, rabbit, and human at three different stages of development, which Haeckel captioned as "very early," "somewhat later," and "still later" (see Figure 10). The similarities of the earliest stages seem to support Haeckel's claim that all eight organisms descended from a common ancestor. The later stages were intended to show how each organism recapitulated ancestral morphologies during ontogeny. Haeckel also used his embryo diagram to show that the longer two organisms paralleled each other, the more recently they had branched off from a common ancestor.

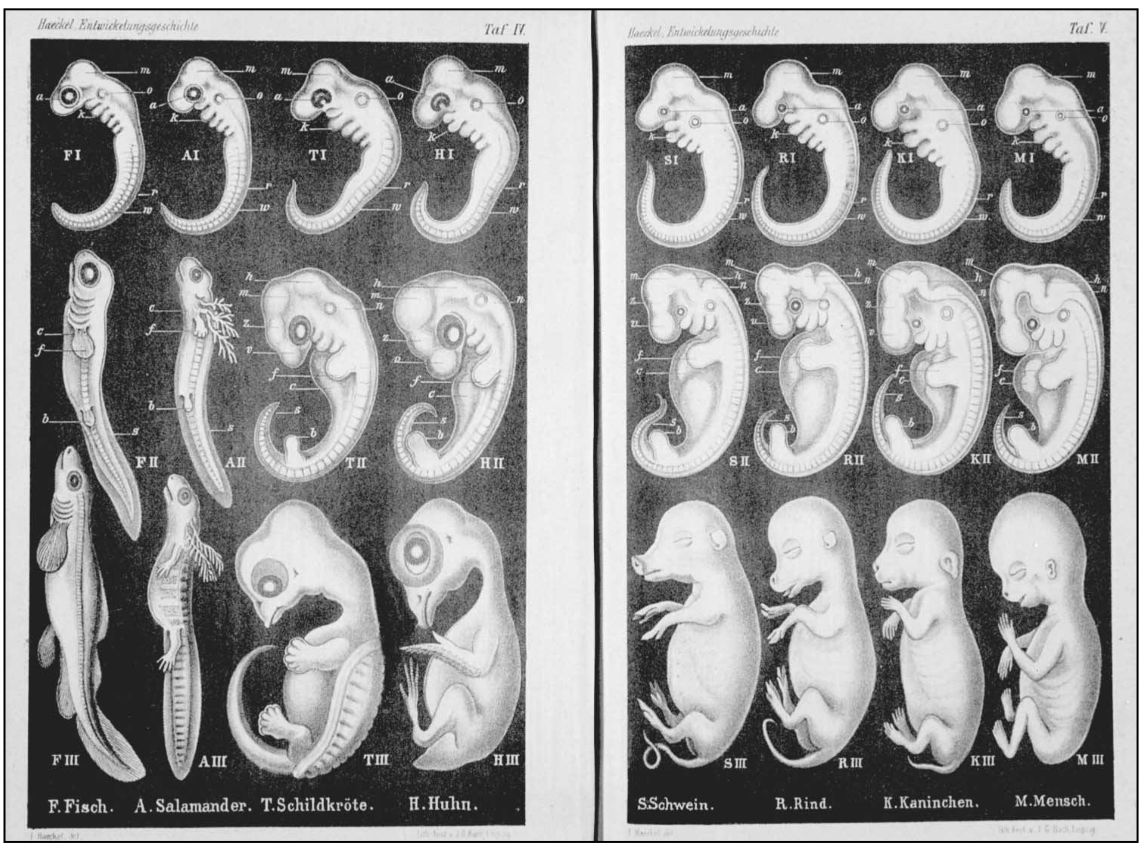


Figure 10. The first 8 x 3 grid published by Haeckel in 1874. From *Anthropogenie* by E. Haeckel, 1874, Leipzig: Engelmann.

Haeckel's long time associate, Carl Gegenbaur reviewed *Anthropogenie* and relayed to Haeckel that "many of the woodcuts" needed changing for the second edition (Hopwood, 2006, p. 292). What those changes were is not known. Gegenbaur eventually came to doubt the work of his Jena colleague. Over time, he objected to Haeckel's sloppiness and thought the Biogenetic Law overrated (Nyhart, 1995, pp. 249–250).

Even though Haeckel made more effort to give credit to other illustrators with his later publications, *Anthropogenie* provided His with more ammunition to fire at Haeckel. In 1874 His published *Unsere Korperform und das physiologische Problem iher Entstehung* (*Our Bodily Form and the Physiological Problem of its Origin*), where His again criticized Haeckel's embryo pictures, claiming that they were too generalized and conjured up an erroneous world-view of embryology. His' criticisms came at a time when scientific practice was changing, but scientists like Haeckel were still allowed to manipulate illustrations in order to portray "types" or a generalized schematic in which all similar species of embryos at the same period of development could fit. In the background of Haeckel's labors, however, was a growing consensus among scientists that science should move towards more objectivity and embryology should forge ahead with experiments and physiological studies.

As accusations ramped up against Haeckel, the Catholic Church more forcefully argued against Haeckel and his anti-theistic beliefs. More embryologists distanced themselves from Haeckel as the term "fraud" became synonymous with his name. Criticism of Haeckel's work soon went beyond his drawings, as His and zoologist Alexander Goette (1840–1922) called for the rejection of Haeckel's recapitulation hypothesis.

Labeling anyone and his or her work as a "fraudulent" is a serious accusation. In the late 1800s, supporters and critics of Haeckel at least knew of the vast amount of work that the embryologist had done with finding new species, writing monographs, and defending evolution. Today, generations removed from Haeckel probably have little, if any, knowledge of the man. But, Haeckel's drawings have never gone away, nor has the notion held by some that the drawings represent such an appalling degree of fraudulence that anyone or any idea even associated with Haeckel is fraudulent too. Why do Haeckel's embryos cause such rage and criticism? Certainly, there were many pictures of embryos around at the time that Haeckel was drawing his first embryo grids. Ludwig argues that Haeckel's embryo drawings, unlike other embryo drawings, were more than just drawings—"they were powerful tools in the public presentation of Haeckel's evolutionary program (p. 149), and not everyone agreed with evolution. This is the idea behind many current criticisms of Haeckel's embryo drawings in biology textbooks.

Recent examinations of Haeckel's embryos.

For many years, textbooks quietly displayed Haeckel's embryo grids in chapters dealing with evolution. The drawings were often redrawn and revised and rarely was Haeckel ever acknowledged as the originator of the embryo grid. This changed in the late 1990s when a study by Michael Richardson and his colleagues (1997) compared photographs of embryos to Haeckel's illustrations as part of the study's methodology. Harsh statements made by Richardson about Haeckel's embryo drawings quickly made headlines. Intelligent design advocates, who assert that the universe is so overwhelmingly complex that there is no other explanation for its existence other than an intelligent designer, quickly picked up Richardson's comments and updated their websites with Richardson's quotes and embryo photographs.

Richardson's 1997 study.

In 1997, Haeckel returned to the forefront of controversy when London-based embryologist Michael Richardson and his research team published a study about embryo development. In the study, Richardson compared Haeckel's *Anthropogenie* embryos with the "mechanical objectivity" of his own research team's photomicrographs taken of similar embryos and at similar stages of development. Richardson's focus was on conserved stages during embryogenesis. These are stage points when embryos pass through a virtually identical (conserved) morphological stage. The fact that embryos of different species have particular stages in development where they look much the same is widely accepted, but when these conserved stages occur, and if they always occur at the same time among different species is debatable.

Currently there are two modes of thought about when conservation occurs. The funnel model places conservation at the very early stages of embryonic development, namely during gastrulation and neurulation. As the embryos develop, they become more diverse. Von Baer and Haeckel alluded to this type of model when they argued that during mid-embryonic development, embryos showed striking similarities in body plan. More recently, the hourglass model has been proposed to show a better representation of when conservation takes place. With this model, divergence appears when embryos are quite young, followed by a conserved stage, followed by another divergent stage. The conserved stage occurs somewhere mid-way through embryo development (see Figure 11).

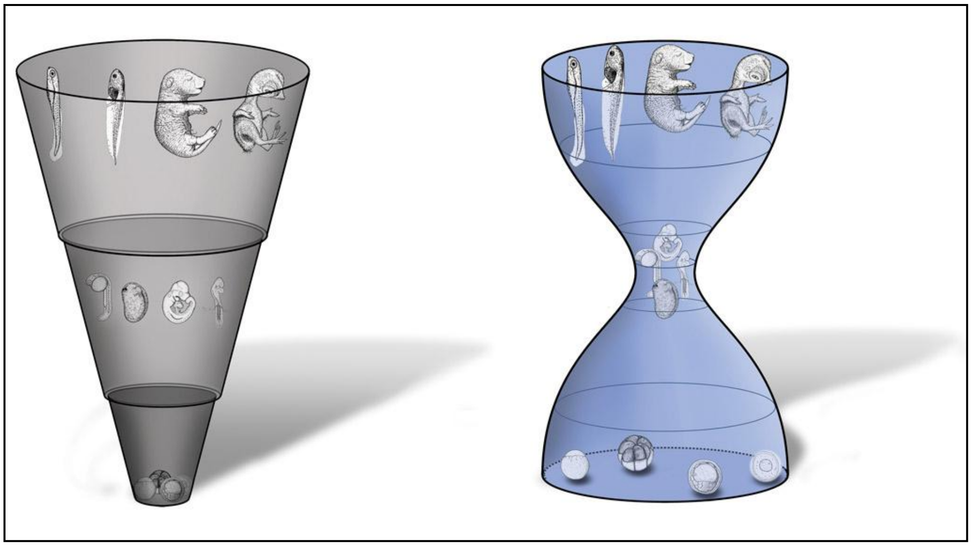


Figure 11. Funnel model of embryonic development (left) vs. hourglass model of embryonic development (right). From “Comparative Transcriptome Analysis Reveals Vertebrate Phylotypic Period during Organogenesis” (p. 248). By N. Irie and S. Kuratami, 2011, *Nature Communications, 2*.

The conserved stage, whether it be in the funnel model or hourglass model, is called the phylotypic stage, or when all members of the same phyla resemble one another. The phylotypic stage results from the conservation of developmental gene expression (Slack, Holland, & Graham, 1993). The question that Richardson’s study posed was, is there such a thing as a readily identifiable conserved stage where all species have the same general morphology? The number of vertebrate embryos used for earlier embryo conservation studies was small and consisted of familiar laboratory animals that hardly approached the diversity of vertebrate embryos. Richards set out to rectify this by using a large number of organisms and photographing the embryos at the tailbud stage, a time when the tail appears just visible, marking the near end of somite formation in the trunk region of vertebrates.

The various same-stage embryos of fish, amphibians, reptiles, birds, and mammals, in all 41 embryos of all vertebrate classes, showed many differences during the tailbud stage, including size, somite number, and pharyngeal arch number. The researchers concluded that the tailbud stage did not represent the conserved stage depicted in the hourglass model. Richardson also pointed out how inaccurate Haeckel's drawings were and that the funnel model, which Haeckel's work would have supported, was suspect. Richardson added himself to the long list of Haeckel critics with his statement, "Our survey seriously undermines the credibility of 'Haeckel's drawings' which depict not a conserved stage for vertebrates, but a stylized amniote embryo" (Richardson et al., 1997, p. 91).

Pennisi's claim of fraud.

The work by Richardson, especially his strong words for Haeckel, was picked up by mainstream media and religious conservatives. Shortly after Richardson's paper was published, science writer Elizabeth Pennisi (1997) wrote of Richardson's accusations, namely that Haeckel sometimes omitted features, neglected to name the species of his embryos, and fudged the sizes of his embryos. In her article, "Haeckel's Embryos: Fraud Rediscovered," Pennisi writes "It looks like it is turning out to be one of the most famous fakes in biology" (p. 1435). The article included a crude grid, with Richardson's photos running along the top, and Haeckel's corresponding embryo drawings below (see Figure 12). It is unclear why the salamander picture is twice the size of Richardson's other photographs. In the same article, embryologist Scott Gilbert tried to soften Pennisi's tone by acknowledging that Haeckel's embryo drawings had long been suspect, but perhaps more importantly, Gilbert said, the Richardson study showed that scientists must pay as much attention to differences as well as to similarities among species.

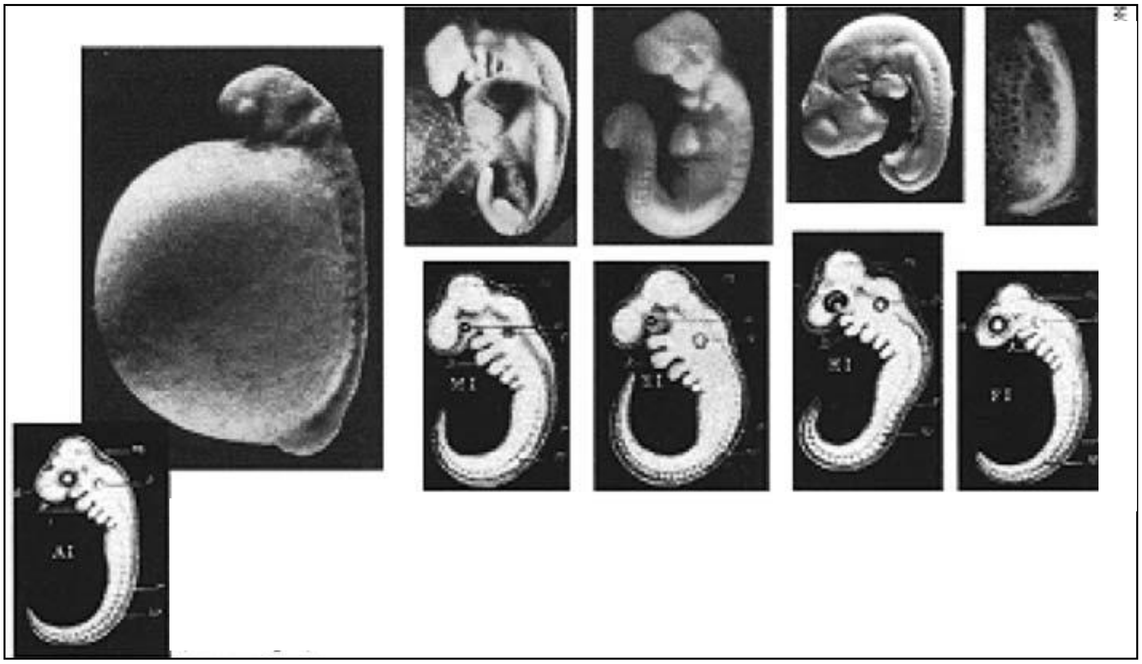


Figure 12. Richardson and Haeckel's embryos. Top photos (Richardson, 1997) and bottom drawings (Haeckel, 1874) of similar stage embryos: salamander, human, rabbit, chicken, and fish (left to right). From "Haeckel's Embryos" Fraud Rediscovered" (p. 1435). By E. Pennisi, 1997, *Science 277*(5331).

Jonathan Wells and science education.

One of the persons profiting the most from Richardson's study and the subsequent renewed charges of Haeckel's malfeasance is Jonathan Wells, a fellow at the Discovery Institute in Seattle, Washington. A holder of higher degrees in theology and developmental biology, Wells used the Richardson study to begin a new round of Haeckel criticism with a 1999 article "Haeckel's Embryos and Evolution: Setting the Record Straight" published in *The American Biology Teacher*. Wells criticized Haeckel like many before had done. In particular, he drew upon some of Richardson's findings to help "set the record straight" as his article title implied.

Wells' accusations were directed against Haeckel's choice of embryos and the stages that Haeckel drew. In effect, Haeckel was accused of cherry-picking embryos to fit with his idea of recapitulation. Wells criticized Haeckel for not using jawless fishes, selecting a salamander rather than a frog to represent amphibians, and disregarding non-placental mammals. The embryos that Haeckel did use, Wells wrote, were not drawn at the earliest of stages, cleavage and gastrulation, because embryos at these stages show wide differences in morphology, rather than similarities.

Wells then called for an end to using Haeckel embryo diagrams in science classrooms, stating that the pictures were unreliable and students who were taught that Haeckel's embryos serve as evidence for evolution may "later learn that teachers misrepresented the facts, [and] may feel betrayed by their former biology teachers and develop a distrust of science in general" (Wells, 1999, p. 349).

Letters to *The American Biology Teacher* concerning Wells' article included many that supported Haeckel and felt that any evaluation of Haeckel's work should incorporate the context of when Haeckel worked (for example, see Blackwell, 2001; Freeman, 2001a & 2001b; Sonleitner, 2001). Wells' article in *The American Biology Teacher* appeared at a time of renewed tension between those who dismissed the idea of giving creationism equal time in the classroom and those who believed it was only right to present creationism as an alternative "theory."

Wells further capitalized on this growing tension and wrote *Icons of Evolution*, published by Regnery Publishing in 2000. Figure 13 is an advertisement for Wells' book that appeared in *The American Biology Teacher*. The advertisement prominently displayed Haeckel's embryos and a quote from Stephen Jay Gould, "Many of our pictures are incarnations of concepts masquerading as neutral descriptions of nature" (Gould, 1989. p. 28). In *Icons of Evolution,* Wells identified Haeckel's embryos as one of several deceiving evidences for evolution and he accused textbook authors of deceit with their continued use of Haeckel's work in their texts. *Icons of Evolution* offered numerous quotes for the Discovery Institute and the myriad of websites run by Christian groups and anti-evolutionists. The book was harshly criticized by reviewers for its twisting logic and Wells' call for the federal government to stop funding evolutionary biologists (for example, see Coyne, 2001; Pickett, Wenzel, & Rissing, 2005) Whether Wells' accusations influenced decisions to continue using Haeckel's embryos in texts will be examined in my study.

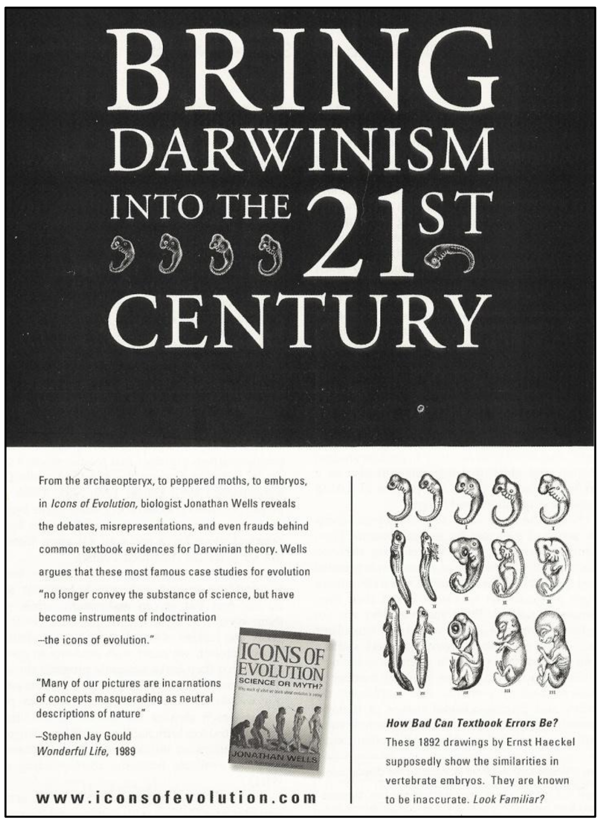


Figure 13. Advertisement for Wells' *Icons of Evolution* featuring Haeckel's embryos. From *American Biology Teacher* (p. 175), March 2001, 63(3).

Richardson responds.

It is doubtful that Michael Richardson and his colleagues set out to lambaste Haeckel so thoroughly that it would make the scientists appear allies to the intelligent design community. Between their study's conclusions and subsequent interviews with Elizabeth

Pennisi in 1997, that is exactly what happened. Richardson attempted to clarify his thoughts with an open letter to *Science* in May 1998, after his Haeckel statements were used in a televised debate to attack evolutionary theory. Richardson responded, stating that he and others, including Haeckel biographer Robert J. Richards, wanted to make clear that data from embryology supported evolution and that Haeckel was correct on several accounts. Haeckel was wrong though, Richardson wrote, on implying that there is little evolutionary change in early vertebrate embryos (Richardson et al., 1998).

Perhaps in response to media articles (for example, see Glanz, J., *New York Times* April 8, 2001 article "Biology Text Illustrations More Fiction than Fact"), the capture of Richardson's study by the intelligent design community, or his participation in the *Haeckel and Modern Biology* symposium held in Jena in 2001, Richardson followed up again on his comments about Haeckel in the early 2000s. Richardson and fellow biologist Gerhard Keuck wrote a short review in *Nature* (Richardson & Keuck, 2001) and a 33-page article in *Biological Review* that reexamined Haeckel's work. The *Nature* commentary made the case that Haeckel and his rival, Wilhelm His, both used liberty when it came to embryo drawings. Richardson and Keuck pointed out that Haeckel altered his drawings to support his theories and "therefore, these are not legitimate schematic figures" (p. 144).

In their *Biological Review* article, Richardson and Keuck identified three uses of Haeckel's embryo drawings: proof of evolution, recapitulation as proof of Haeckel's Biogenetic Law, and phenotypic divergence as proof of von Baer's law. They acknowledged that Haeckel's embryo drawings became more accurate over time, that Haeckel responded to criticism about uniform sizing, and that the German embryologist became more consistent in telling his readers which of his embryos were scaled differently from other embryo drawings.

In the same article, Richardson moderated his view of Haeckel, claiming that Haeckel was still relevant to comparative embryology, especially in light of new research that emerged in the area of conservation of early development (Richardson & Keuck, 2002, p. 497). The authors reviewed Haeckel's Biogenetic Law and explained why some current researchers were not so quick to dismiss Haeckel. Presently, there is a building of modern scientific support for parts of Haeckel's law, as it seems obvious that there is some degree of parallelism between ontogeny and phylogeny. Ontogeny does not recapitulate phylogeny, but the two processes do appear to have connections (Prud'homme & Gompel, 2010, p. 768; Richardson & Keuck, 2002, p. 501).

Richards responds to Richardson.

In 2009, Haeckel biographer Robert J. Richards of the University of Chicago, who also participated in the 2001 *Haeckel and Modern Biology* symposium, responded to Pennisi's 1997 *Science* article that claimed Haeckel a fraud. Richards took Richardson to task over several things. First, Richards argued that Pennisi and Richardson denigrated Haeckel for his focus on embryo similarities when in reality, even Haeckel's most vocal critic, Wilhelm His also exaggerated similarities in his own drawings.

Second, Richards addressed Richardson's statement that Haeckel fudged the scale of his embryos. Richards pointed out that Haeckel often indicated when images were scaled up or down to facilitate ease of comparison (Richards, 2009, p. 149). Richards also drew attention to the photographs used in Pennisi's article. Here, photographs of the salamander, fish, and human embryos showed large bulges, which exaggerated the differences between the photographs and drawings. In addition, the chick embryo photo appeared in a tucked position rather than Haeckel's less-tucked chick embryo illustration. Richards attributed this to Richardson's use of a chick embryo that was slightly older than Haeckel's chick embryo. In Figure 14, Richards compared Richardson's photos and Haeckel's drawings with the yolk sacs of the salamander, fish, and human digitally removed. Richards also straightened Richardson's chick embryo and reduced the size of the salamander picture.

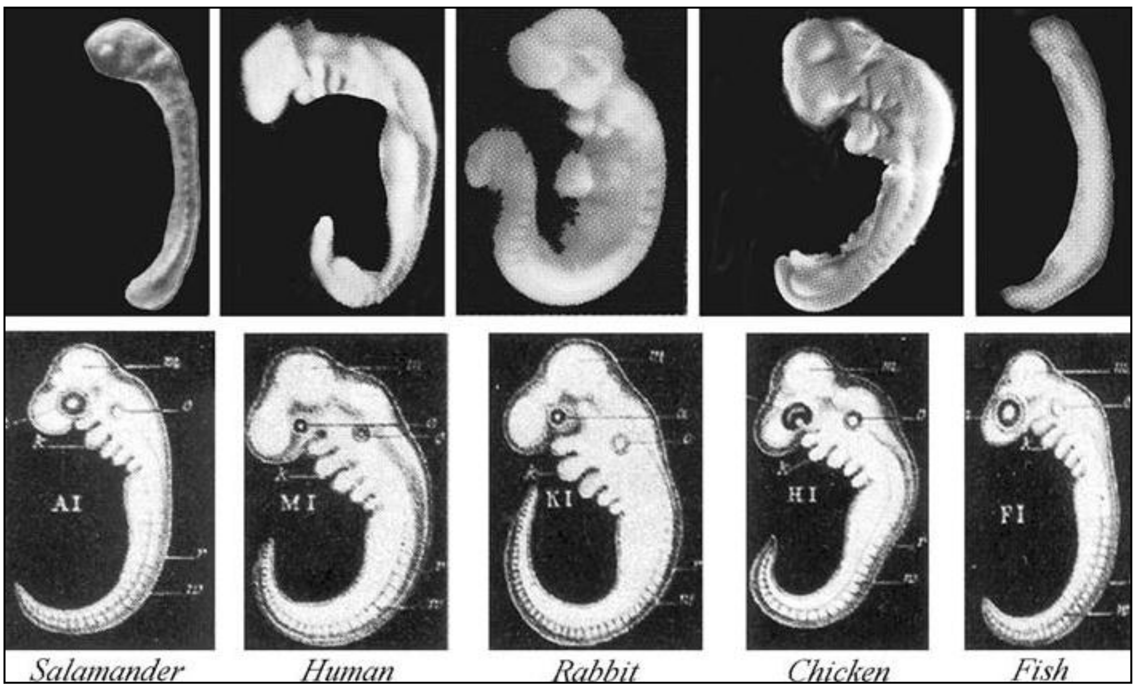


Figure 14. A comparison of Richardson's photos and Haeckel's illustrations with the yolk sac of the fish, human, and fish removed and the chick embryo straightened. From "Haeckel's Embryos: Fraud not Proven" (p. 152). By R. J. Richards, 2009, *Biology and Philosophy*, *24*.

Stephen Jay Gould.

Intelligent design proponents such as Michael Behe readily incorporated Richardson's comments about Haeckel and his embryo drawings into various publications and websites. Their arguments became more boisterous when a 2000 article written by

Stephen Jay Gould appeared in *Natural History* as “*Abscheulich!*” (Atrocious). Gould acknowledged that he wrote his article in response to “recent commentary” and a letter written to Gould by Michael Richardson in 1999. Gould hoped to clarify some of the attacks on Haeckel and evolution, based on historical misapprehension and creationist misuse of Richardson’s 1997 study. But, if one were prepared to see Gould defend Haeckel, he or she would be greatly disappointed. Gould wrote that Haeckel exaggerated similarities while disregarding embryo differences and that Haeckel was fraudulent in simply copying the same figures over and over again (Gould, 2000).

Gould scolded textbook authors for taking shortcuts and allowing Haeckel’s drawing to enter biology books. Once information such as Haeckel’s drawing becomes entrenched in texts, Gould wrote, the drawings contribute to the “dumbing down” of students. Gould praised Richardson for directing new attention to Haeckel’s old problem and remained astonished and ashamed by the repeated use of Haeckel’s “phony” embryo drawings in modern biology textbooks. He also took sensationalist science writers and Behe to task for using Richardson’s work as evidence that variation in embryos weakens the idea of evolution.

Distinguished biologist John Moore (1993) believed that Haeckel stepped over his bounds with recapitulation but his tone is softer than Gould’s. Moore emphasizes that Haeckel did not have a “molecular advantage” and did the best with what was available to him. What is rarely discussed, Moore says, is that Haeckel’s approaches gave him predictive power. After studying embryos and fossils, Haeckel correctly predicted that intermediate forms of life, in the shape of fossils, were waiting to be discovered and would link the evolutionary history of apes with that of humans.

In summary, Haeckel and his embryos have undergone a long and circuitous path. Haeckel's illustrations were initially successful in the public eye because they presented theories and laws (e.g., evolution and the Biogenetic Law) through vivid and nontechnical illustrations (Ludwig, 2013, p. 149). This success, though, eventually wore off and Haeckel's ideas about recapitulating embryos were challenged by internal circles of scientists and external circles of science writers, book authors, and creationist and intelligent designers. One might think that the long-tarnished image of Haeckel's embryos would find no place in the quasi-scientific world of biology textbooks. We know, however, that this is wrong.

Section III. Twentieth Century Biology Textbook Publishing

Before 1900, there was no such thing as a standard American high school biology course. If you wanted to learn about insects or frogs, you went to a museum or collected these organisms in their natural settings. This changed when biology became a formal school subject in the U.S. in the early 1900s and textbooks became a vital component of the biology classroom. The authors of the first generation of textbooks made decisions about what they thought was important or not so important for students to learn. Textbooks also took certain directions based on the cultural norms of the writers, publishers, and users who created, distributed, and read the textbooks. The complexity of what students should learn has led to lead to a rich history of decision making and direction taking.

Science educator Joseph J. Schwab, an original member of the Biological Sciences Curriculum Study (BSCS), divides high school biology texts into three phases. The first phase extends from the initial delivery of texts in 1900 through 1929. These early biology texts were entirely descriptive with many basic facts about plants and animals and later, physiology. The material, however, did describe current research and findings in the area of biology. This is most evident in chapters about public health and the copious number of graphs used to show how vaccines prevented disease or how research on the effects of alcohol on the brain resulted in fatal car accidents. These subjects were intensely value laden, with the intent to make students, many of whom were recent immigrants, good American citizens (Pauly, 2000, p. 171).

In Schwab's first textbook phase, authors of biology textbooks were predominately New York State high school teachers like George Hunter, Benjamin Gruenberg, and William Smallwood. The proximity of the authors to each other and to science powerhouse institutions like Columbia University and the Rockefeller Institute allowed for collaboration and interaction (Shapiro, 2013). College biology professors were typically not involved in writing high school textbooks, but they did influence their students, some of whom went on to become teachers. College professors also sat on many curriculum committees during the early 1900s (Hurd, 1961, p. 158).

Textbook authors, in addition to living near each other, were often located close to east coast publishers such as Macmillan and the American Book Company (ABC) in New York City and Ginn Publishing in Boston. In this environment, textbook authors worked on a personal basis with these large publishing companies and some sat on committees that would shape the state's biology syllabus (Pauly, 2000, p. 173). In this way, teacher/writers were the first to know what needed to be included in their own textbooks. Prior to 1925, evolution was not a major element in most classrooms and biology syllabi. Darwin's work ended up marginalized in texts because of the historical nature of the subject—evolution just did not fit well with the theme of observational and experimental biology (p. 191). The descriptions of natural selection often served as only a partial explanation of evolution and more often, only discussed as the foundation to improve crops and cattle (Ladouceur, 2008, p. 455).

These early biology textbook authors wrote for a familiar audience, namely biology students who sat in front of them day after day. The authors emphasized a scientific worldview with current and descriptive biology for college preparation and because the teachers shared a set of norms, their texts often read similarly. Shapiro cautions against viewing textbook production as a product of a single community of progressive science teachers. Another community that influenced what went into textbooks was the textbook salesmen who competed against one another to sell their company's line of texts. Recommendations given back to the publishers, by the salesmen, often made their way back to the textbook writers too. Usually, the recommendations were ignored by the writers, but not by the publishing company (Shapiro, 2008, p. 43).

Schwab's second phase of American biology textbooks begins in 1930 and continues to 1957. Textbooks remained descriptive but with less emphasis on keeping the field of biology current. Rather than the text looking like a college prep book, biology texts were now organized in a manner recognizing that (a) not all biology material was developmentally appropriate for high school students, and (b) biology should help students become smart citizens. As teacher education programs severed ties with college science departments, pre-service science teachers spent less time in college biology laboratories and more time in education courses and classrooms. State and local education committees saw university and college professors leave their positions (Hurd, 1961, p. 158), and professional biologists' influence on high school biology curriculum waned. Most biologists did not embrace these changes to biology education. Zoologist Oscar Riddle summed up what many felt when he wrote about a growing sentiment that biology was now held on a leash, as Americans were "complacently drifting on or within the borders of anti-intellectualism" (Riddle, 1954, p. 184).

Schwab's third textbook phase, beginning in the early 1960s, resulted from an apprehensive awareness of the Soviet Union's technological prowess. Cold war fears helped the U.S. Congress pass the 1958 National Defense Education Act, which awarded grants to improve science literacy and to develop new textbooks in all areas of high school science. This of course is the beginning of the BSCS program. Here, teachers, scientists, and university educators were encouraged to collaborate in order to produce better materials for schools, in hopes to raise the bar higher for biology students (Green, 2012; Hurd, 1961).

Where Schwab's third phase ends is debatable because he wrote about the three phases in 1963, which put him squarely within the third textbook phase. I believe that the third phase might possibly have ended in the early 1980s, as textbook publishing companies consolidated, leading to only a few large publishing houses employing multiple authors to complete enormous biology texts.

In the early 1900s, textbooks were often identified not by their title, but by the authors who wrote them. For example, *Hunter's Elements of Biology* (1907) or *Moon's Biology for Beginners* (1921). Today, with as many as five or more authors per text, the publisher, rather than the authors is prominently connected with the text. For example, *Heath's Biology* (1991) or *Holt's Modern Biology* (2009) were produced by "teams of experts" because no single person has the knowledge (or the time) to produce textbooks that are thousands of pages long and cover so many subdisciplines in the ever-growing field of biology.

Evolution and early biology textbooks.

There is a long and contentious history of teaching evolution in American high school biology classrooms. The first attacks on textbook evolution did not make headlines until the 1920s, but certainly, there was a steadfast opposition to the teaching of evolution before WWI (Shapiro, 2013). By the end of WWI, a perceived decline in morality and a desire to return to simpler lives saw an uptick in religious fundamentalism (Moore, 1998a; Numbers, 1998). Meanwhile, people across the U.S. were leaving their farms and small towns for urban areas. For the first time, there were now more people living in cities than rural areas. Textbook publishers recognized a growing urban market and began offering different biology textbooks by the same author. For example, George Hunter's *New Essentials of Biology* (1923), written for rural classrooms, was marketed alongside the more urban and public health oriented *A Civic Biology* (1914) (Shapiro, 2008, p. 426).

As Christian fundamentalists linked the perceived growing immorality in the U.S. to Darwin's theory of evolution, the stage was set for a growing antievolutionism movement. While fundamentalism grew, so too did the expansion of compulsory public education, the development of secondary biology curricula, and state control over curriculum design. I also add a change in the teaching of evolution. Prior to the mid-1920s, textbooks that addressed evolution did so by embedding an exaggerated version of natural selection into discussions involving social Darwinism and eugenics (Clausen, 2012; Green, 2012). In the 1920s, new findings in genetics and inheritance changed the way that evolution was discussed as authors added information about evolutionary ancestors and how natural selection might work on a cellular level (Green, 2012). With Darwin's theory of evolution now seemingly everywhere, antievolution activists soon targeted the teaching of evolution in anthropology, geography, history, sociology, and psychology, as well as biology (Lienesh, 2012, p. 687).

Evolution, biology, and a disenfranchised rural South all came together in 1925 with the well-known Scopes Trial in Dayton, Tennessee. Many individuals have researched and written about the trial, including Edward J. Larson (*Trial and Error* and *Summer for the Gods*), Peter Bowler (*Monkey Trials and Gorilla Sermons*), and more recently, science historian Adam Shapiro (*Trying Biology*). These authors allude to the idea that the trial, in which high school teacher John Scopes was accused of violating Tennessee's Butler Act (making it a crime to teach evolution of man in public schools), was based more on whether or not a state had the right to prescribe a curriculum for its students than on the actual teaching of evolution (Larson, 1997; Schapiro, 2013).

Before the Scopes trial, some Southern states had enacted state-level uniform textbook adoption to protect citizens from price fixing and corruption in the form of textbook adoption kickbacks to school districts. States could choose a more traditional rural biology textbook or they could adopt a more progressive and urban text that usually focused on public health and eugenics. According to Shapiro, when it became a law that all children should attend school, rural residents saw forced education as an infringement upon their rights. Rural residents, if they took the time to look at Hunter's *Civic Biology* or Gruenberg's *Elementary Biology*, may have noticed how biology was intertwined with urban society rather than their traditional rural lifestyle. The combination of mandatory schooling and biology textbooks focused on city life, created tension between urban and rural residents, creationists and evolutionists, and state's rights versus federal oversight, leading to the commencement of the Scope's Trial (Shapiro, 2008).

In the much followed trial, Scopes was found guilty of teaching evolution (his verdict was soon after reversed on a technicality), and the antievolution movement, which was already influencing textbook publishers and authors before the Scopes trial, picked up steam. Immediately after the Scope trial decision, areas in Mississippi reported the burning of texts and pages torn from texts containing evolution information. The Moody Bible Institute urged its followers to boycott any school that taught evolution (Moore, 1998b), and Texas governor Miriam Ferguson ordered the state textbook Commission to recommend only biology books with no discussion about evolution (these sanitized books are identified with a "Texas version" in their titles).

Throughout the 1920s, state legislatures introduced a myriad of anti-evolution laws. Tennessee, Arkansas, Louisiana, Mississippi, and Oklahoma all passed laws making it illegal for schoolteachers to teach evolution in their classrooms (Moore, 1998b). However, by 1927 the call for state's rights and anti-evolution bills declined. Political scientists Berkman and Plutzer (2010) attribute this decline mainly to the onset of the Great Depression (p. 16).

Historians grapple with the question of what effect the Scopes Trial had on biology textbooks. In a groundbreaking 1974 study, Judith Grabiner (now the Flora Sandborn Pitzer Professor of Mathematics at Pitzer College, California), and her graduate student Peter Miller, compared the prevalence of evolution in biology texts published before and after 1925. They found that books published before 1925 usually had the term "evolution" in the index, even if discussion of evolution in the text was minimal. After 1925, some books continued to discuss evolution, but the word "evolution" was no longer in the index or the table of contents (Grabiner & Miller, 1974, p. 833).

According to Grabiner and Miller, the most widely used biology text after the Scopes Trial and throughout the 1930s was Arthur O. Baker and Lewis H. Mills' *Dynamic Biology* (Grabiner & Miller, 1974, p. 834). In this text, evolution was carefully tucked away in the last chapter of the book (there were no Haeckel embryo drawings), but the word "evolution" was not in the index or the glossary. Interestingly, fossil evidence was provided to show how animals had changed over time, but the authors ended the "Changing Forms of Living Things" chapter with the statement, "Darwin's theory, however, like that of Lamarck, is no longer generally accepted (Baker & Mills, 1933, p. 681). Grabiner and Miller believe that Darwin's decline in textbooks was partially the fault of scientists who were not paying attention to high school science.

Ladouceur (2009) believes that Grabiner and Miller overstate the impact of *Scopes* on decisions to not to include evolution in textbooks, especially during the 1930s. Rather than drop evolution outright, Ladouceur claims that authors wrote around evolution and learned how to substitute the word "evolution" with weak synonyms like "progressive development" and "biological change." An in depth analysis of these types of "write-arounds" might show that *Scopes* actually had a minor impact on textbook revisions.

Today's biology texts.

Who currently decides what is important for biology students to learn? Is it scientists, publishers, textbook authors, or school boards? Every state has its own method of textbook adoption. Many states allow school districts to pick from a state-selected list (Tobin & Ybarra, 2008). Books on the list have passed through committees to see that state standards are met and public comment has occurred. Textbooks are expensive to make and if a publisher's book does not make the state-selected list, the publisher makes make no profit. It has become so increasingly expensive for publishers to get their books into classrooms that they have to try to keep everyone happy—to offend various user groups is self-defeating.

In the spirit of competitiveness, one might think that certain texts would rise above the rest. But, in Harriet Tyson-Bernstein's (1988) book, *A Conspiracy of Good Intentions*, she argues that what is in the best interest of the student is often not what is in the best interest of the publisher. With California and Texas driving the adoption of texts, small groups within these two states manage to influence what goes in, and what is left out, before state approval occurs. This leads to books that are "provocative but not so different as to be controversial" (Nelkin, 1977, p. 22). Because the publishing industry's prime interest is sales, an almost impossible task is created: publishers must make their textbooks stand out in some fashion, yet their texts must be standardized sufficiently to attract the largest possible share of the textbook market.

Another aspect of textbook publishing is volume. Biology textbooks have always presented a great deal of content, but in trying to stuff more and more content into larger and larger biology textbooks, publishers commit a pervasive sin called "mentioning," a term coined by literacy researcher Dolores Durkin (1992). Mentioning refers to writing that quickly reads from fact to fact, and topic to topic, without giving students the necessary context to help make sense of the concept and why the concept is important to know about. For example, a text might display Haeckel's embryos without any information about why the embryos are important evidence for the theory of evolution by natural selection. While the goals of my study do not include a complete pedagogical analysis of biology textbooks, the fact that there are so many outside forces acting upon the publication of textbooks will undoubtedly factor in on how Haeckel's embryo drawings are presented to students.

Four textbook series.

In addition to looking at a large number of biology texts written by different authors, I will also examine multiple editions of four series of texts. The use of "same texts, different editions" may help identify levers where the use of Haeckel's diagrams changed for a particular author or a particular publisher. The authors are George W. Hunter (1873–1948), Truman J. Moon (1879–1946), Ella T. Smith (1897–1972), and BSCS texts, published from 1963 through the present and written by various authors, all under the umbrella of "BSCS authors."

George W. Hunter (text series 1907–1955).

Historian Philip J. Pauly examines textbooks and the development of high school biology in *Biologists and the Promise of American Life* (2000). In his chapter "The Development of High School Biology," Pauly attributes the growth of high school biology curricula in the early 1900s to three prominent educators at DeWitt Clinton High School in Manhattan. The teachers, Henry R. Linville, Benjamin C. Gruenberg, and George W. Hunter were each highly educated and individually undertook writing biology texts that reached a wide number of American classrooms. Of the three, Hunter is considered most influential in terms of textbook writing (Ladouceur, 2008; Pauly, 2000) and teacher education—his longevity in the field of American science education lasted for over fifty years (Webb, 1948).

Hunter was born in Mamaroneck, New York in 1873 and began his undergraduate career at Williams College in Massachusetts. After graduating with a bachelor's degree in biology in 1895, Hunter spent the next summer at Woods Hole Marine Biological Laboratory. Hunter then attended the University of Chicago and worked with Charles O. Whitman who encouraged him to study the anatomy and cytology of tunicates. Hunter began his teaching career in the zoology department at the University of Chicago and at Chicago's Hyde Park High School. Although he did not receive a degree from the University of Chicago, Hunter was well prepared in biology to begin a twenty-year high school teaching career at DeWitt Clinton High in New York City. He eventually obtained a PhD from New York University in 1918 and shortly thereafter left secondary schools to teach science education at several colleges.

The American Book Company (ABC) published all of Hunter's books, from his first high school biology book, *Elements of Biology* in 1907 to his last biology text *Biology in our Lives* in 1955. In all, Hunter wrote fourteen biology texts, with an array of titles. He also collaborated with other writers to publish general science texts and teacher education materials and played an instrumental part in publishing *Biological Abstracts* in the 1930s. Hunter was an early advocate of the use of educational filmstrips, especially those using time-lapse photography to show cell division. He urged fellow educators to toss aside their skepticism about the usefulness of film, and accept films as valid tools for learning (Peterson, 2012, 155).

Hunter is perhaps most famous for his 1914 text, *A Civic Biology*, used by a majority of students nationwide, including students in rural Kentucky, even though ABC originally intended this text for a more urban audience (Shapiro, 2008, p. 413). *A Civic Biology* addressed Darwin's theory of evolution by claiming that evolution was the progression of primitive organisms to advanced organisms and that Caucasians were the most advanced of any of the five human races (Weiss, 2007, p.127). Hunter's 1914 text is one of the first to include discussion of euthenics (improving one's environment by selecting a good mate) (Selden, 1999, p. 63).

A Civic Biology was at the center of the 1925 Scopes trial because teacher John Scopes used *A Civic Biology* in his biology classroom. Authors Larson and Shapiro discuss Hunter's text in detail, but the actual content of Hunter's book was hardly referred to at all during the trial (Weiss, 2007, p. 127). This may be because, after my own examination of *A Civic Biology*, there are no Haeckel embryo grids and little is written about evolution, only short paragraphs titled "The Doctrine of Evolution," "Evolution of Man," and "Charles Darwin and Natural Selection." On the other hand, there is a great deal written about cultural eugenics, that is, improvement of the human race through better breeding.

The 1926 edition of *A Civic Biology* had a slight title change—the book was now called *New Civic Biology*. In this post-Scopes edition, the paragraph "The Doctrine of Evolution" disappeared and the word "evolution" was removed from the index. The paragraph on "Evolution of Man" was changed to "Development of Man" and Charles Darwin was discussed in a chapter "Great Names in Biology." Hunter credits Darwin with the study of heredity and the development of life on Earth, but there is no mention of the concept of evolution anywhere in the text.

Truman J. Moon (text series 1921–present)

Moon attended Cornell University, completing his B.S. in 1903. Immediately after graduation, Moon moved closer to New York City, spending the latter half of his life as vice-principal and head of the Science Department at Middletown High School. Moon's first biology text was *Biology for Beginners*, published in 1921. Moon's first book was not widely sold, although later versions of his books became increasingly popular with classroom teachers. Like Hunter, Moon was a prolific textbook writer. Unlike Hunter though, who wrote many biology books with different titles, Moon quickly settled on one title, *Modern Biology* (starting with his 1947 text), and stuck with it.

Moon's *Biology for Beginners* and the subsequent *Modern Biology* is the longest running biology textbook series with the newest, seventeenth edition of *Modern Biology* published in 2009. Moon originally worked with the publishing company Ginn, but in 1933, Henry Holt overtook publication. Holt remains the current publisher of *Modern Biology.*

Later co-authors of *Modern Biology* include Paul Blakeslee Mann, James Howard Otto, and Albert Towle. Mann (1876–1943) was born in Potsdam, New York and received a B.S. and M.S. from Cornell University in the early 1900s. He began work as a high school biology teacher in 1904 at Morris High School in Bronx, New York and taught evening biology classes at City College. Mann served as president of the New York Association of Biology Teachers and was an AAAS fellow. He became a co-author with Moon in 1933 with the third edition of *Biology for Beginners.*

James Otto attended Butler University in Indianapolis, where he received a B.S. in 1934 and a Master's degree in 1938. He served as the head of the science department at George Washington High School in Indianapolis from 1940 until his death in 1972. Otto served on the Scientific Advisory Editorial Board for the journal *Evolution: A Journal of Nature*. Otto joined Moon and Mann in 1947 as a co-writer of *Modern Biology.* Otto is credited with significantly revising Moon's text and dropping discussion about cultural evolution, but *Modern Biology* with Otto as the lead author continued to discuss eugenics in the form of IQ testing and accepting one's "fixed" heredity (Selden, 2007).

In 1963, biology teacher Albert Towle replaced Paul Mann (Mann's name had remained on the masthead even though Mann died in 1943). Towle taught biology at James Lick High School in San Jose, California before becoming a biology professor at San Francisco State University. He died in 2002. Since then, *Modern Biology* has been written by teams of writers led by I. Edward Alcamo with 2002's *Modern Biology* and most recently, John H. Postlethwait as lead author for the 2006 and 2009 editions.

To say that *Modern Biology* has been profitable for Ginn and Holt would be an understatement. In the long list of biology textbooks published in the U.S., many have only been published once. The fact that many biology texts have only one publication run is a direct reflection of the inability of texts to capture enough lucrative market shares. After WWII, biology texts entered a very competitive market phase, as the number of biology texts available exploded in number during the 1950s and 1960s. Even with more texts to compete against, *Modern Biology* continued its hold on the textbook market.

Grabiner and Miller gave special attention to Moon's *Biology for Beginners* (now *Modern Biology*) in their 1976 study, which examined texts for evolution content. They wrote that Moon's 1926 *Biology for Beginners* served as a prime example of how fundamentalist pressure, stemming from the Scopes Trial in 1925, changed the delivery of evolution to students. According to the researchers, Darwin's presence and the idea of evolution in *Biology for Beginners* were both downplayed (Grabiner & Miller, 1974, p. 833). From my own examination of the 1921 and 1926 editions of *Biology for Beginners*, I feel that Grabiner and Miller overstated their observations. Moon always was and remained a proponent of evolution, and his texts do discuss evolution. In fact, both 1921 and 1926 editions of *Biology for Beginners* include embryological resemblances as evidence for animal relatedness. Although a Haeckel embryo drawing is not present, Moon states, "certainly, if animals were not related, they would not repeat the structure of lower types as they develop into their final form" (Moon, 1921, p. 322; Moon, 1926, p. 360). In his 1921 and 1926 editions, Moon wrote that evolution and religion could peacefully coexist, probably in response to the creationist mood of the country at that time.

Ella T. Smith (text series 1938–1966)

Ella Thea Smith was born in 1897 and raised in a Quaker household in Salem, Ohio. She did well academically and received a B.S. in botany from the University of Chicago in 1920. Smith's biography is short, but one wonders whether she studied with embryologist Frank R. Lillie while at Chicago. Upon graduation, Smith returned to her home town of Salem where she taught high school biology until 1956. Smith retired to Cave Creek, Arizona where she died in 1972.

Like many teachers in the early 1900s, Smith relied on her own college notes to help teach high school students. Smith piecemealed her biology notes together and in 1935, the superintendent of Salem's schools showed Smith's biology notes to a Harcourt and Brace textbook salesperson. Within four weeks, Harcourt and Brace, which had not published a high school textbook in over a decade, convinced Smith that her notes should be edited and published for nationwide distribution (Ladouceur, 2008, p. 446).

Smith's first text, *Exploring Biology* was published in 1938 and was positively reviewed by Carleton E. Preston in "The High School Journal." Preston found Smith's work easy to read, well written, and he praised it for portraying the big picture of biology rather than facts stacked upon facts (Preston, 1939, p. 304). Smith's first text is but one out of a handful of biology texts that discussed evolution in the late 1930s. Shortly after its first publication, *Exploring Biology* was adopted for citywide use by the Detroit and Atlanta school systems and statewide adoptions were made by the state education boards of Oregon and Kansas (Reid, 1969).

Smith formatted *Exploring Biology* differently from texts written by Hunter and Moon. Contrary to many textbooks at the time, Smith did not organize her book phylogenetically. That is, she did not start her text with lower organisms like bacteria and worms, and progressing up to separate chapters on higher animals and humans. Smith wove organisms together and placed less emphasis on progressive evolution by suggesting that all species were different, but not necessarily inferior or superior (Ladouceur, 2008, p. 457).

Biology teachers quickly embraced the first editions of *Exploring Biology*. Bentley Glass, who later became the first chairman for BSCS, gave a glowing review of Smith's 1945 edition of *Exploring Biology*, declaring, "no one but a high school teacher of a most exceptional character could have written this book. Other high school teachers should give it an enthusiastic reception" (Glass, 1945, p. 169).

Glass also reviewed Smith's 1949 edition of *Exploring Biology*, noting that the text was updated with the dangers of radiation and the "understanding of evolutionary mechanisms" (Glass, 1949, p. 227). Glass was not so admiring of Smith's competition, the 1947 edition of *Modern Biology* by Moon, Mann, and Otto. For example, Glass wrote that while Moon discussed embryos as evidence of evolution, there was no story of embryonic growth and development. Glass also criticized Moon's use of the "dubious hereditary defects of the Jukes and Kallikaks," a sideswipe to *Modern Biology's* eugenics emphasis (Glass, 1948, p. 44).

While Smith was not reading reviews written about her *Exploring Biology* texts, she wrote reviews of other teachers' works for *The Quarterly Review of Biology*. Smith was regarded as shy and retiring and shunned academic conferences, but she expressed herself well through her writing. From 1949 until 1954, Smith published 26 reviews of mainly textbooks or science books written for children and adolescents.

Smith and *Exploring Biology* are the focus of a recent study by Ronald Ladouceur in which he contends that BSCS committee members overgeneralized when they stated that 1940s and 1950's textbooks did not adequately address the theory of evolution. Ladouceur uses Smith's *Exploring Biology* to contradict the notion that textbooks published prior to 1964 removed evolution from its pages to appease Christian fundamentalists and anti-intellectuals. Not only was Smith the first author to present the modern evolutionary synthesis in her 1949 text (Ladouceur, 2008, p. 436) but she was also invited to join the steering committee of the BSCS in 1959. The chairman of the committee was Bentley Glass, who previously had given glowing book reviews of *Exploring Biology*.

Even with positive reviews by individuals involved with the BSCS project, Ladouceur and historian Lisa Anne Green point out that Smith's work was lumped together with all pre-BSCS biology textbooks and accused of giving into the pressure of religious fundamentalists. In fact, Smith always had, and continued to do so up until publication of her last edition of *Exploring Biology* in 1966, included a lengthy discussion of evolution and natural selection in her texts. The only *Exploring Biology* text in which evolution content decreased was the 1959 edition. Harcourt Brace admitted editing much of the discussion about evolution to make the text more competitive against Moon's *Modern Biology*, which was outselling all other high school biology texts during the 1950s (Green, 2012, p. 154; Ladouceur, 2008, p. 460). These criticisms leveled against Smith may have led her to resign from the BSCS steering committee in 1960.

BSCS (text series 1963–present)

The Biological Science Curriculum Study was established in 1958 by the American Institute of Biological Sciences (AIBS) and funded by the National Science Foundation (NSF). The intent of the BSCS was to update the content of secondary school biology, especially in the fields of molecular biology and the nature of science. This was of course, a time when Sputnik and the Cold War convinced Americans that the country's students needed to hunker down and study, or end up Red. Around the same time, the Darwinian Centennial Celebration of 1959 sought to popularize Darwin's work and to draw attention to the modern evolutionary synthesis.

After the BSCS organized itself, and with geneticist H. Bentley Glass as spokesperson, the BSCS committee declared that the central organizing feature of the BSCS textbooks would be evolution (Green, 2012, p. 17). Meeting these goals would require that the BSCS improve teacher education and produce new textbooks. The BSCS would also need to convince teachers, who often placed health, physiology, and human heredity at the top of their teaching emphasis lists, that the emphasis would now be placed on evolution, inquiry, and research rather than healthy living.

Reforming high school biology and retooling textbooks would prove challenging. Authors such as Ella T. Smith, George Hunter, and Truman J. Moon were practitioners—long-term high school biology teachers who used their notes, written in longhand to serve as the template for their first published biology textbooks (Ladouceur, 2008; Selden, 2007). They wrote in an era when a single person could conceivably keep abreast of biology research and edit biology texts along with having full-time teaching positions. And, it was not as if they had competition from university biologists. Well-known educational researcher Paul DeHart Hurd documents how professional biologists had little, if any involvement in developing high school biology curriculum from the 1920s to the 1950s. Without serious competition, many of the editions by Moon, Smith, and Hunter appeared suspiciously identical to previous editions. Moon, Mann, and Otto's *Modern Biology* and Smith's *Exploring Biology* were viewed by BSCS director Arnold B. Grobman as little better than a hodge-podge of biological facts with little coherency or integration of genetics and molecular biology (Rudolph, 2002, p. 142).

Partly due to this observation, BSCS promoted the use of scientists, rather than experienced teachers, for the writing of its materials. Science was moving at such a fast pace after World War II that it was proving difficult for almost anyone, including high school teachers, to remain up to date with new information and research. The Executive Committee of the BSCS made it clear that the primary responsibility of biologists hired by the BSCS was to transmit biology content to teachers who would then teach this content to students (Green 2012, p. 101). In addition, it was felt that high school teachers would lend little, if any prestige to the BSCS project. The greatest concern of the BSCS was echoed by Hermann J. Muller's belief that high school students be taught a more modern view of science and a more modern view of life (Green, 2012, p. 75).

Under the direction of Glass and zoologist Arnold Grobman, the BSCS program, centered at the University of Colorado at Boulder, set out to improve secondary biology teaching on all levels, with new textbooks, laboratory guides, filmstrips, and summer teacher institutes held on university campuses. Over the course of the 1960s, the BSCS was awarded over $7,000,000 to fund these secondary biology improvements (Nelkin, 1977).

Prior to the 1963 publication of BSCS' first commercially available texts, approximately 75 per cent of high schools were using either *Modern Biology* written by Moon, Mann, and Otto or *Exploring Biology* written by Smith (Engleman, 2002). The BSCS Steering Committee focused on publishing inquiry-based materials that it felt would distance itself from the descriptive texts available at the time. Outside observers and BSCS committee members agreed that most textbooks from the 1950s were "for all intents and purposes, reprints stripped of their energy and drive (Ladouceur, 2008, p. 455). What the BSCS textbook writers could not agree upon though, was what should go into a large, but single biology textbook. Differences among BSCS participants split along three lines: those who felt that cellular and developmental biology should serve as an overarching organizer; those who saw molecular biology as the future of biological research; and still others who saw the growing interest in ecology as the framework for a textbook.

The idea of writing a single biology textbook fell by the wayside, as teams of scientists, high school biology teachers, and editors assembled to write three introductory high school biology texts. The three texts would be differentiated by emphasis and color; the blue version had its emphasis on molecular biology, the yellow version on cell biology, and the green version on ecological communities. Even though each BSCS textbook had a different focus, BSCS scientists agreed that the modern evolutionary synthesis would be the common organizing principle behind all three texts (Green, 2012, p. 4). Another reason for three separate editions was to curb potential criticism from publishers and politicians who stood poised to accuse the BSCS committee of attempts to establish a single, national curriculum for biology (Webb, 1994, p. 131).

Scientist-writers who were paid to develop BSCS texts and materials had on their hands vast new changes that occurred in biology during from the 1950s and early 1960s. The field of embryology, for instance, had become part of the larger field of developmental biology and evolution was heavily supported by genetics and population biology. But, while developmental biology had become incorporated into high school biology textbooks, evolution maintained its distance. Many scientists working with BSCS echoed BSCS member Joseph Schwab's belief that "it was no longer possible to give a complete or even a coherent account of living things without the story of evolution"

(Schwab, 1963, p. 31), and they shared in his dismay that evolution was nowhere to be found in many high school biology textbooks.

In order to try to organize textbooks in some fashion, BSCS textbook writers used seven levels of organization: molecular, cellular, tissue and organs, organisms, societal, communal, and biome. The executive committee singled out two themes for fullest development—the nature of inquiry and the historical development of biological ideas—believing that this would help biology be recognized as a true scientific discipline, much like that of physics and chemistry (Schwab, 1963).

The *Biological Science: An Inquiry into Life—The Yellow Version* focused on development and cellular biology. The Yellow Version's primary author was John A. Moore, a Columbia University zoologist (Green, 2012, p 33). The Yellow Version curriculum is considered the most content oriented of any of the BSCS versions (Lazarowitz, 2007), which may explain why it was the one adopted by most schools and teachers in the U.S.—it did not appear too radical.

The *Biological Science: Molecules to Man—The Blue Version*, approached biology from a molecular biology and biochemistry standpoint. It was never a best seller, no doubt owing to the difficulty of the college-level content and the newness of the content for teachers to have to teach. Marston Bates, a University of Michigan zoologist already known for writing *The Forest and the Sea* in 1960, served as primary author for *High School Biology—The Green Version.* Written from an ecology perspective, the green version was adopted primarily in rural high schools throughout the U.S. (Engleman, 2002).

After testing draft texts and other teaching materials from 1961 through 1962, the BSCS was ready to move forward, but it needed publishers. Invitations were sent to publishing companies, asking them to place bids on the texts of their choice, but they did so knowing that there were certain constraints. In a novel idea, the BSCS retained the copyright to all of its materials, which meant that publishers could not change, delete, or add content to influence sales. Rand McNally was contracted to publish *High School Biology* (green version), Harcourt, Brace, Jovanovich became responsible for *An Inquiry into Life* (yellow version), and Houghton Mifflin published *Molecules to Man* (blue version).

By the end of 1963, BSCS textbooks sat in more than 50 per cent of American high schools (Mayer, 1989). Other textbook publishers quickly took note of their own sinking sales and following the age-old business model that success breeds imitation, they revised their texts to resemble the content, organization, and even color of the BSCS books. William Mayer, former director of BSCS, argues that some publishers weighed in against BSCS because of its threat to the status quo. Competing textbook companies planted the idea that BSCS was too big and that it would eventually become a national curriculum, all in itself. The BSCS texts were also not well received by fundamentalist Christian groups who were alarmed with a growing secularism in the U.S., much like the concerns they had in the 1920s (Larson, 1997, p. 249). Creationists, touting a decline in family values, started to reorganize in the U.S. with newly formed organizations such as the Creation Research Society. By 1973, sales of the *BSCS Green Version* made up 33% of the national sales; the *BSCS Yellow Version* made up 14%; and *the BSCS Blue Version* made up only 1%. About 49% of the sales went to *Modern Biology* (Lowery & Leonard, 1978).

The time span from about 1960 through 1975 was a period of innovation in science education. Molecular biology, genetics, and ecology became established as core content areas, influenced no doubt by early BSCS textbooks and laboratory guides. Federal money and support, however, proved short-lived. In 1975, the U.S. Congress withdrew all further funding for NSF-sponsored science curriculum development, in response to investigations showing loose oversight of BSCS budgets. Another reason for government withdrawal from the BSCS program was not that science education had finally reached its goals, but due to a growing concern about the inclusion of sex, reproduction, and evolution in the biology curriculum (Yager, 1982).

In the mid-1980s, state legislatures in the U.S. debated bills brought forth by creationists calling for the balanced treatment (or equal time) of evolution and creation science in public schools. In the 1990s, intelligent-design theorists (ID) sought to "teach the controversy" or in their words, to allow teachers to teach how evolution was fraught with issues and questions. The creationists and intelligent designers suffered many losses in courtrooms, including the U.S. Supreme Court. Their attention getting techniques however, including heated charges of fraudulent embryo pictures, which I will show, did not fall on the deaf ears of classroom teachers, administrators, or textbook publishers.

RESEARCH METHODS

Textbook images, including Haeckel's embryo pictures, possess a certain amount of intellectual inertia, or fixedness that may leave a lasting impression. With that in mind, I cataloged and coded Haeckel's embryo drawings in high school biology textbooks, along with embryo illustration captions and any accompanying paragraphs (deictic text) that explained the embryo illustration.

In addition to looking at a large number of texts written by dissimilar authors, I also examined a series of texts with multiple editions, written by the same authors, over a span of decades. This part of my study included biology textbooks written by George W. Hunter, Truman J. Moon, Ella Thea Smith, and BSCS committees. I hoped that the use of "same texts, different editions" would help identify periods where the use of Haeckel's diagrams changed, and could help further the discussion about the politico-social context in which Haeckel's embryos appeared, disappeared, or underwent alteration. That is, what events in history may have acted as "levers" to change the narrative that the authors and embryos were trying to tell?

The Textbooks

I analyzed 240 commercially developed high school biology textbooks (see Appendix) to determine how Ernst Haeckel's embryo drawings and other comparative embryo diagrams aided in the teaching of evolution by natural selection. I searched for texts with a publication date no earlier than 1900. This date marks the time when biology courses first became available for students in the U. S. and biology textbooks appeared on the market. Prior to this time, students chose from yearlong courses in anatomy and physiology, zoology, and botany to fulfill their science requirements. The textbooks for these courses were not designed for a general biology class, so I opted not to examine them.

Based on time period and accessibility, the oldest textbook I examined was published in 1907 and the most recent biology text was published in 2010. All other texts fell into a range between these two publishing dates. A decision to use textbooks published only before or during 2010 provided me with a slight social and intellectual distance from the texts.

Haeckel's Embryos

One of my goals was to catalog the use of Haeckel's embryos and to describe how authors and publishers used the diagrams to support the theory of evolution, including the idea that organisms show evidence of their evolutionary ancestors in their embryonic development. I was also interested to see if the organisms originally used by Haeckel in his diagrams had changed over time, including Haeckel's use of human embryos to support the theory of evolution.

Haeckel's embryo drawings made his ideas easily exportable and the drawings are easy to identify as Haeckel-type images, even if they are not identical to his own. The embryo drawings are mainly found in chapters about evolution and are most recognizable by the use of a grid, with different embryo species on one axis and developmental chronology on the other axis. Within the grid are drawings (and more recently, photographs) of different species of embryos at different developmental periods.

Before beginning my study, I made a decision concerning how strict a guideline I would follow when looking for Haeckel's embryo grids. Would I only accept grids that fit Haeckel's original scheme, or would I also include embryos that, while not exactly presented like Haeckel's drawing, appeared to have been inspired by Haeckel's original work? Haeckel was not the first to draw comparative embryology pictures, nor was he the last, but he is the embryologist who is most associated with the idea. Because of this recognition, Haeckel's embryo drawings have served as a template for others to draw their own comparative embryo grids or charts.

For this research, I opted to cast a wide net: any comparative embryo drawing that was represented by a grid was included in the research design. For example, in Figure 15 are two embryo grids that, while not exactly like Haeckel's 8 x 3 grid, still represent a comparison of different organisms at different stages of development. Both of these drawings fit the definition of a "Haeckelian grid" and were included in this study.

I scanned and uploaded the textbook embryo illustrations into NVivo9, a software platform that aids with the analysis of text and graphic data for deriving categories and clusters. An example of a category would be recapitulation and embryo drawings and a cluster might be a series of grids in which monkey and human embryos appear in the same decade. That cluster would then be part of my qualitative analysis—why did monkeys and humans occur during this decade?

Quantitative Elements

Textbook embryo drawings themselves provide a variety of quantifiable elements including publication date, publisher, the number of embryos and developmental stages used, types of organisms, and whether an illustrator for the embryo grids is identified. These types of quantitative data were tabulated and grouped by decades. Choosing to report data by decades was done for several reasons. First, it is common practice in educational research to do so, and second, many of my textbooks were editions were published at least once every decade, for several decades. The use of decades as starting and stopping points for my analysis however, was not set in stone. It might be likely that a significant change in Haeckel's drawing took place over the course of several decades, rather than one decade.

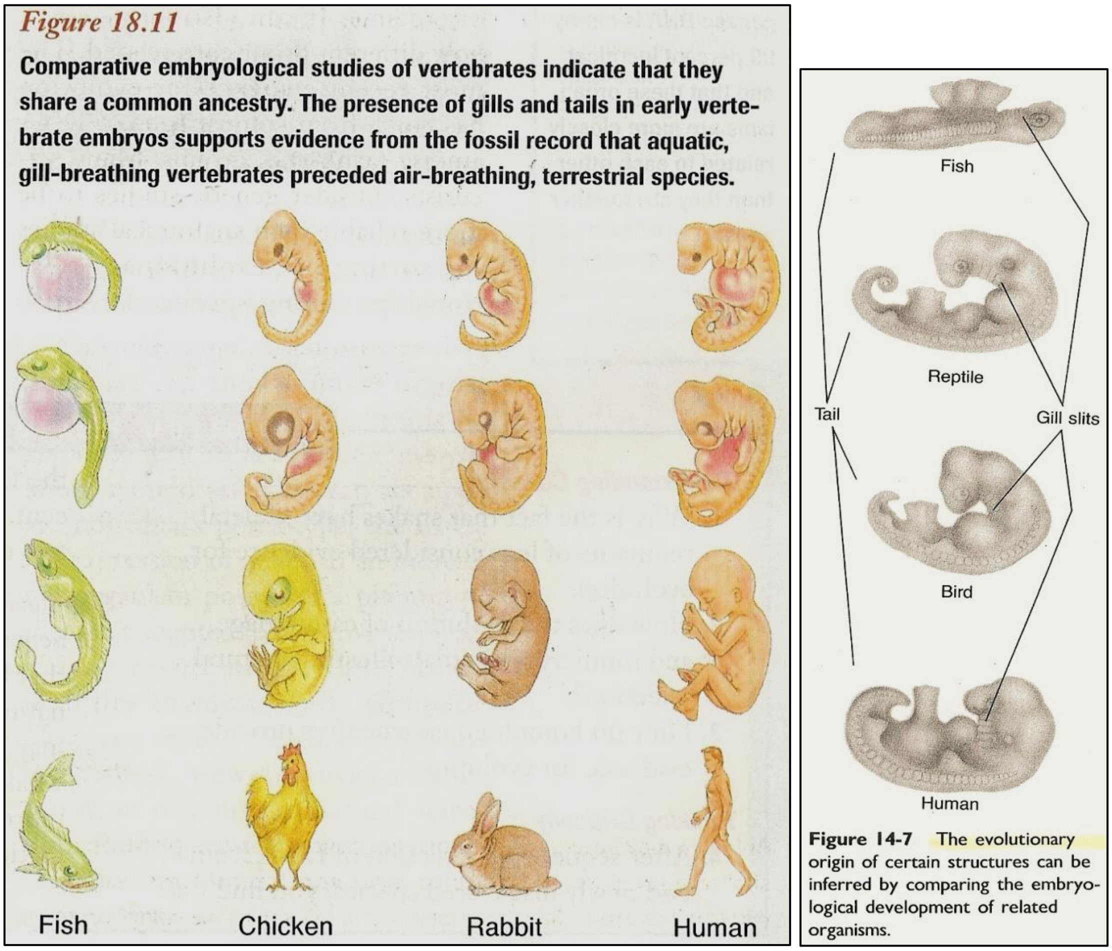


Figure 15. Examples of embryo grids used in this study. The grid to the left is a 4 x 4 grid while the grid to the right is a 4 x 1 grid. From left to right, *Concepts in Modern Biology* (p. 416). In D. Kraus, 1984, New York: Globe and *Biology: The Dynamics of Life* (p. 433). By A. Biggs, C. Kapicka, & L. Lundgren, 1998, New York: Glencoe.

Devising Categories for Text Descriptions of Haeckel's Embryos

With so many texts to review, a coding system was designed to organize how authors used captions and deictic text to describe embryo drawings, and to provide a framework for analysis. I categorized embryo diagrams, diagram captions, and any accompanying text that described the Haeckel embryo grid with the coding scheme shown in Table 1.

This classification scheme made it easier to see patterns and to help with the discussion of the results.

Table 1

Coding Categories

Code	Description
1	Embryo drawing and caption/text refer to gill slits and/or tails
2	Embryo drawing and caption/text show embryo similarities
3	Recapitulation is used as support for evolution or common ancestry
4	Recapitulation is identified as no longer scientifically accepted
5	Embryo drawing and caption/text use genes to explain embryo similarity
6	Embryo drawing and caption/text use biochemistry to explain embryo similarity
7	Human embryos in the grid support human evolution
8	Embryo drawing and caption/text give historical context or nature of science explanation for Haeckel's embryo drawings
9	Embryo drawing and caption/text used to support common ancestry
10	Embryo drawing and caption/text used to support the theory of evolution

Qualitative Analysis

Discrete points of data do not give you a story. Coding Haeckel's drawings aids in establishing patterns, which in turn helps generate arguments and interpretations about what we see. This research was not undertaken with the idea of looking for best teaching practices, but to help explain why Haeckel's embryo drawings, one of the most common drawings used in the history of biology textbooks, have changed in terms of instructional purpose. The research also examines changes that have occurred to the embryo drawings such as species types, number of embryos presented, how the embryos are used to teach biology, and so forth. Why these changes occurred requires a thorough review of the literature about science education pedagogy and the cultural and scientific development of comparative embryology and evolution from the late 1800s to the present.

RESULTS AND DISCUSSION

The data analysis for this study includes quantitative and qualitative examinations of Haeckel's embryo drawings, or embryo grids, in high school biology textbooks. In Section I, I examine the embryo drawings by themselves. Section II examines the question, how did authors describe or use embryo comparisons to convey information about evolution to students? To answer this, I coded captions and text used to explain or situate the embryos in Haeckel's grid. Section III provides a more detailed analysis of embryo grids in biology texts written by George W. Hunter, Truman J. Moon, Ella T. Smith, and BSCS authors.

Section I. The Embryo Grids

After examining many texts with Haeckel's embryo drawings, I can state with confidence that there are no actual Haeckel embryo drawings in any American high school biology text. There are however, many embryo drawings that are "Haeckel-like" in that the idea of an embryo grid was borrowed from Haeckel and in some instances, the embryos appear drawn quite similarly to those that Haeckel drew in *Anthropogenie.*

The closest that any embryo grid comes to matching Haeckel's embryo grids is that drawn by English physiologist George Johns Romanes (1848–1894). Romanes' embryo drawing first appeared in his 1882 book, *Darwin and after Darwin Vol. I* and is an exact copy of Haeckel's *Anthropogenie* embryo grid (see Figure 16). Haeckel biographer Robert Richards argues that the use of an embryo grid with Romanes credited as the illustrator, rather than Haeckel, helped distance Haeckel from readers at time when his name was falling out of scientific and public favor (Richards, 2008, p. 341).

If early biology texts did not use Romanes' drawing, they used second-hand copies of Haeckel's (or Romanes') embryos with credit rarely given to the illustrators. This seems humorously odd in that people accused Haeckel of doing the very same thing. Beginning in the 2000s, grids began sporting photographs of embryos rather than illustrations. In this discussion I nonetheless, will refer to these embryo drawings and photographs as Haeckel's embryos or Haeckel's embryo grid.

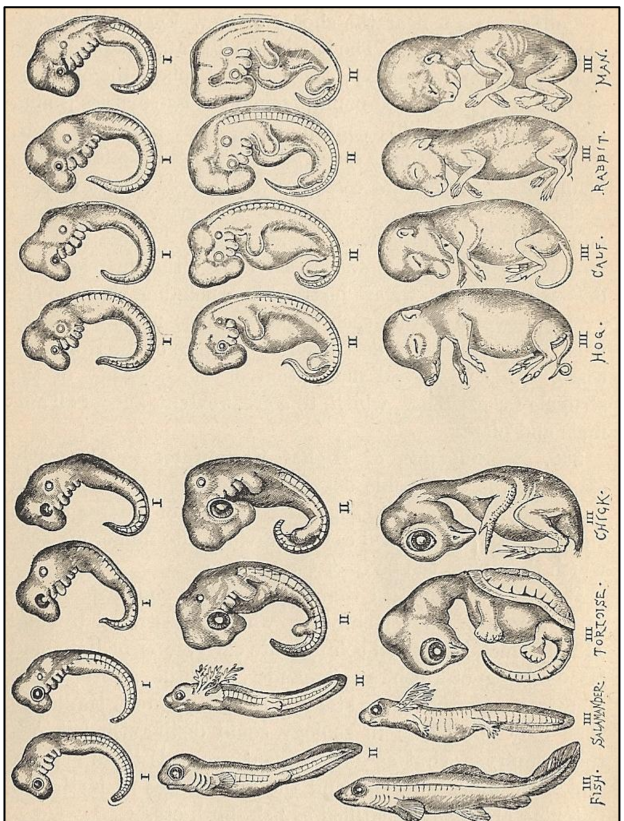


Fig. 113. Similarity of early stages of vertebrate embryos (in column I) and differentiation before birth or hatching (column III). (*From Romanes, after Haeckel.*)

Figure 16. Romanes' copy of Haeckel's embryos. From *Applied Biology* (p. 444). By M. Bigelow & A. Bigelow, 1911, New York: Macmillan.

Figure 17 shows how common Haeckel's embryo drawings are in biology texts. The earliest embryo grid that I encountered appeared in Bigelow and Bigelow's 1911 text, *Applied Biology*, but this was a rare find for that time. One of the reasons for the scant use of embryo grids in the early 1900s is the rarity of discussion about evolution. Up to the 1925 Scopes Trial, 35 percent of textbooks in this study used Haeckel's embryos. After 1925 and through 1939, this number dropped slightly to 30 percent. Considering that historians often identify the Scopes Trial of 1925 as a lever that influenced more and more textbook authors (or publishers) to distance themselves from the topic of evolution, it is peculiar that Haeckel's embryo grid retains nearly the same presence in the 1920s and 1930s.

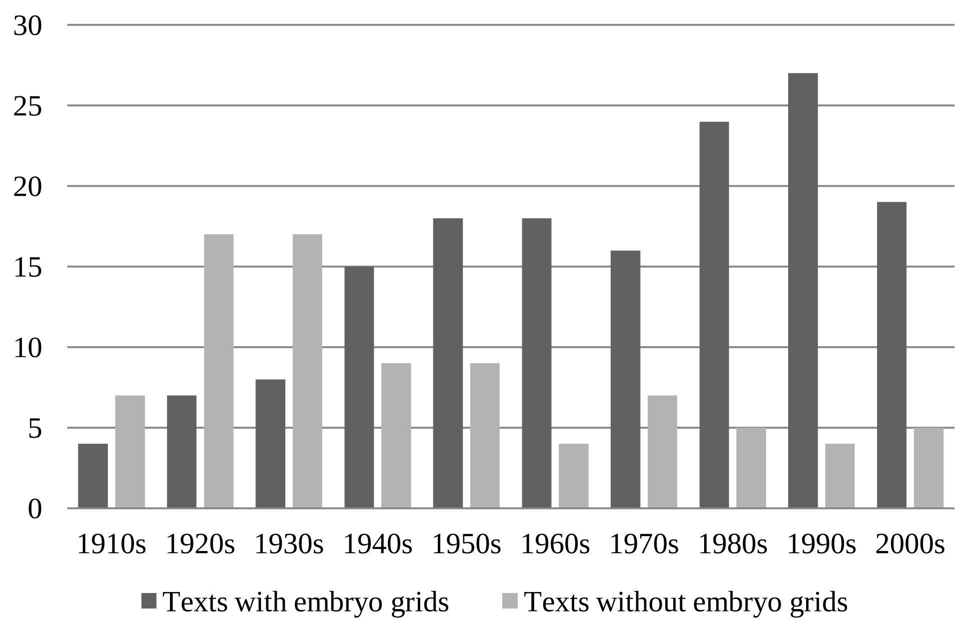


Figure 17. Embryo grids in high school biology textbooks.

One would think that if evolution went, so too would any notion of using Haeckel's embryos in a text. What I found was that Haeckel's grid found temporary refuge in chapters dealing with the environment and animal development. Evolution in textbooks did not totally disappeared after Scopes, but providing visual evidence to support *evolution*, in the form of an embryo grid, may have not been in the interest of most publishers at that time. In the early 1920s, four authors used embryos grids: Lorande Loss

Woodruff (1922), Benjamin Gruenberg (1924 and 1925), and Maurice and Anna Bigelow (1922 and 1925). Out of these four authors, only Woodruff and Gruenberg continued to write biology textbooks after 1925. Gruenberg's 1924 text, *Elementary Biology* uses a large Haeckel-like grid but his 1925 text, *Biology and Human Life* does not use a grid. This is most probably due to different intended audiences, with Gruenberg's 1925 text devoted more to public health and making good citizens, and less to evolution. In 1944, Gruenberg wrote *Biology and Man* and this text uses the same grid that appeared in *Elementary Biology,* minus the human embryo.

As author of *Foundations of Biology,* Woodruff was a protozoologist and a biology historian who taught at Yale University. He also instructed at Woods Hole Marine Biological Laboratory and served as president of the American Society of Zoologists in the early 1940s (Benson & Quinn, 1990). Woodruff's science and history background may have led him to use an embryo grid at a time when few other textbook authors were doing so. Shown in Figure 18, Woodruff's grid is simple, using one developmental stage and three embryos, a shark, bird and human. The label "g" indicates gill slit location, implying similar structures in different vertebrates.

Regardless of any Scopes Trial influence, embryo grid use remained quite low during the early 1900s. This changed in the 1940s when for the first time, more than half of the biology textbooks used some type of embryo grid. This modification, which remained consistent up through the early 2000s is probably due to several factors. By 1940, there was enough chronological distance from the Scopes Trial to give authors more freedom to address evolution as a principle of biology. This led to a variety of different authors willing to use embryo grids. Several of these authors also published multiple editions during the 1940s and each edition used yet another embryo grid. For example, Francis Curtis published four biology textbooks in the 1940s and each edition contained an embryo grid of vertebrates (but no humans). John W. Ritchie published two editions of *Biology and Human Affairs* using a 4 x 3 embryo grid and Ella T. Smith wrote three editions of *Exploring Biology* in the 1940s, also using a 4 x 3 grid.

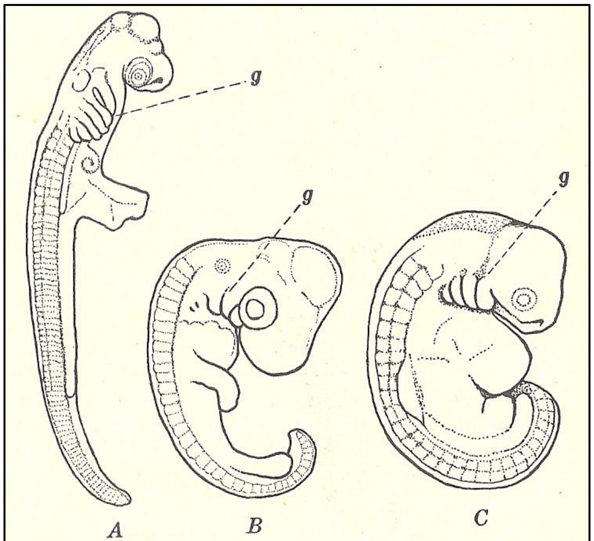


FIG. 239. — Embryos in corresponding stages of development. *A*, Fish (Shark); *B*, Bird; *C*, Man. *g*, gill slits. (From Scott.)

Figure 18. Woodruff's embryo grid used in five of his *Foundations of Biology* text. From *Foundations in Biology* (p. 358). By L. L. Woodruff, 1930, New York: Macmillan.

The introduction of BSCS texts in 1963, followed by the 1968 second-edition releases of all three versions played a significant role in seeing more embryo grids. Credit, however, should not be given solely to BSCS. *Modern Biology,* associated with Truman J. Moon, also continued its use of the embryo grid, something that the text had done since 1933. Also making an appearance in the 1960s were two editions of John Kimball's *Biology*, in which the author and publisher Addison-Wesley chose to use Romanes' embryo grid, or at least part of it. Fish, salamander, tortoise, chick, rabbit, and human embryos are in Kimball's the grid, while Romanes' calf and hog embryos apparently did not make the final cut.

The 1960s also saw a new biology textbook written by Stanley Weinberg, founder of the National Center for Science in 1983. Weinberg was an active grassroots organizer of scientists and teachers who responded to local creation and evolution controversies, including state legislation bills calling for the balanced presentation of evolution and scientific creationism in public schools.

With Weinberg's background, it is no surprise that all four of his biology texts (1966, 1971, 1974, and 1977) address evolution and use a Haeckel embryo grid with monkey and human embryos. What is a bit surprising, though, is that Weinberg's embryos are shaded in green and lack Haeckel's precision. Weinberg's grids, shown in Figure 19, are shaded to help with directionality of development. The shading, combined with a lack of detail draws one's attention to the shape of the embryo rather than to morphological similarities or differences. Weinberg's grid also presents an interesting change to Haeckel's original grid by incorporating even earlier stages of embryogenesis. This is discussed further in the next section on developmental stages.

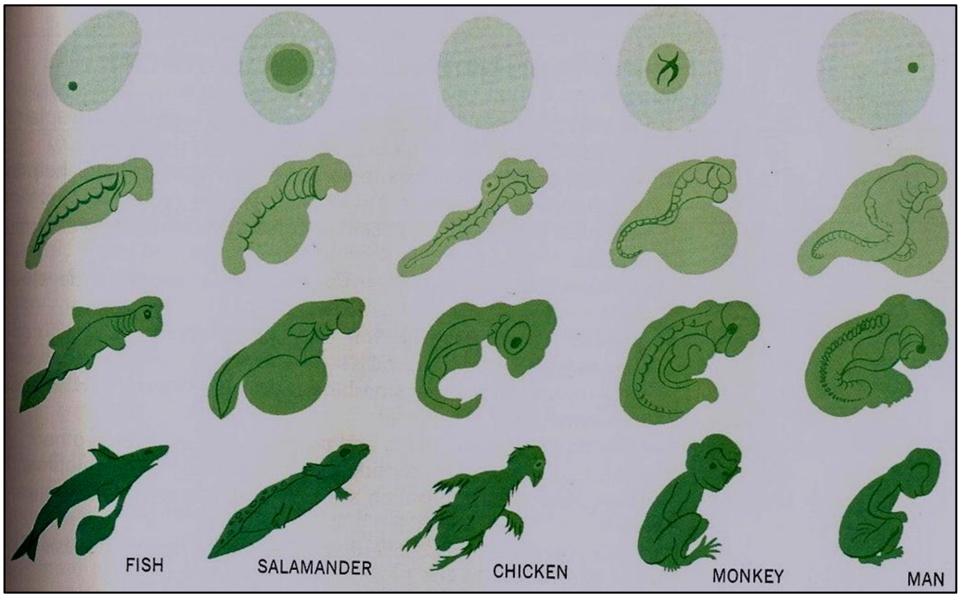


Figure 19. Weinberg's embryo grid from the mid-1960s to 1977. From *Biology: An Inquiry into the Nature of Life* (p. 81). By S. L. Weinberg, 1977, Boston: Allyn & Bacon.

Developmental stages in the grid.

The size of embryo grids is altered by adding or deleting organisms, or adding or deleting developmental stages. Haeckel's original grid was eight vertebrates by three stages of development (an 8 x 3 grid). A majority of texts in this study (58 percent) held true to Haeckel's original three stages of development, but other texts altered the number of developmental stages, using as few as one stage or in some instances, using as many as seven (see Table 2).

An increase in the number of developmental stages in grids occurred in the 1960s. The incorporation of early stage embryos in all BSCS grids is responsible for this increase. It is unclear whether students now saw similarities between early embryos of similar species based on their spherical shape, or if they saw morphological differences during cleavage. For example, Figure 20 shows these early stage additions (boxed in red) in the 1963 *BSCS Yellow Version* text. The seven-celled stage of the pig and human are more similar to each other than the equivalent stages of the salamander and chicken. In this

Table 2

Number of Developmental Stages Presented in Embryo Grids

# stages	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	Total
1		2	1	1	1		1	2	2	8	18
2					1	1		2	2		6
3*	4	4	5	8	14	9	5	12	13	5	79
4			1			1	4	1	6		13
5						3	1	4			8
6								1			1
7						3	5	1	2	6	17

*Haeckel's original embryo grids contained three developmental stages

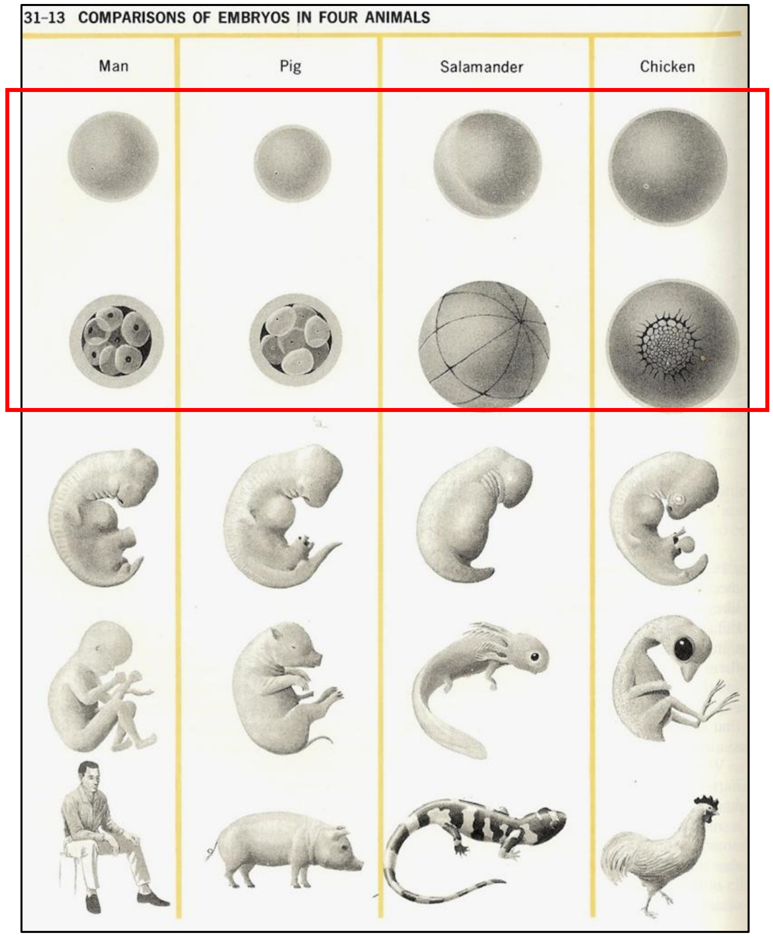


Figure 20. BSCS incorporates two early stages in its embryo grids beginning in 1963. From *BSCS Yellow Version* (p. 609). In BSCS, 1963, New York: Harcourt, Brace.

way, the authors use von Baer's observation that the closer the adults of two groups resemble each other, the longer their embryonic development follows a similar path. Similar early embryo additions to grids appeared in the *BSCS Green Version* and *BSCS Blue Version* in the 1960s, along with Weinberg's 1966 *Biology: An Inquiry into the Nature of Life.*

In the 2000s, the average number of developmental stages in embryo grids decreased, with eight out of 18 grids using only one developmental stage. With these smaller grids, authors tended to focus on embryo gill slits and tails as homologies to suggest common ancestry, rather than using the grids to show early embryonic similarities (see Figure 21).

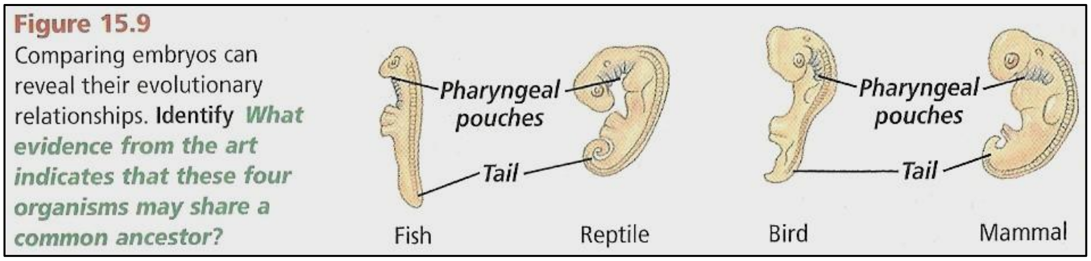


Figure 21. A Haeckel grid comparing four vertebrates during a single stage of development. Note the use of the word "art" in the caption. From *Biology: The Dynamics of Life* (p. 244). By A. Biggs et al., 2004, New York: McGraw-Hill/Glencoe.

Number of organisms in the grid.

Haeckel's original embryo grid examined eight vertebrates, a number that now seems quite large. As one increases the number of organisms and the number of stages in a grid, it becomes easier to visualize what recapitulation might look like, and that is exactly what Haeckel intended for his grids to do. During the early 1900s, textbook publishers tended to use the Romanes' embryo diagram or a close facsimile of Haeckel's embryo grid. This resulted in many different grid organisms up to 1930 (see Table 3). After 1940, grids showed more variability, with some texts using only three organisms and others using eight organisms.

Table 3

Number of Organisms in Embryo Grids

# organisms	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	Total
1					1						1
2					1				2	4	7
3		2	2	3	1	1	4	4	4	5	23
4		1			4	6	2	8	16	10	47
5			2	3	4	5	5	5	1		25
6					4	4	2	2	1		13
7			2	4	1	4	2	5			18
8*	4	3	1	1	1				1		11

*Haeckel's original embryo drawings consisted of eight different vertebrates

During the 1960s through the 1980s, grids closely resembled each other in terms of number of organisms. The average number of vertebrates per grid in each of these three decades was close to five. During the 1990s, the average number of organisms per grid dropped to four and the decline continued into the 2000s, where the average number of organisms per grid dropped to three.

I noticed that more recently published texts used embryo grids that looked less and less like Haeckel's original drawing. Accompanying this change is the fact that the number of biology textbooks published in the 2000s dropped. Perhaps the trend of less authors (and publishers) resulted in more uniformity of content and embryo grids, similar to what happened to biology textbooks in the 1950s. If authors changed their embryo grids due to outside pressure from school boards and textbook review committees, other authors may have followed suit.

Types of organisms in the grid.

How true to Haeckel's original vertebrate organisms have textbook authors and publishers been? Fish and chicks are usually in embryo grids. In textbooks, most fish embryos are simply labeled, "fish" but reptiles are identified as turtles or tortoises, and occasionally as lizards. Amphibian embryos are represented exclusively by salamanders and birds are most identified as chicks. Mammals are always present in embryo grids, but I found that the types of mammalian embryos used varied (see Table 4).

From the 1910s through the 1950s, most biology textbook grids continued with Haeckel's choice of vertebrate embryos. By the 1950s, however, authors and publishers appeared to think that four mammals in a grid was overdoing things, and over time, fewer mammals were seen. Humans are the most commonly identified mammal in textbook grids, followed by pigs, rabbits, and monkeys. Sometimes Haeckel's original embryos fell out of favor in texts, including the calf. Occasionally, organisms like the dog, enjoyed a brief appearance. Dog embryos appeared in some 1940's texts, but fell out of the grid after 1953. The 2000s saw the greatest range of organisms used, perhaps stemming from the introduction of embryo photographs to replace standard hand-drawn embryo illustrations. Publishers now had access to photographs of more "exotic" embryos to place in the grid, including rats, cats, and dogfish.

Table 4

*Types of Organisms in Embryo Grids**

Organism	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	Total
Fish	4	7	6	15	14	18	16	21	20	9	130
Amphibian	4	5	6	11	9	15	8	6	5	6	75
Reptile	4	5	6	13	13	13	7	9	9	6	85
Bird	4	7	8	14	15	17	13	24	21	16	139
Pig	4	4	6	10	15	8	2	8	13	2	63
Calf	3	3	1	1	3						11
Rabbit	4	4	5	5	5	3	3	4	8	2	43
Human	4	7	3	2	7	15	13	18	21	9	99
Sheep	1	1	2	1	1				1		7
Dog				3	1						4
Cat										2	2
Rat										2	2
Monkey						6	8	4	2	5	25
Gorilla								3	3	1	7
Mammal							1		1	3	5

*The first eight organisms listed represent those vertebrates that Haeckel used in his embryo grid

On occasion, embryo species and embryos magically changed their names. For instance, in Gruenberg's 1919 text, Haeckel's calf (German = rind) became a sheep. In later editions of *Everyday Biology* by Curtis, Caldwell, and Sherman (1940, 1943, 1946) the sheep embryo that was once a calf now became a dog. Sometimes all mammalian embryos were lumped together to form a single “mammal” embryo. There were four instances when a generic “mammalian” embryo was used instead of a more a specific mammal like a hog, rabbit, or human. This change occurred recently, with three mammal embryos appearing in the 2000s. It may be that the author or publisher, in an attempt to avoid using an embryo labeled as “human” decided that humans would be best served by placing them under the umbrella of the less controversial “mammals” embryo category.

In most of the grids, a fish remained a fish, remained a fish, except in the case of the early BSCS textbooks. With their characteristic large embryo grids, BSCS green and blue versions did not use a generic “fish” embryo, but used two fish illustrations, a shark and a lungfish. The *BSCS Yellow Version* never used fish in its embryo grids. Because the lungfish made a rather sudden appearance (it disappeared from the *BSCS Green Version* in 1992 and the *BSCS Blue Version* in 2000), one might think that BSCS was capturing new research on lungfish embryology and presenting it in Haeckel’s grid. The embryological plates of the lungfish, though, are quite old.

In the late 1800s, embryologist Franz Keibel (1861–1929) called for collaborators to provide illustrations of their embryos for his sixteen-volume vertebrate embryology book set. The illustrations became starting points for creating stages of development in the twentieth century (Hopwood, 2007, p. 23). At the time, the illustrative morphologies of vertebrate embryos were scattered throughout Europe and had no “central gathering place” so to speak, for the ease of embryo comparisons. Keibel set out to rectify this, gathering many normal plates (illustrations by which further species’ embryos are compared) and publishing them in *Normal Plates of the Development of the Vertebrates*

(1897). Keibel's book includes illustrations of the Australian lungfish drawn by German Richard Semon, the South American lungfish draw by John Kerr in Glasgow, and the African lungfish drawn by John Budgett at Cambridge. Thus, the lungfish embryo plates were not new information, having existed long before BSCS incorporated this particular organism in its embryo grids.

Why BSCS decided to use lungfish and sharks is a question that I posed to biology historian Garland Allen. With no BSCS written records that I could find detailing the use of Haeckel-like embryo grids, Allen suggests that "perhaps the authors wanted to include one non-bony vertebrate and one primitive bony fish, two groups closely related phylogenetically to the 'higher' vertebrates that Haeckel used" (personal communication, January 26, 2014).

Beginning in 1963 and continuing into the 2000s, BSCS grids were the first to display adult forms of organisms. Other authors and publishers copied this idea, which undoubtedly led to decisions about how to portray their adult humans. Should they be naked to infer that humans are vertebrates just like every other vertebrate, or should they wear clothes, which would seem to elevate the status of humans? Should they be men or women? Should they sit on the ground or sit in a chair? Should they be represented by someone other than a Caucasian? Figure 22 shows four ways in which these questions were answered.

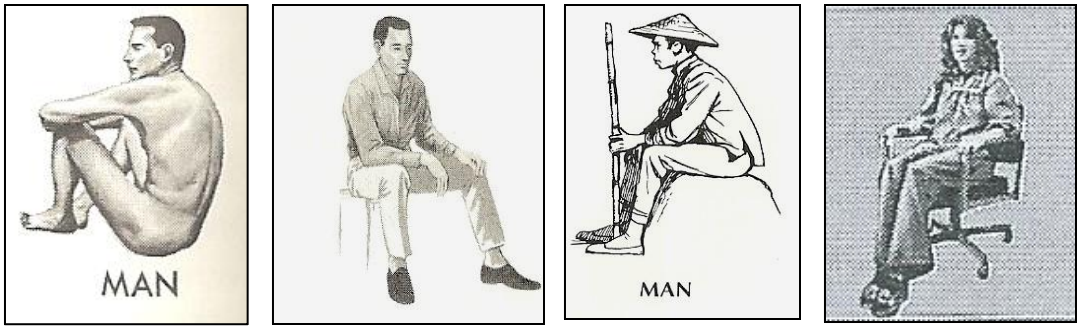


Figure 22. Adult humans in embryo grids range from naked men, clothed men, Asian men, and clothed women. From (l to r) *BSCS Blue Version* (p. 358). By BSCS, 1968, New York: Houghton-Mifflin; from *BSCS Yellow Version* (p. 584). By BSCS, 1968, New York: Harcourt Brace; from *Biology: Living Systems* (p. 299). By R. F. Oram, 1973, Columbus, OH: Merrill; and from *BSCS Yellow Version* (p. 282). By BSCS, 1980, New York: Harcourt Brace.

Monkeys and gorillas.

Primate embryos were never a part of Haeckel's original comparative embryo illustrations, nor were they included in Keibel's *Normal Plates of the Development of the Vertebrates*. It may have been that monkey embryo drawings did not exist at the time that Haeckel devised his embryo grid, but by the late 1950s, monkey embryos had arrived. Primates were now prominently placed in several textbook grids, including the 1961 version of Edward Heiss and Richard Lape's *Biology: A Basic Science*, the 1963 and 1968 versions of *BSCS Blue* and *BSCS Green*, and the 1966 version of Stanley L. Weinberg's *Biology: An Inquiry into the Nature of Life.* Heiss and Lape's grid identifies the mammalian organism as a "mammal," but the rather crude and shaggy looking animal shown in Figure 23 is hard to mistake for anything but a monkey. The entire drawing accompanied a more typical Haeckel-like 6 x 3 grid of embryos on a previous page.

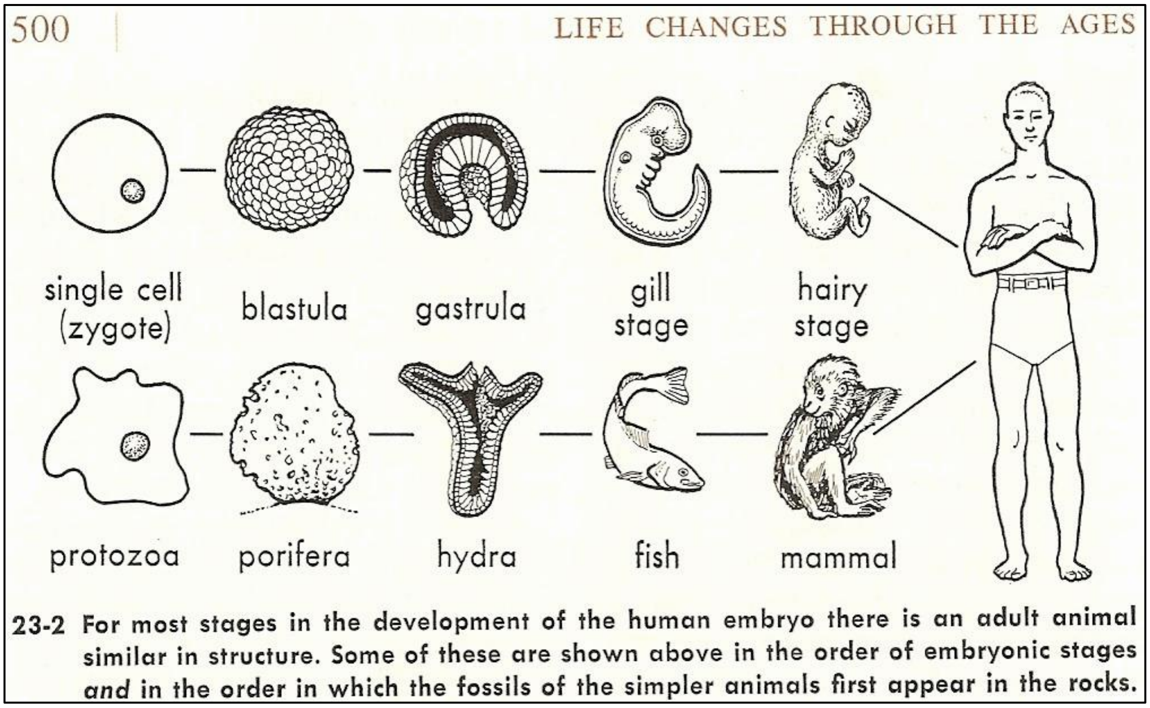


Figure 23. One of the first grids to use a monkey, but identified simply as a mammal. From *Biology: A Basic Science* (p. 500). By E. D. Heiss and R. H. Lape, 1961, New York: Van Nostrand.

Embryo grids in the 1963 BSCS texts identified their primate embryos as chimpanzees rather than monkey embryos. This trend continued into the 1970s, with eight texts, some BSCS and some not, using either a monkey or chimpanzee embryo in their grids. Raymond Oram's three texts, *Biology: Living Systems*, published in the 1970s, followed BSCS closely in terms of illustrations and content arrangement. In Oram's texts, chimpanzees sat next to humans, following the same embryo placement adapted by BSCS. Oram and publisher Merrill, however, changed its adult human from a white Caucasian male to an Asian male and in 1979, *Biology: Living Systems* was one of the first texts to apply color to Haeckel's grid (see Figure 24).

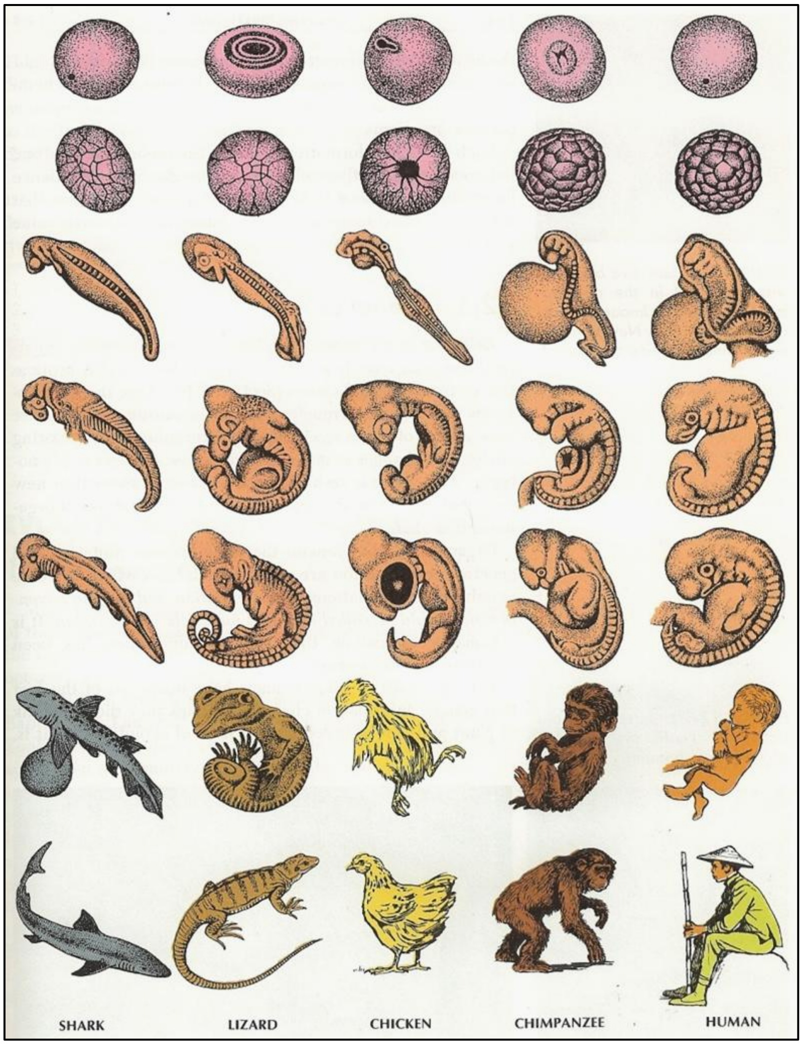


Figure 24. The 1979 edition of *Biology: Living Systems* replaced the decades-old white Caucasian male with that of an Asian male. From *Biology: Living Systems* (p. 257). By R. F. Oram, 1979, Columbus, OH: Merrill.

In the 1980s, an interesting thing happened with the popular *Modern Biology* texts. The tenth and eleventh editions (1981 and 1985),written by James Otto and Albert Towle, used fish, bird, and human embryos in a 3 x 3 grid. In 1989, with Towle as the sole author, the twelfth edition of *Modern Biology* removed the bird and human embryos from its grid and replaced them with rabbit and gorilla embryos. The new grid also incorporated adult forms and changed its long time use of a monochrome blue grid to a multi-colored grid (see Figure 25).

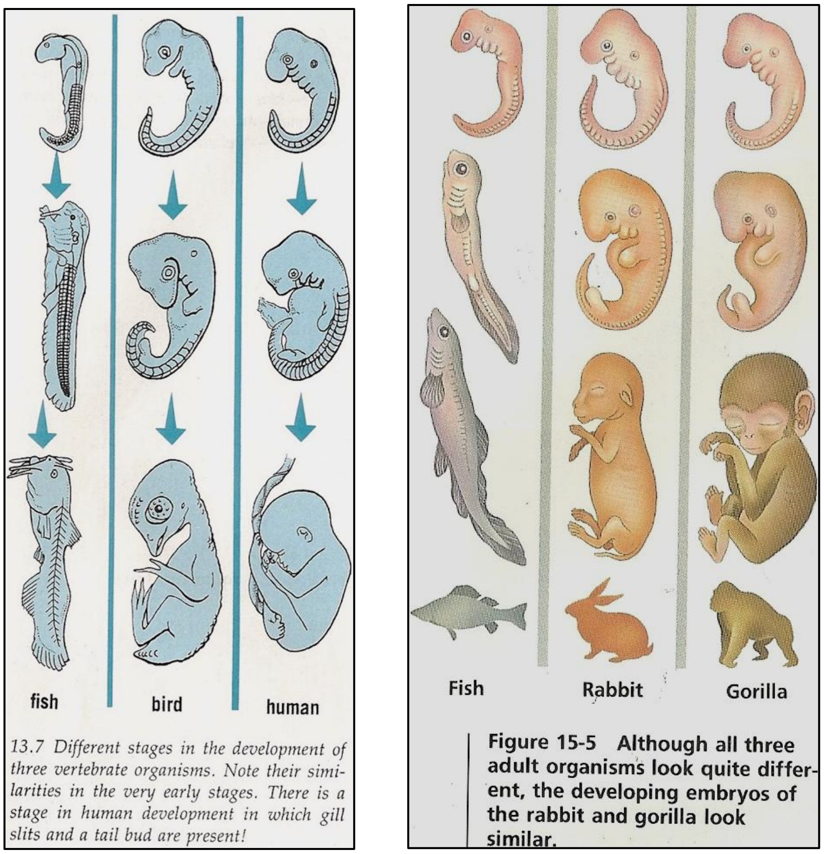


Figure 25. Modern Biology changes its embryos. The 3 x 3 grid on the left is identical in the 1981 and 1985 editions. The 3 x 4 grid on the right, with a gorilla is from 1989. From *Modern Biology* (p. 165 left; p. 224 right). By J. H. Otto and A. Towle, 1985, New York: Holt and A. Towle, 1989, New York: Holt.

The replacement of humans with gorillas may be a reflection of the tension between creation scientists and science educators during the 1980s. Creation scientists believed that there was a new “science” in town and demanded that biology teachers teach creation along with evolution, believing that it only fair to give equal time to different opinions. The number of texts using Haeckel embryo grids had already dropped to 70 percent in the 1970s and the 1980s saw continued backlash against evolution education. Placing humans alongside birds and fish and pointing out that tails and gill slits implied shared ancestry may have proved too much to bear in terms of unwanted publicity and potential boycotts for Holt, the publisher of *Modern Biology*.

In the 1990s, *Modern Biology* continued to use gorilla embryos and the *BSCS Green Version* continued to use chimpanzee embryos. By the 2000s, chimpanzees were seen in only four texts, all published by BSCS (*BSCS Blue Version* 2001 and 2006; *BSCS Green Version*, 2002 and 2006). The 2002 edition of *Modern Biology* continued to use a gorilla, but thereafter *Modern Biology* used photographs of embryos and the gorilla disappeared. Overall, most primate embryos were found in either BSCS Green and Blue versions or *Modern Biology.* The two series did differ in that BSCS always placed human embryos side-by-side with a chimpanzee, while *Modern Biology* never placed humans and primates in the same grid.

Human embryos.

Haeckel's original embryo grid included human embryos, as did Romanes' copy of Haeckel's grid. This explains why all texts with embryo grids from 1907 through 1919 had human embryos—these texts used Romanes's drawing or something quite similar. A steady increase in the number of texts using some semblance of Haeckel's grid occurred from the 1930s through the 1950s, but the same is not true for their use of human embryos (see Figure 26).

Human embryos make a substantial comeback in embryo grids in the 1960s, due mainly to BSCS' incorporation of humans in their grids. Whether human embryos were included to provide explanation of human evolution, which also became more commonplace in texts at this time, will be discussed in Section II. The trend to keep humans in the grid held steady from the 1960s through the 1990s, with nearly 80 percent of grids using human embryos. In texts published in the 2000s, this percent decreased to

47 percent. Even though embryo grids have maintained their popularity in recent textbooks, the act of placing humans in these grids has not.

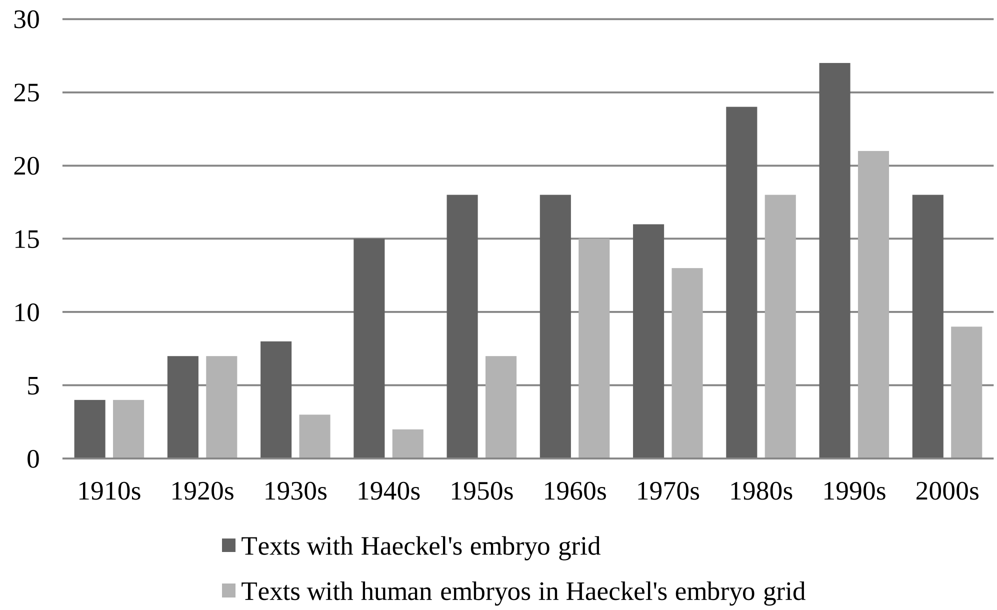


Fig. 26. Use of human embryos in embryo grids by decade.

I expected to see far less human embryos used in the grid during the 1980s based on the studies of Moody (1996) and Skoog (2005), which showed a decrease in discussion about human evolution, even to the point of its exclusion from 1980's textbooks. In my examination, over 80 percent of the textbooks published in the 1980s used embryo grids and of these, 75 percent used human embryos. Human embryos in the grid were rarely used to help explain human evolution or to provide evidence for social or political implications (Social Darwinism). More often, human embryos illustrated general embryonic development and embryo similarities, resulting in no significant difference in how human embryos were discussed, compared to other embryos in the grid.

Photographs and embryo grids.

Photographs project "self-evidence" because they are a mechanical reproduction of an image (Myers, 1990, p. 235). Knowing this, we like to say that photographs "speak for themselves." In the 2000s, six texts replaced their embryo drawings with embryo photographs and of these texts, four used only a single developmental stage. As the number of stages in a grid decrease, the grid loses its effectiveness to show patterns of similarities or differences over time.

The appearance of photographs in embryo grids coincides with the publication of Michael Richardson's 1997 study and his and other's subsequent denunciation of Haeckel. One of the first texts to acknowledge the new criticisms of Haeckel was *Biology: The Living Science,* written by Ken Miller and Joseph Levine (1998). Figure 27 represents the colorized Haeckel 4 x 3 grid, appearing with far less detail than previous embryo illustrations used by the authors.

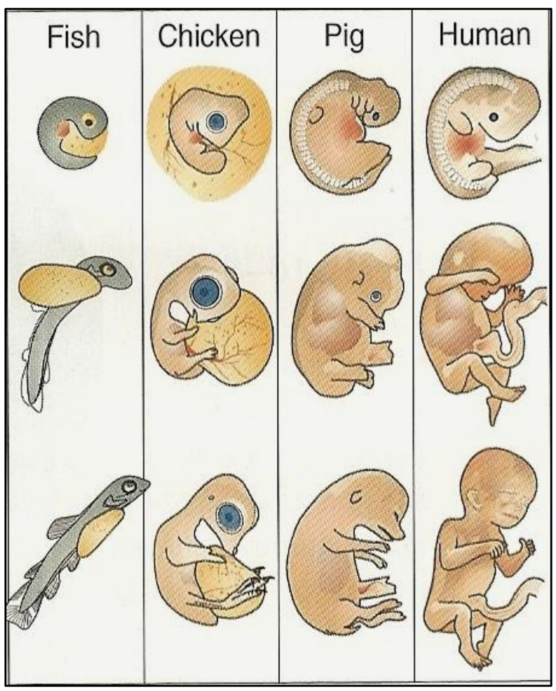


Figure 27. Miller and Levine changed their embryo grid to include drawings of Lennart Nilsson's embryo photomicrographs in 1991. From *Biology: The Living Science* (p. 223). By K. R. Miller & J. Levine, 1998, Upper Saddle River, NJ: Prentice Hall.

On their textbook website, Miller and Levine discussed Richardson's study and Richardson's later accusations against Haeckel (Miller & Levine, 1997). To calm textbook buyers and reviewers, Miller declared that their new 1998 biology text would fix the “problem” by continuing to use drawings of Nilsson’s “absolutely accurate” photographs; implying that (a) Haeckel’s “fraudulence” was now removed from their texts and (b) drawings of photographs never lie.

The drawings of Nilsson’s photographs in Miller and Levine’s embryo grids proved short-lived. The 2002 edition of *Biology* saw drawings of Nilsson’s photos replaced with photographs of embryos. This is the first text in this study to use photographs of embryos rather than drawings. Here, the embryo grid consisted of chicken, turtle, and rat embryos. Viewed in Figure 28, it is difficult to see any similarities between these embryos, even though Miller and Levine ask students to think about how the embryos could help show “relationships among animals with backbones.”

The three organisms are clearly not in the same stage of development and the orientation of the turtle is opposite that of the chicken and rat. The caption also states that in early stages of development, the three organisms look similar (p. 185). It is unclear if the three photographs are intended to show early stage similarity (which they do not) or if the student assumes that the three embryos look alike in an even earlier stage, not depicted by the three photographs.

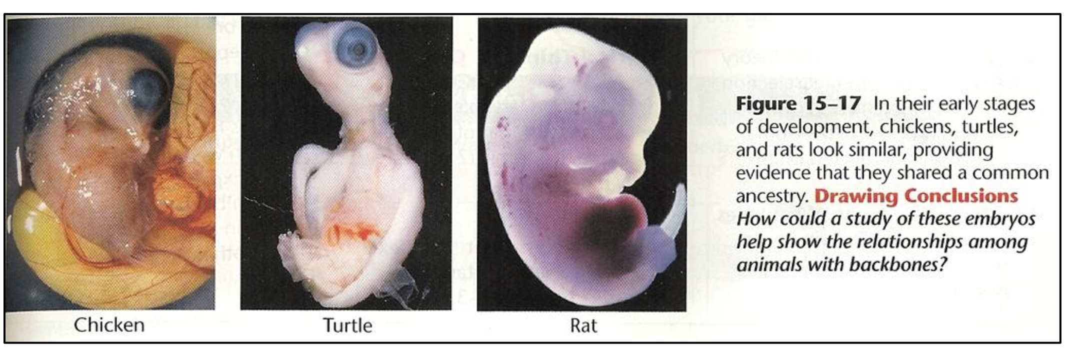


Figure 28. A first instance of photographs used in an embryo grid. From *Biology* (p. 185). In K. R. Miller and J. Levine, 2002, Upper Saddle River, NJ: Prentice Hall.

Perhaps my reactions were shared by others. In the 2008 edition of *Biology*, Miller and Levine used nearly the same grid caption, but the previously used chicken and turtle embryo pictures were replaced with photographs that showed younger embryonic stages. The embryos were also oriented in the same manner, reminiscent of Haeckel's orientations (see Figure 29). While the chicken and rat embryos had a black background, the electron micrograph picture of the turtle embryo was not altered and made the turtle look far different compared to the photographs of the chicken and rat.

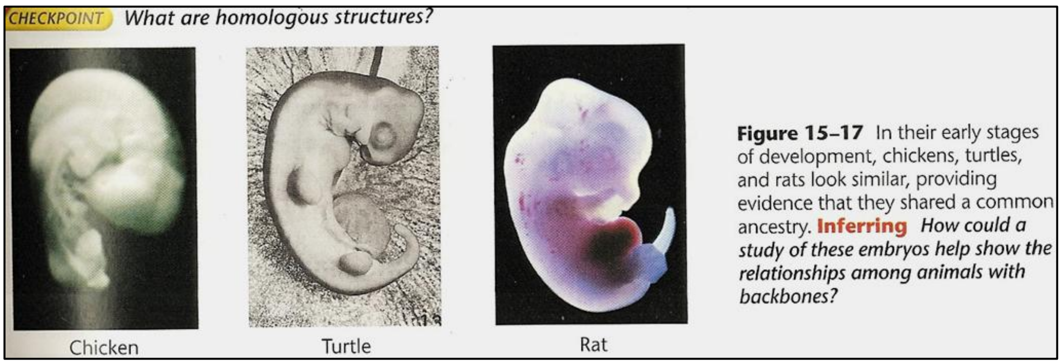


Figure 29. Miller and Levine's revised embryo grid in 2008. From *Biology* (p. 385). In K. R. Miller and J. Levine, 2008, Upper Saddle River: Pearson/Prentice Hall.

In this first section, I have reported what embryo grids look like, changes that have occurred to grids in terms of organisms, stages, and the type of visual media format used to present grids to students. Embryo grids, though, are more than just a visual snapshot. Authors and publishers often provide text and commentary to help explain the grid and why comparative embryology is important to the field of biology. My analysis of author intent, or the various ways that authors used text to describe their embryo grids follows in Section II.

Section II. Providing Meaning to the Embryo Grid

Textbook authors highlight Haeckel's embryo grids with two explanatory passages, (a) a caption, which tells the students in brief what they are looking at, and (b) paragraphs that discuss the grid (referred to as deictic text). Captions often give authority to pictures by crediting the image to an illustrator or photographer. In the case of embryo grids, Romanes' embryo grid is the most commonly cited secondary source. In most instances, however, embryo grid drawings appear copied second-hand with no credit to the original illustrator.

To organize explanatory passages about Haeckel's embryo grids, I used a coding scheme to help categorize the different ways that authors used to help explain their embryo grids. Based on a previous study of developmental biology and textbooks, I knew that gill slits, similarities, recapitulation, and genes would be associated with embryo grids and would serve as separate categories for analysis, but I was also interested to see if authors used embryo grids to support the idea of common ancestry and/or the theory of evolution.

As I coded, I made minor adjustments to my original categories. For example, in the 1960s I noticed that some authors mentioned how urinary excretion proteins were similar in embryos of different vertebrates. Other authors highlighted similarities in mammalian hemoglobin proteins in relation to the embryo grid (interestingly, no author discussed the newest research at the time indicating that gorilla, chimpanzee, and humans hemoglobin was virtually indistinguishable) (Zuckerkandl, Jones, and Pauling, 1960).

This type of information represented the "new" research that BSCS strove for in updating biology textbooks and led me to a separate embryo grid category of biochemical support for evolution. I also wondered if finding human embryos in an embryo grid would also lead to some sort of discussion about human evolution. That led to a separate category, "human embryos support human evolution" for my coding analysis. If an author used the embryo grid to discuss evolution in general and not human evolution specifically, I coded the deictic text with a number code of “10” (embryos support evolution).

Keep in mind that a single textbook could use several different ways to explain or use an embryo grid, resulting in multiple codes for one book. Table 5 shows the final categories and coding results by decade. The rest of Section II will discuss the coding results and reasons for them, using a decade-by-decade approach. At the end of Section II is an overall discussion of one of my categories, human embryos in the grid and discussion about human development and evolution. Human embryos in particular raise eyebrows, no matter if you are examining early 1900s or late 2000’s biology curricula, and warrants its own detailed discussion.

1907–1919.

With only one text available for review prior to 1910, I decided to add Hunter’s *Elements of Biology* (1907) with biology texts written from 1910 through 1919. Of the eleven texts available to me in this period, only four used Haeckel’s embryos. These texts placed embryo grids in chapters about animals or reproduction mainly because the books had no evolution chapters. Authors, however, did point out that embryos in the grids illustrated early embryo stage similarities and common ancestry. Two texts used embryo grids to show how gills slits serve as evidence for ancestral inheritance, and one text (Gruenberg, 1919) went so far as to state that the idea of recapitulating embryos was no longer accepted by most scientists.

Table 5

Coding of Embryo Grid Deictic Text and Captions by Decade

Code	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	Total
1 Embryos' have gill slits/tails	2		1	9	13	9	8	13	13	5	73
2 Embryos are similar	4	4	5	12	9	13	14	23	26	16	126
3 Supports recapitulation		1	1	11	10	5	3	1			32
4 Recapitulation not supported	1	2	3	1	1	5	4	9	9	6	41
5 Genes support embryo similarities						2	4	11	7	5	29
6 Embryo biochemistry supports evolution						4	4	1	3	3	15
7 Human embryos support human evolution	1	2	1	1	4	9	9	7	11	3	48
8 Embryos and NOS/history of biology						3	6	2			11
9 Embryos support common ancestry	3	6	5	8	10	13	14	23	23	13	118
10 Embryos support evolution		3	2	1	2	4	8	19	20	8	67

Maurice and Anne Bigelow wrote three of the texts with embryo grids. Maurice A. Bigelow was a Harvard-trained biologist who later served as a biology professor at Teacher's College, Columbia University in New York City. Anne Bigelow was Maurice's wife and taught biology at Miss Chapin's School for Girls in New York City. While at Columbia, Maurice Bigelow wrote several high school editions of *Applied Biology*, and during and after World War II, he served as president of the American Eugenics Society. The Bigelow and Bigelow texts stayed true to a particular formula—there was always a heavy emphasis on sex education, public health, social hygiene, and eugenics (Popenoe, 1955), and the use of an embryo grid.

The grid that the Bigelows' used was a Romanes drawing (see page 2) credited to George John Romanes (1848–1894), an English physiologist who was a staunch supporter of Darwin and evolution. Bigelow and Bigelow described the embryos in von Baer fashion. That is, "there is a great similarity in the early stages of all vertebrates…but as development proceeds there is more and more differentiation, and the final stages at birth or hatching are easily identified as fish, bird, etc." (Bigelow & Bigelow, 1911, p. 445; Bigelow & Bigelow, 1913, p. 445; Bigelow & Bigelow, 1916, p. 445).

The 1911 and 1916 editions of *Applied Biology* mark the beginning of a long history of textbook authors using Haeckel's embryos and gill slits to provide evidence of common ancestry. While it is was clear in the early 1900s why fish and amphibian embryos had gill slits, the authors asked why a mammal would need gills slits. At the time, there was no known physiological function for gill slits in human embryos so the authors merely stated that gill slits in mammals were ancestral reminiscenes. Since the authors avoided mentioning humans at all in this section, the reader might have believed that human embryos do not have gill slits. There was also no mention of evolution associated with Haeckel's embryos by Bigelow and Bigelow.

The other text to include Haeckel's embryos during this early period of high school biology is *Elementary Biology* by Benjamin C. Gruenberg, published in 1919. Here, the embryos were traced and flipped so that Haeckel's embryos now all faced right rather than left. This drawing appears similar to the future *Biology for Beginners* and *Modern Biology* texts by Truman J. Moon. The drawing's caption explained that early stage backboned embryos look similar. The deictic text accompanying the diagram states, "This parallelism between the stages in individual development and in whole animal series was observed long ago, and is known as von Baer's Law of Recapitulation" (p. 278). Here is the first instance of Haeckel's work presented as von Baer's work, and it certainly is not the last. Gruenberg's 1919 text is also the first that I found criticizing the idea of recapitulation:

> Some biologists have gone so far as to say that each individual passes through stages representing all the types of his ancestors. In a general way this is true only as a restatement of von Baer's law. But, strictly speaking, it is not true, for example, that you once passed through a hydra stage or a fish stage. All we can say is that we have passed through stages that are similar to corresponding stages in many classes of animals. (p. 278)

1920–1929.

In the 1920s, more biology texts appeared on the market as more high schools added biology courses to their curricula. Authors who had previously published books in the 1910s, including Bigelow and Bigelow, Hunter, and Gruenberg, continued to publish in the 1920s. Other authors made their first textbook appearance in the 1920s, including books written by Truman J. Moon, Lorande Loss Woodruff, and Alfred C. Kinsey. While biology teachers now had a greater number of texts to select from, the number of Haeckel embryo grids in texts did not increase. One reason for this is the 1918 Commission on the Reorganization of Secondary Education's decision to exclude evolution from its proposed biology curriculum (Hurd, 1961). Nonetheless, the purpose of the small number of embryo grids that did appear in textbooks during the 1920s was not that different from the purpose of embryo grids in the 1910s—vertebrate embryos were sometimes similar in appearance. It is incorrect to conclude, though, that a text lacking a Haeckel embryo grid automatically meant that the author avoided discussion of evolution. For example, Kinsey's 1926 *Introduction to Biology* gave extensive coverage to evolution (Skoog, 1979, p. 628) and even mocked antievolutionists, but the text did not use an embryo grid.

One new author in the 1920s was William H. Atwood, an advance-degreed high school biology teacher in Milwaukee. In his first 1922 edition of *Civic and Economic Biology*, Atwood included a Haeckel embryo grid in a chapter titled "How Plants and Animals Live." The purpose of the grid was to show that organisms possess similar stages of development, an argument proposed by von Baer in 1828. Atwood also addressed recapitulation with, "the fact that historical development of the species is summed up or repeated in the embryological development of the individual is known as *recapitulation theory*. The history is never perfectly repeated, and there are many short cuts and slight omissions" (p. 19). Atwood's writing is reminiscent of Garstang and others who were criticizing Haeckel's recapitulation ideas at this time. However, rather than condemning recapitulation outright, Atwood takes a softer tone, implying that recapitulation, while not perfect, might still be valid in some ways.

Atwood and Gruenberg provide us with an examination of evolution education before and after the 1925 Scopes trial decision. Atwood's 1922 text and Gruenberg's 1924 text

(*Elementary Biology*) used embryo grids. The next publications by these authors, Atwood's *Biology* in 1927 and Gruenberg's *Biology and Human Life* in 1925, have no embryo grids and they offer little to students in the way of evolution discussion (Shapiro, 2013). Unlike his 1922 text, Atwood's 1927 biology book makes no mention of von Baer or recapitulation, and Gruenberg, always a strong proponent of evolution, probably had to give in to publisher Ginn's advice to tone down his discussion of Darwin and evolution.

Woodruff's texts (1922 and 1927) provided a different look at how evolution was treated. Here, the author and publisher (Macmillan) retained embryo grids and discussed recapitulation. Instead of stating that organisms of higher animals pass through adult stages of lower organisms, Woodruff wrote that the *organs* [emphasis added] of higher animals pass through developmental stages, "which correspond with the adult condition of similar organs in lower forms. The correspondence is not exact, to be sure, but it is not an exaggeration to say that embryological development is parallel to that which anatomical study leads us to expect" (Woodruff, 1927, p. 365).

Woodruff pointed out the importance of the "clear fact" that the history of the individual (ontogeny) frequently corresponds in broad outlines to the history of the race (phylogeny) as indicated by evidence from the comparative anatomy of embryos. He then discussed chambered hearts, brain development, and skull development—all types of evidence to support the "so-called recapitulation theory, or biogenetic law" (Woodruff, 1922, p. 365; Woodruff, 1927, p. 380). In contrast, at about the same time, biologists had almost completely divorced the idea of recapitulation from the theory of evolution. (Bowler, 1983, p. 101).

1930–1939.

The story of evolution and textbook publishing in the aftermath of the 1925 Scopes Trial has been told ably by historians and science educators. Most researchers agree that biology textbooks published in the 1930s did address evolution, but the treatment was brief, with human evolution practically ignored (Skoog, 1979). While the number of embryo grids in the 1930s was not noticeably different from the previous decade (eight grids in the 1930s compared to seven grids in the 1920s), I found that human embryos were noticeably absent from 1930's grids. The seven embryo grids in the 1920s used human embryos but in the 1930s, only three grids used human embryos. As time passed from the Scopes Trial, authors may have felt a bit more emboldened to use embryo grids, but erred on the side of "safety" by not including human embryos.

Woodruff's fourth edition of *Foundations of Biology* (1930) presented the same embryo grid and text that his first and second editions contained. Unlike other 1930s authors, Woodruff's embryos were firmly placed in a chapter titled "The Origin of the Species," a decision that must have appeared daring considering that the chapter appeared only five years after the Scopes Trial. Curtis, Caldwell, and Sherman placed their embryo grid in a chapter titled "Reproduction with Sex." There is little explanation of the grid but the authors asked why a pig, sheep, and rabbit would remain similar for a longer period of their development compared to the fish, salamander, tortoise and chick. In a second drawing, the stages of higher organisms, from fertilized egg to embryo were compared to simple organisms like the paramecium, volvox, hydra, and earthworm. The caption asked how the diagram illustrates the fact that complex animals pass through more stages of development than do the simpler ones (see Figure 30).

Although this diagram might appear strange now, early recapitulation advocates often used simple organisms like the hydra and volvox to show how each individual animals passed through embryonic stages that closely resembled adult stages of simple organisms. Thus, a mammalian embryo showed in its growth a one-celled paramecium stage, a hollow-bodied volvox stage, and a segmented or divided body (worm) stage. Curtis et al. however, used the diagram to show that complex animals go through more stages of development than simple organisms. The inference was that the more stages of development an organism goes through, the higher the order of that organism.

Ralph Benedict, Warren Knox, and George Stone published their first high school biology text in 1938. The authors used a Romanes' embryo grid, including "man," to provide an example of recapitulation given a slight twist—ontogeny repeats phylogeny is "true in a broad sense, [but] it is not necessarily true in a particular sense. If it were universally true, there would be no differences between the young of different kinds of animals, for example." (p. 128).

In contrast, Moon and Mann's 1933 and 1938 *Biology for Beginners* used embryo grids to provide evidence that each animal in its individual development passes through stages, which resemble its remote adult ancestors. This statement is closer to Haeckel's idea of recapitulation. In 1938, Moon and Mann used their embryo grid to draw attention to long tails and gill slits found in all vertebrate embryos. Prior to this, it had been sixteen years since an author discussed gill slits and tails as evidence for evolution. Moon is the only author in the 1930s to use embryos' tails and gill slits as evidence for common ancestry. This is quite different from the 1940s when a majority of authors discussed gill slits and tails in reference to embryo grids.

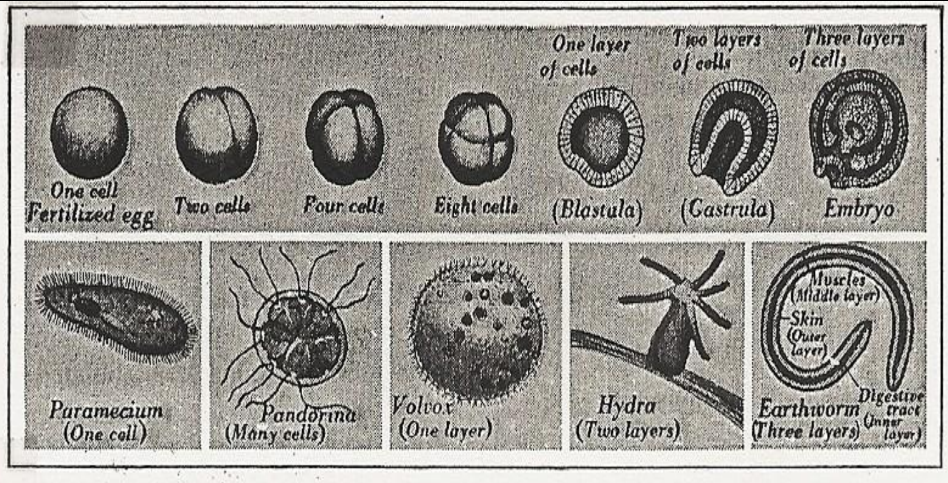


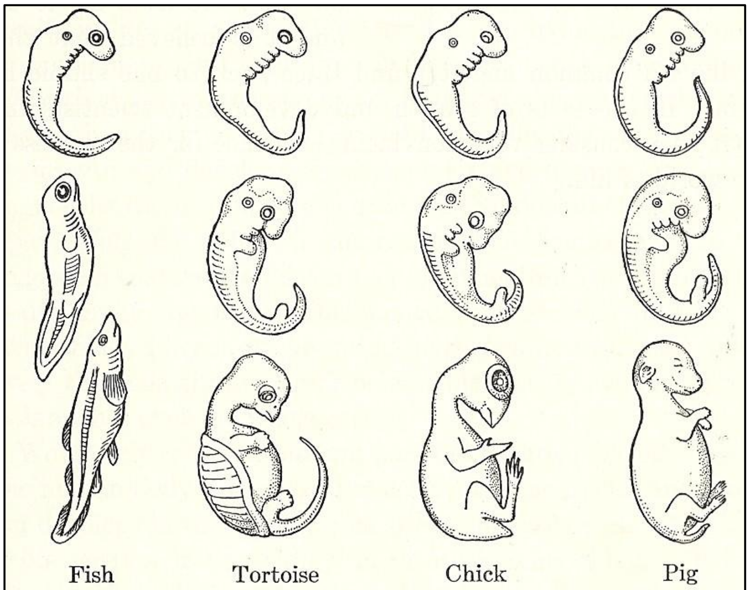
FIG. 385. In reaching the adult stage, the more complex animals pass through more stages of development than do the simpler ones. Explain how this diagram illustrates this fact

Figure 30. Early embryo development of vertebrates compared to similar morphological types of simple organisms. From *Biology for Today* (p. 592). By F. C. Curtis, O. W. Caldwell, and N. H. Sherman, 1934, Chicago: Ginn.

1940–1949.

Until the 1940s, you had only a small chance of seeing an embryo grid in a high school biology textbook. After 1940, with the modern synthesis underway and natural selection and gene mutations recognized as evolutionary mechanisms, the number of embryo grids in high school biology texts rose. New authors used embryo grids, as did older authors such as Curtis, Caldwell, and Sherman whose 1940's high school biology texts used embryo grids similar to those in their 1930's texts.

One of the new authors included John W. Ritchie, former science editor for World Book Company and perhaps most well known for his series of sanitation and hygiene education books. Ritchie's embryo grids represent a transitional stage for Haeckel's embryos, as embryo drawings became less elaborately detailed. Ritchie's embryo grids appear the same in his 1941 and 1948 editions of *Biology and Human* Affairs (see Figure 31). The first sentence in the caption recognizes similarities in early embryos, much like what von Baer proposed in 1828. The second sentence in which embryos repeat the history of it race, is more in tune with Haeckel's idea of recapitulation.



Vertebrate embryos. In the early stages they are much alike, but as they develop they become more and more different. In its development each is supposed to repeat the history of its race.

Figure 31. Ritchie's 1948 embryo grid caption supports von Baer and Haeckel. From *Biology and Human Affairs* (p. 63). By J. W. Ritchie, 1948, New York: World Book.

Ritchie also wove von Baer and Haeckel's work together in a paragraph describing the embryo grid. Ritchie wrote, "Biologists believe that in its development an individual plant or animal repeats in a greatly shortened way the history of its race. The theory is that the individual in its early growth goes through the same changes that its ancestors went through in the geologic ages of the past. In their adult stages organisms may seem very different, but they all start life as a single cell and it is believed that they all have a common ancestry and trace back to one simple life form" (Ritchie, 1941, p. 135). The first part of the paragraph targets recapitulation while the last sentence, with similar early stages and different adult morphologies, targets von Baer's ideas of embryo similarities. Many texts comingled von Baer and Haeckel's ideas like this, but it was not only biology textbook authors who blended von Baer's rules and Haeckel's law together. Gould points out in *Ontogeny and Phylogeny* (1977) that biologists and historians were also guilty of mixing up the work of the two embryologists.

Ritchie discussed recapitulation further by implying that children go through "less civilized" stages as they develop towards a civilized adult form:

> The theory that each individual in its development repeats the stages its ancestors went through in the development of the race is called the recapitulation theory; sometimes it is spoken of as the biogenetic law. In your reading you may find reference to it under these names. Psychologists have applied the theory in interpreting the instinctive development of children, holding that various ages represent different stages in the rise of the human race." (p. 136)

This statement reflects the strong influence that recapitulation had in areas outside of biology. Herbert Spencer in the late 1800s and Stanley G. Hall in the early 1900s used Haeckel's idea of recapitulation to suggest that children cognitively advance by passing through the history of our biological species. When young, children learn how to walk and use simple tools like "cavemen." Children then take steps towards social play and progress to solving abstract problems like civilized adults. In my study, Ritchie is the only author who used an embryo grid to discuss how recapitulation could predict cognitive development in children.

In 1944, Gruenberg returned with his last biology textbook, *Biology and Man*. He used the embryo grid shown in Figure 32, with a caption explaining that individuals of different species were most alike in the egg stage and become less alike as embryos developed. Because the egg stages were absent from the grid, one might assume that Gruenberg was using the top-most row of embryos in his grid to represent differences. In most other embryo grids, the authors intended for the top-most row of embryos to show similarities between embryos. This is not the only confusing element related to Gruenberg's grid.

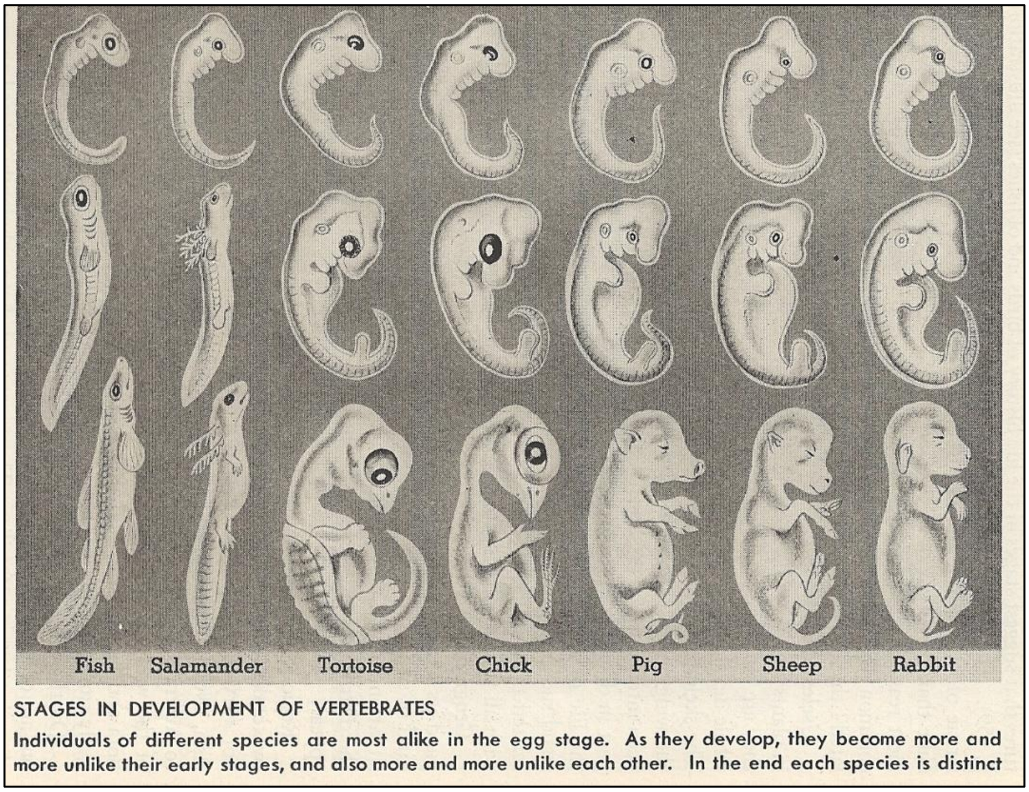


Figure 32. Gruenberg's last embryo grid in 1944. From *Biology and Man* (p. 459). By B. C. Gruenberg & N. E. Bingham, 1944, New York: Ginn.

Also puzzling is Gruenberg's descriptive paragraph about the embryo grid. He discusses the uniformity of embryos under the guise of "von Baer's Biogenetic Law." Gruenberg writes that half a century after von Baer, "some biologists" expanded recapitulation into the theory that each individual recapitulates in his development the history of his race. Gruenberg continues, telling us that recapitulation "is true only as a restatement of von Baer's law. But strictly speaking, it is not true, for example, that once you passed through a hydra or a fish stage. All we can say is that each of us passed through stages, which resemble corresponding stages in many classes of animals" (p. 357). This appears to be an instance where Haeckel's work becomes von Baer's work, an irony that is not lost to those who know that the two scientists were often at odds with each other.

Overall, use of embryo grids in the 1940s illustrated three things: (a) embryos have gill slits, tails, and swim bladders, (b) embryos of different organisms are similar, and (c) embryos pass through developmental stages. Sometimes authors clearly discussed Haeckel's recapitulation without mentioning Haeckel, but in other cases, the work of von Baer and Haeckel were jumbled together leading to overgeneralizations and inaccuracies.

1950–1959.

Little changed in the 1950s concerning gills slits, von Baer's similarity of early embryo rules, and Haeckel's idea of recapitulation. These topics continued to dominate the textbook conversation about embryo grids. With authors like Hunter, Smith, and Curtis and Caldwell publishing new, but little-changed editions in the 1940s *and* 1950s, the two decades experienced little variance in embryo grid use. One new embryo drawing however, appeared in Ruth Dodge's *Elements of Biology* (1952). Earlier editions of this text were written by William Smallwood, Ida Reveley, and Guy Bailey. Smallwood et al. wrote briefly about evolution in these earlier editions and did not use any embryo grids. This changed when Dodge, a high school biology teacher who shared in with the text's writing, became the sole author. In her 1952, 1959, and 1964 editions (publication of *Elements of Biology* ended in 1964), Dodge used a quasi-embryo grid that clearly illustrated how recapitulation worked (see Figure 33). To dispel any questions, the diagram was labeled "embryology (development of the individual) repeats phylogeny (history of the race)."

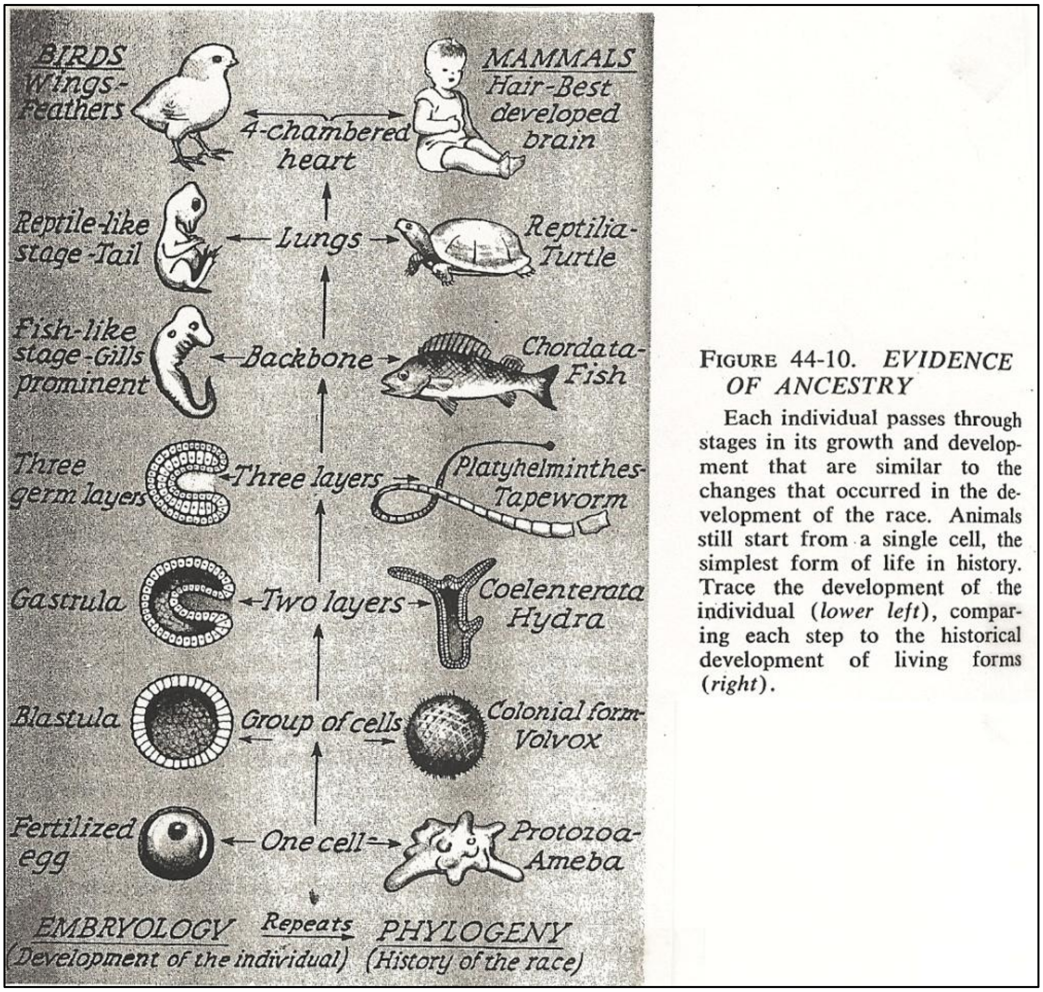


Figure 33. Recapitulation as part of embryo discussion in the 1950, 1952, and 1959 editions of *Elements of Biology*. From *Elements of Biology* (p. 626). In R. A. Dodge, 1959, Boston: Allyn & Bacon.

A similar recapitulation diagram appeared in *Everyday Biology,* written by Curtis, Caldwell, and Sherman. Curtis was a long-time education professor at the University of Michigan and a colleague Sherman, a high school biology teacher. Caldwell was a botanist and education professor at Columbia University, perhaps most well known as an early advocate for general science courses in high school. Over the course of several revised editions (1940, 1946, 1949, and 1953), the same picture and caption addressing animal development was used (see Figure 34). Curtis and Dodge's diagrams represent another way in which early development of higher organisms supposedly mirrored the adult stages of simpler protozoans and invertebrates, and is highly suggestive of Haeckel's first rule of his Biogenetic Law, or the concept of correspondence.

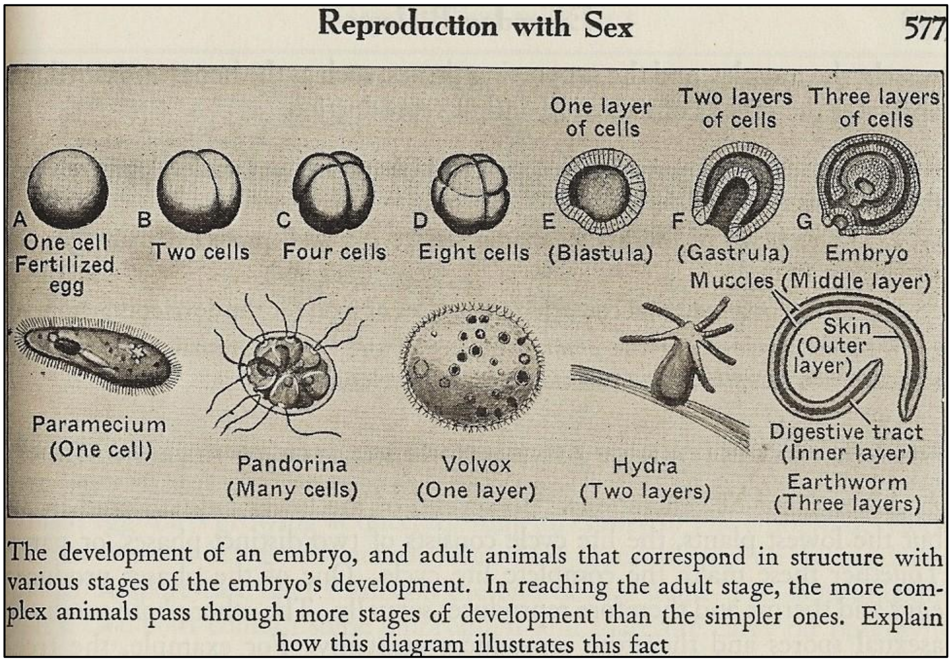


Figure 34. Haeckel and von Baer. While the caption is reminiscent of von Baer, the pictures illustrates how higher organisms go through the adult stages of lower organisms, much in line with Haeckel's idea of recapitulation. From *Everyday Biology* (p. 577). By F. D. Curtis, O. W. Caldwell, & N. H. Sherman, 1953, Chicago: Ginn.

The rest of the texts addressed recapitulation similarly to how recapitulation was discussed in 1940's texts. For the most part, authors stated that animals in their individual development passed through stages resembling its remote adult ancestors. While Haeckel's name did not appear in the deictic text, his famous phrase "ontogeny recapitulates phylogeny" was quoted.

How is it that textbooks were still telling students about an erroneous scientific idea in the 1940s and 1950s? Perhaps it is because of a lack of review by scientists in the field. Earlier in this thesis, I discussed Joseph Schwab's three phases of high school biology texts. Schwab identifies the 1940s and 1950s as a time when texts were highly descriptive and lacked new biological information. Professional biologists were not involved with secondary education and so, high school biology books went uncontested and unchanged. This condition was one that BSCS founders sought to rectify, beginning in the 1960s.

1960–1969.

In 1959, conferences and displays commemorated Darwin on the centenary of the publication of *The Origin of Species*. The public events would have left Ernst Haeckel, if he still were still alive, most invigorated. The celebratory events and the formation of the BSCS in 1958 carried over into the 1960s, a decade that many educators identify as a watershed period for evolution education. Along with new BSCS textbooks, there were other textbooks, including old favorites such as *Modern Biology* by James Otto and Albert Towle, *Elements of Biology* by Dodge (which still read the same as previous editions), and *Exploring Biology* by Ella T. Smith.

Several new authors also entered the increasingly competitive textbook market. Much like BSCS texts written by specialty-area biologists, authors John Kimball and Stanley Weinberg represented the new wave of biology text authors in the 1960s—experienced high school biology teachers with resumes that included biological research. Weinberg did graduate work in biology at Columbia University and at the Woods Hole Marine Biological Laboratory (Scott, 2001). Kimball's wrote his first edition of *Biology* (1965) while teaching biology at Phillip's Academy in Andover, MA. He returned to Harvard for graduate study, obtaining a PhD in Biology before revising *Biology*.

Overall, Haeckel's idea of recapitulation in the 1960s, was viewed in a negative light. Prior to the 1960s, a total of only eight texts (out of 86) stated that recapitulation was no longer considered correct by scientists. In the 1960s alone, five textbooks (BSCS Yellow

Version, 1963, 1968; Kimball, 1969; Kraus & Perkins, 1969; & Weinberg, 1966) stated the same.

Support for recapitulation though, did not totally disappear. *Modern Biology* continued to discuss recapitulation in Haeckel fashion by stating that, "the evidence from embryology seems to indicate that each animal in its individual development passes through stages which resemble those of its remote ancestors" (Moon, Otto, & Towle, 1960, p. 662; Otto & Towle, 1965, pp. 182–183). Other texts such as Kraus' *Concepts in Modern Biology* (1969) advanced the idea of recapitulation in only the broadest of generalizations, using common structures like gill slits (and not the complete adult organism) to show that homologies appear in a wide range of embryo species.

With more scientists and fewer high school teachers writing texts in the 1960s, it was not surprising to see genetics and molecular biology now associated with embryo grids. Whether influenced by BSCS writers who incorporated molecular biology and biochemistry in their texts, or whether the time was just right to examine embryos within a modern synthesis framework, Kimball's 1965 text presents what appears to be a new way at looking at recapitulation. Kimball used a graph (see Figure 35), to show how chicks experience biochemical recapitulation. The graph illustrates how young chick embryos excrete ammonia, just like adult fish. Within a few days, ammonia production is succeeded by urea production, much like that of adult amphibians. On the tenth day of embryogenesis, the chick begins excreting uric acid, much like its most recent ancestor, the reptiles.

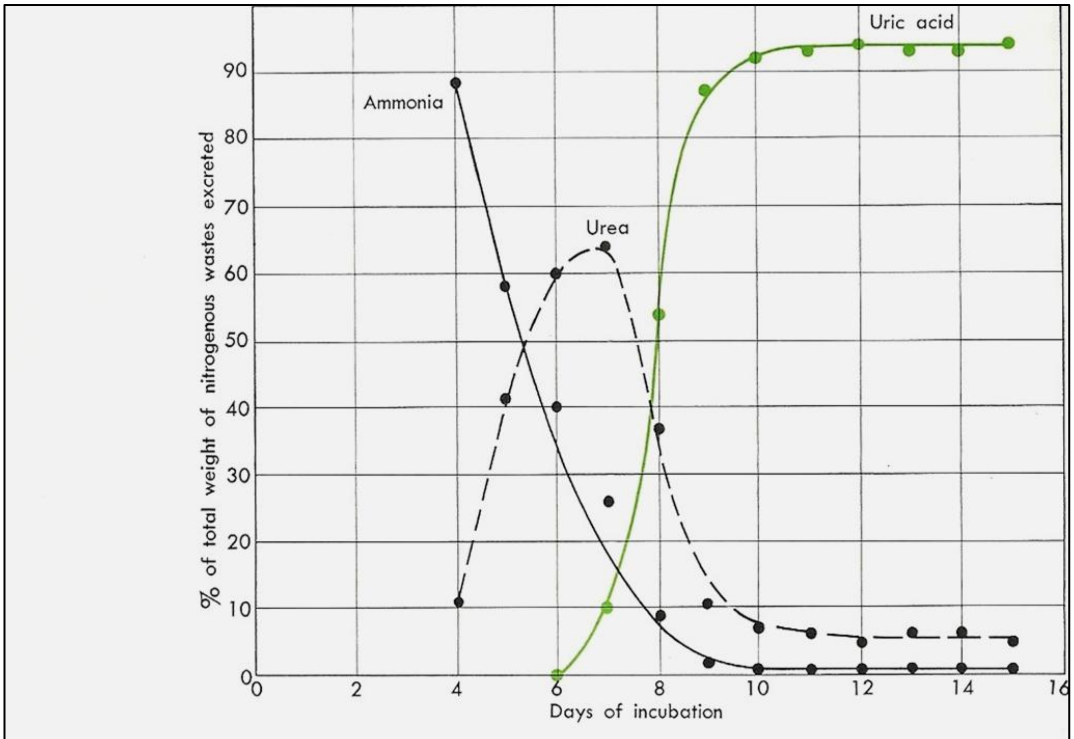


Fig. 31–7. Biochemical recapitulation in the chick embryo.

Figure 35. Biochemical recapitulation of a chick embryo. From *Biology* (p. 707). By J. Kimball, 1965, Reading, MA: Addison-Wesley.

Kimball's use of biochemical recapitulation occurred at a time when biochemistry and molecular biology were new additions to high school biology texts. Because of this, one might think that biochemical recapitulation was a new concept in the 1960s. However, this is not true—Kimball simply capitalized on work carried out by biochemist John Needham some 45 years earlier. Needham's research focus in the 1920s was the biochemistry of the developing embryo (Armon, 2010, p. 178), and Kimball's redrawn graph is from Needham's 1926 article describing protein metabolism in chick embryos. Needham discovered that early chick embryos use protein as an energy source and release first urea, then ammonia, and finally uric acid. Needham believed that the passage of the chick embryo through various protein metabolism end products, illustrated a recapitulation of birds' aquatic ancestry (Needham, 1926).

Kimball's graph illustrates two things other than chick embryo metabolism. First, Kimball's biochemical recapitulation is an example of taking something old and making it look new. This is common in textbooks because content, in this case Needham's work and Kimball's subsequent use of Needham's work, is rarely situated in the history of biology or the nature of science. Second, biochemical recapitulation shows that biologists in the early 1900s may have rejected Haeckel's Biogenetic Law, but nevertheless, like Needham, they remained active in finding the meaning and causality for ontogenetic and phylogenetic similarities.

It is these examinations of rudiments like gill slits, tails, and swim bladders, and the fact that animals retain (and so "recapitulate) various organs from their ancestors that lead to what I call "recapitulation-lite" statements, in which organs and not whole adult stages are recapitulated in embryos. To Needham and Kimball, chicks move through ontogeny (ammonia to urea to uric acid excretion) in the same order as their ancestry (fish to amphibians to reptiles). This is somewhat different from how Haeckel explained recapitulation, but readers who are not experts in the field may very well feel that Kimball supported Haeckel's recapitulation ideas, especially when he also used a Romanes' embryo grid—the closest one can get to Haeckel's original grid without using Haeckel's grid itself.

Embryos in the grid also went molecular with the 1965 edition of *Modern Biology* by Otto and Towle. Here, embryos were presented as resembling one another in structure, development, and function. Similarities in function arise from the fact that "all embryos produce nucleic acids, especially DNA, and all use ATP in energy transfer" (p. 184). In their 1969 edition of *Modern Biology*, Otto and Towle replaced the use of nucleic acids and DNA with genes, making this text the first in my study to discuss embryonic genes and common ancestry. The authors state, “It would seem that all these animals received, from remote common ancestors, sets of genes that control development for a time. Later in the process, however, other genes assume control of the process and cause the fish, bird, and mammal to develop in different ways” (Otto & Towle, 1969, p. 187).

1970–1979.

By the end of the 1960s, basic notions of individual liberty championed by the ACLU made antievolution statutes seem virtually un-American, and fundamentalists sought new avenues of protest against the teaching of evolution in public schools (Larson, 1997). Coinciding with the return of evolution to the classroom in the 1960s, another round of antievolutionism appeared in the U.S. represented by the creation science movement in the 1970s. Creation scientists soon became a national force in biology education.

In May 1979, the Institute for Creation Research (ICR) proposed a resolution encouraging school districts and state legislatures to promote a balanced presentation of evolution and scientific creationism in public high schools. The ICR was careful to construct its resolution to appear simply as a suggestion; a suggestion that the ICR hoped would be adopted by boards of education. Antievolutionist Paul Ellwanger of South Carolina used the ICR’s resolution to develop sample legislation, requiring that public schools give equal time to creationism in the classroom. Louisiana and Arkansas soon passed balanced treatment bills, although the laws were later declared unconstitutional.

The “back-to-basics” movement also began in the U.S. during the 1970s, with a call to teach more basic facts and discuss less about controversial subjects like evolution. Perhaps in response to outside pressure, some publishers began dropping their embryo grids. Even the *BSCS Blue Version* removed its grid (the grid would return in 2001). Paralleling the drop in embryo grids was a decline in the emphasis on evolution in 1970's texts (Skoog, 1979). Other texts by BSCS, Weinberg, and Kimball though, continued with evolution and embryo grids despite the backlash against Darwin and evolution.

The 1970s mark the first time that some type of historical context was given to Haeckel's embryo grid. However, the history was not always correct. In Weinberg's 1977 issue of *An Inquiry into the Nature of Life*, von Baer is credited for the Biogenetic Law and students read that "biologists no longer accept von Baer's concept, though it lingers in popular legend" (Weinberg, 1977, p. 82).

In the 1970s, genes and DNA helped explain why embryos were similar. Others texts examined hemoglobin, nitrogenous waste, and ATP to explain similarities and common ancestors. At first I was surprised to see three texts still writing about recapitulation, but upon closer examination, I noted that the texts, written by Kimball or Oram, emphasized that biochemical recapitulation helped explain ancestry and not Haeckel's recapitulation of adult stages.

Overall, almost all grids in the 1970s provided an illustration of embryo similarities and nearly all authors explained how similarities in development suggested a common ancestor somewhere in evolution's history. These texts also gave the grids more historical background. This was fleeting though, as only two texts in the 1980s briefly discussed late 1800s embryology. After that, the historical reasons for the development and use of embryo grids was not discussed.

1980–1989.

In the early 1980s, creation advocate Paul Ellwanger returned to prominence with an "equal time" bill that soon appeared in states all over the country; by March 1981, 15 states had introduced bills calling for the teaching of creationism in the science classroom. The legal fight over these bills led to the 1981 *McLean v. Arkansas Board of Education*, where Arkansas's new balanced-treatment law was declared unconstitutional. In 1988, Ellwanger returned with his "Uniform Origins Policy," a second attempt at including creationism in the biology classroom as an alternative "theory" to evolution. Amidst the backdrop of legal and political debate over creation science in the classroom, I was interested in seeing if biology texts and embryo grids might now appear different from texts published in previous decades.

After the rather volatile 1970s in terms of evolution education, I expected that the number of embryo grids would decrease in the 1980s. The number of grids, however, increased, perhaps attributable to the fact that there were a number of new authors, often university biologists, who made the decision to publish embryo grids. Almost all of these books had specific evolution chapters and almost all of the embryo grids were used to support evolution.

While a large number of 1980s texts used embryo grids (83 percent), most of the authors described the embryos in the same way—similarities and common ancestors. Gills slits, kidney development, and tails served as examples of similar structures and common ancestry. Only one text described recapitulation, but even then, this was Kimball's familiar description of chick nitrogenous wastes serving an example of biochemical recapitulation.

An increased number of texts explained that recapitulation was not a valid way of explaining embryo development and ancestral lineages. In Garstang fashion, authors exclaimed that human embryos do not pass through fish, amphibian, and reptile stages but that embryos do show varying degrees of similarity in their development. Kraus' *Concepts in Modern Biology* (1984) takes a softer tone by saying, "biologists today accept the general idea of recapitulation only in the broadest sense, and Haeckel's precise statement is no longer recognized as valid" (p. 416). Kraus makes no attempt to explain what he means by general recapitulation and precise recapitulation, making the concept of recapitulation even more confusing.

Geneticist and former BSCS board member, Bruce Wallace and biologist George M. Simmons wrote *Biology For Living* (1987), published by Johns Hopkins University Press, the only text in this study published by a university press. Although classified as a biology book for college non-majors, this book was used by high school students across the country and even reviewed by former BSCS chairperson Bentley G. Glass as a suitable high school biology text (Glass, 1988). Wallace and Simmons declared that recapitulation, "taken literally of course, is nonsense" (p. 267). Their embryo grid was peculiar in that *Biology for Living* is the only text in this study to incorporate a higher being" into the discussion about embryo grids. Wallace and Simmons pointed out, "a Creator as a Master Engineer" could possibly direct embryo development, but that the process of evolution supported the traces of common ancestry that appeared during each organism's embryonic development. This could be a weak attempt to give equal time to creationism but the authors are clearly on the side of evolution by natural selection.

Overall, most of the embryo grids in the 1980s focused on how the embryos were similar during early stages of development and less similar during later stages. Closely related embryos like humans and monkeys remained similar for a longer period of time than say a human and a fish, leading to the assumption that humans and monkeys share a recent common ancestor. Tails, gills, and kidney development served as examples of common structures, which indicated common ancestry, and genetic expression served as a “new” mechanism to make early stage embryos appear similar and later stage embryos to differ.

1990–1999.

The 1990s is distinguished by teams of authors writing enormously thick biology textbooks. One exception to the multiple authors approach was John Kimball’s sixth edition of *Biology*, returning to the classroom after an eleven-year absence. True to form, Kimball used a Romanes’ embryo drawing, although two of Haeckel’s organisms, the hog and calf, were no longer present. I noted earlier in this section that Kimball wrote about biochemical recapitulation in his 1974 and 1978 editions of *Biology.* In 1994, however, Kimball declares that recapitulation is “a misconception.” Other texts also pointed out the invalidity of recapitulation and a few took liberty to call out Haeckel by name, as the originator of the idea of recapitulation.

The 1990s also mark the beginning of a text series by molecular biologist and ardent evolutionist Ken Miller (Miller also served as an expert witness in *Kitzmiller et al. v Dover Area School District et al.*) and biologist Joseph Levine. The 1991 and 1993 editions of *Biology* devoted five paragraphs to discussing the embryo grid. The authors stated that as far back as the late 1800s, scientists noticed that embryos of different organisms looked similar. The next sentence changes abruptly, stating that "today, no scientist would say that a human embryo is identical to a fish or a bird embryo." I found that statement to be a common one whenever authors felt the need to write a disclaimer about recapitulation. Discussion about why humans may have been thought to be, at one time identical to birds or fish is lacking. Because there is no context provided, the sentence always seems awkwardly placed, as if authors or publishers needed to make a statement to the peering eyes of fundamentalists or intelligent designers, to acknowledge that humans were never fish and subtly negating Haeckel's work.

In a different text by the same authors (Levine was lead author), the 1994 edition of *Biology: Discovering Life* provides more historical details to the embryo grid. The authors explained that Darwin and his contemporaries knew that early embryos looked similar and that the "earliest stages of development in 'lower' animals seem to be repeated in the early development of higher' animals such as ourselves" (Levine & Miller, 1994, p. 162). From there, Levine and Miller stated that embryo similarities led some of Darwin's contemporaries (but not Darwin) to believe that the embryological development of an individual repeats its species' evolutionary history, or in other words Haeckel's Biogenetic Law, even though Haeckel was not identified and ontogeny and phylogeny was not mentioned. The authors then asked, "Why should the embryos of related organisms retain similar features when adults of their species look quite different?" They explained in contemporary fashion that early embryo stages are "locked in" while later stages can have cells and tissues change freely without harming the embryo or fetus.

Other texts also addressed recapitulation such as the 1992 and 1998 editions of *BSCS Green Version*. The authors did not identify Haeckel or his Biogenetic Law, but in Miller and Levine fashion, they note that embryo similarities do not mean, "…that a human passes through fish, amphibian, or reptile stages during development" (BSCS, 1992, p. 216). In *Concepts in Modern Biology,* author David Kraus identified Haeckel by name and also wrote, "at no time does the human embryo swim and breathe like a fish or have scales like a fish" (Kraus, 1993, p. 421, Kraus, 1999, p. 421).

A key finding in this study is that textbooks dismissed recapitulation in the early 1990s, well before Michael Richardson's 1997 study and Jonathan Wells' subsequent attacks against Haeckel. *Modern Biology,* which now was written by teams of authors, appears to be the first text to quickly update its 1999 text in response to the renewed debate about Haeckel's drawings. For the first time in *Modern Biology's* long history, the authors identified Haeckel as the originator of the term "ontogeny recapitulates phylogeny" and wrote that "we now know that this is a bit of an exaggeration…and that during no stage of development does a gorilla look like an adult fish" (p. 291). In stating that the authors "now know," there is the feeling that scientists had only recently determined recapitulation to be questionable, along with maybe the whole of comparative embryology. The attempt to distance their texts from Haeckel was most likely due to Behe (1998) and Wells' (1999) claims that embryological support for evolution in textbooks continued to reference the "fraudulent" drawings of Ernst Haeckel.

Even with the renewed debates about Haeckel's suitability for textbooks, the 1990s represent the decade in which more Haeckel's embryo grids appeared in biology textbooks, compared to any other decade. For the most part, discussion of the grids remained unchanged from that of the 1980s, with Haeckel's embryos supporting von Baer's observation that embryos of different species appear similar in early stages of development.

2000–2010.

In the future, the early 2000s may signal the start of the disappearance of embryo grids. Reasons for this may vary, but one cannot rule out the influence of the intelligent design community and fundamentalist groups on school boards and text-decision making at the local and state levels. In 1998, anti-evolutionists upped their criticism of Haeckel by drawing their "facts" from Michael Richardson's 1997 study and from all places, an article written by Stephen J. Gould. Gould's 2000 article in *Natural History* criticized Haeckel for his embryo drawings and textbook publishers for their continued of Haeckel's embryo drawings in biology texts.

Scientists and creationists continued to square off over the teaching of evolution in high school classrooms and in the early 2000s, many states attempted to pass antievolution bills that would have limited or done away with the teaching of evolution in public schools (AIBS, 2014). Most of the bills never came up for a vote, but creationists pushed on, with their fight culminating in the *Kitzmiller et al. v Dover Area School District et al.* U. S. District court case in 2004.

The Dover School Board passed a resolution on October 18, 2004, requiring high school biology teachers to read a statement to their students before teaching evolution. The statement read that evolution was not a fact and that an alternative "theory" to evolution existed in the form of intelligent design. The Court struck down the Dover

High School Board's decision to require that biology teachers teach intelligent design alongside the teaching of evolution in 2005.

Biology textbook authors and publishers were undoubtedly aware of the increasing challenges against evolution. The concern for market shares in large textbook buying states like Texas and California may have led to changes in how textbooks presented evolution to students, including the use of embryo grids. I found fewer embryo grids (79 percent compared to 87 percent in the 1990s) and fewer human embryos in the grid. In the 1990s, 87 percent of the embryo grids contained human embryos; in the 2000s, this number dropped to 78 percent. In addition, the grids were not uniform. Unlike previous decades where several organisms and several developmental stages were drawn, the grids of the 2000s were a hodge-podge of organisms, stages, visual media, and intent of use. It seemed as if the grids were losing their gridness.

Textbooks published in the early 2000s also changed the role that embryo grids played in supporting the theory of evolution (see Figure 36). In examining all of the textbooks, a majority used embryo grids to point out similarities between early embryos, which authors then used to support the idea of common ancestors. In the 2000s, the number of texts using embryo grids to provide support for concept of common ancestry *and* the theory of evolution, dropped significantly. For example, the 2006 edition of *BSCS Green Version* states, "these [embryological] similarities do not mean that a human passes through fish, amphibian, or reptile stages during development. Rather, the similarities show that the same fundamental processes occur in the development of many different structures found in vertebrates (BSCS, 2006, p. 235). Whereas previous editions addressed the similarities as evidence for common ancestry, the green version in the

2000s addresses similarities as evidence of common development with no link to evolution or ancestry.

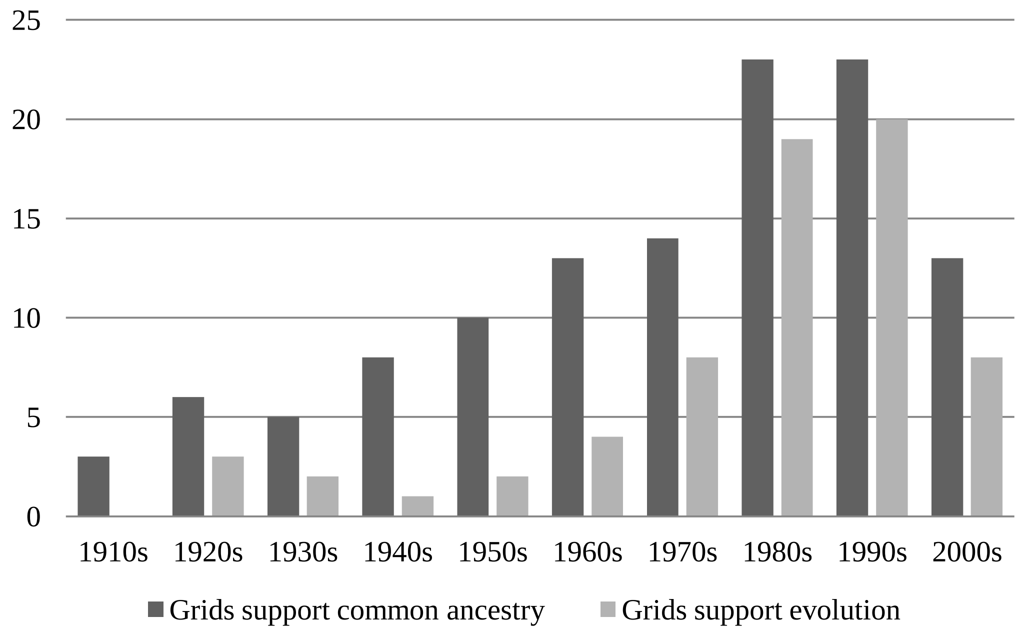


Figure 36. Grids showing support for common ancestry or evolution by decade.

Miller and Levine did not remove embryo grids from their *Biology* text, but in 2002, they did change their grid by replacing embryo drawings with embryo photographs. The authors addressed outside concerns about Haeckel by admitting that while the embryologist had "fudged" his drawings, there was still scientific merit to the idea that embryos are similar in certain stages of development:

> There have, in the past, been incorrect explanations for these similarities. Also, the great biologist Ernst Haeckel fudged some of his drawings to make the earliest stages of some embryos seem more similar than they actually are! Errors aside, however, it is clear that the same groups of embryonic cells develop in the same order and in similar patterns to produce the tissues and organs of all vertebrates. These common cells and tissues, growing in similar ways, produce the homologous structures discussed earlier. (Miller, 2002, p. 385)

In their 2008 edition of *Biology*, Miller and Levine used nearly the same deictic text to describe the embryo grid. With a slight rewording, the authors no longer saw Ernst Haeckel as a "great biologist," but merely a "biologist." Other authors and publishers did not expend the energy to change pictures or address the brewing debate over Haeckel's "forgeries." Here, authors used a standard embryo grid but made no mention of Haeckel, evolution, or controversies. For the most part, these texts used the grid to show that species are related and have homologous structures, or that related species have the same genes. The authors were careful not to include any hint of common ancestry in an embryo's road to relatedness, nor that related species and their homologous structures supported the theory of evolution. In this manner, the 2000s appear a bit like the 1930s where evolution was still discussed, but the word "evolution" itself was coded in such a way that kinship or relatedness was used in evolution's place.

Not all texts of course, disassociated embryo grids from evolution, but that does not mean that the relationship between grids and evolution was made clear. For example, in the 2006 edition of *Biology the Dynamics of Life* by lead author Alton Biggs, four photographs of embryos are shown (one is black and white and the rest are in color). Rather than a human embryo, there is a generic mammal embryo. The caption, shown in Figure 37, is confusing in that the authors do not state if the photographs are showing how similar embryos are or how different they are. A quick glance might lead you to believe that the embryos are similar because they are all curved and oriented in the same manner, but the fish has a long tail and the reptile embryo is hard to see it because it is still within a protective sac. The bird almost appears to be a cross-section rather than a whole organism. In the attempt to use photographs for embryo grids, the purpose of the grid is baffling.

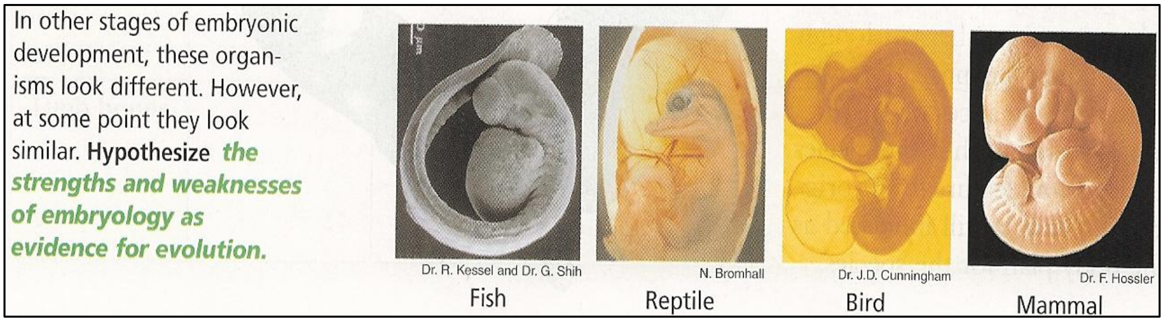


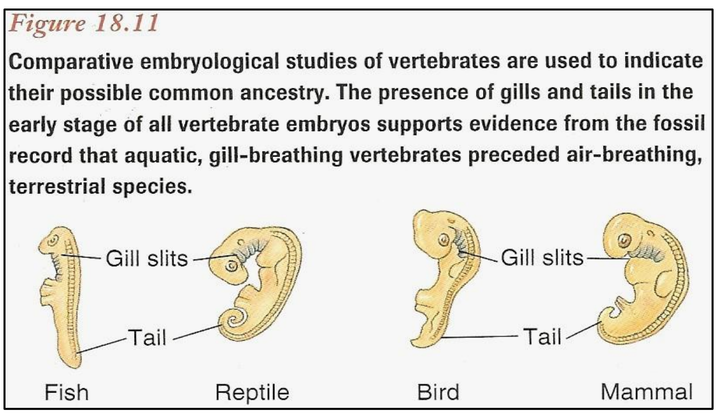
Figure 37. Grids in the 2000s became more difficult to interpret because of the use of photographs that were not standardized. From, *Biology the Dynamics of Life* (p. 402). By A. Biggs et al., 2006, New York: McGraw-Hill/Glencoe.

Along with substituting photographs for drawings, terminology changes were also in store for certain anatomical structures, namely gill slits. Gill slits and tail have always been part of the explanatory discussion of Haeckel's embryos. Haeckel did use the term gill slits, and so did other embryologists in the 1800s. Richardson and Keuck (2002) state that Haeckel did not believe the pharyngeal apparatus in humans represented adult fish gills and that Haeckel continues to be accused of advocating absurd recapitulatory scenarios like human embryos with actual fish gills, Regardless, like Haeckel's embryos themselves, gill slits have shown lasting presence in textbooks and are most often used to show anatomical homologies in embryos.

Most anatomy texts refer to prominent "gill" structures in the neck region as branchial or pharyngeal pouches, grooves, or ridges. Human pharyngeal ridges and folds develop into parts of the human face, ear cavities, thyroid, thymus gland and muscles for chewing. In the 1800s, embryologists noted the morphological similarities of the gill-forming structures of fish embryos to those of similarly placed structures in human embryos. The structures were colloquially named "gill slits," and although scientists make no claim that humans have ever had gills, the term is still used in scientific journals and textbooks.

Gill slits came to the public's attention when intelligent design follower Jonathan Wells, released his book, *Icons of Evolution* in 2000. In this publication and on his website, Wells insisted that embryonic mammals do not have gills. Wells claims that the only way to see gill slits in human embryos is to be fooled by the idea of evolution. While embryologists may have scoffed at Wells' arguments against the term gill-slits," publishers took notice.

In Alton Biggs' 1980 and 1990s editions of *Biology: The Dynamics of Life*, the term "gill slits" identified neck areas on embryos (see Figure 38). Beginning in 2004, Biggs used the term "pharyngeal pouches" to identify the same anatomical area. Authors Campbell, Reece, Mitchell, and Taylor replaced "gill slits" with the term "throat pouches" in *Biology Concepts and Connections* (2003).



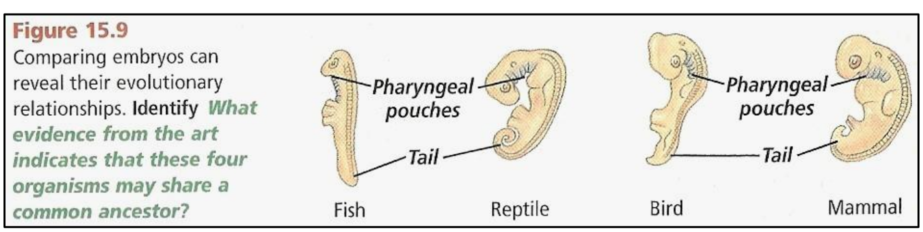


Figure 38. Gill slits and pharyngeal pouches. In *Biology the Dynamics of Life*, the 1998 edition uses the term "gill slits" (top) while the 2004 edition uses the same pictures but a different term, "pharyngeal pouches" (bottom). From *Biology the Dynamics of Life* (p. 433, top; p. 224 bottom). In A. Biggs, K. Dapicka, & L. Lundgren, 1998 and Biggs et al., 2004, New York: Glencoe.

Other authors simply dropped the use of the term “gill slits” entirely. Out of 19 texts that used embryo grids in the 2000s, only five mentioned gill slits in relation to the embryo grid. This is a noticeable drop from the 1980s and 1990s. In the world of embryologists however, gill slits are still important, especially with the knowledge about Hox genes, gene expression, and the field of evolutionary development. The largest amount of conservation in gene expression occurs in embryos that possess a pharyngeal arch and for years, textbooks considered the arch or gill slit part of the basic body plan of most vertebrates. One might think that Haeckel’s embryos would be a natural choice to illustrate these new research areas with, but this opportunity was lost in the 2000s, as publishers became homogeneously cautious about Haeckel and evolution.

Human embryos and human evolution.

Writing about evolution in secondary high school textbooks has never been easy for authors. Although most biologists accept evolution as the leading theory under which biology operates, the theory has always remained controversial in the U.S., thus making the teaching of evolution in public schools quite complicated. Early textbook authors often compromised by talking about evolution in a most general way and removed human evolution from discussion entirely. And yet, I found many embryo grids with human embryos in them. I was curious if authors would single out the human embryos and discuss them in terms of human evolution, human development, or common evolutionary ancestors.

The nature of textbooks is to provide students with more breadth than depth of a subject matter, so I knew that any discussion of human evolution would be at most, brief. As I coded the deictic text, I paid attention to discussion of human embryos. Figure 39 highlights those texts with human embryos in their Haeckel embryo grid and if the texts discussed human evolution (a quick survey showed that embryo grids *without* human embryos rarely discussed human evolution).

Textbooks published during the first four decades of the 1900s offer little discussion about human embryos, even when humans are in embryo grids. This is not surprising given that evolution was mainly invisible during this time. From the 1910s to the 1940s, humans were lumped with rabbits, pigs, and other mammals and simply described as “embryos of mammals look similar.” On the one hand, you could argue that authors wanted to avoid the controversy that might occur by using the term “human evolution,” while on the other hand, you could argue that authors wanted to make clear that humans are mammals and all mammals have similar evolutionary patterns.

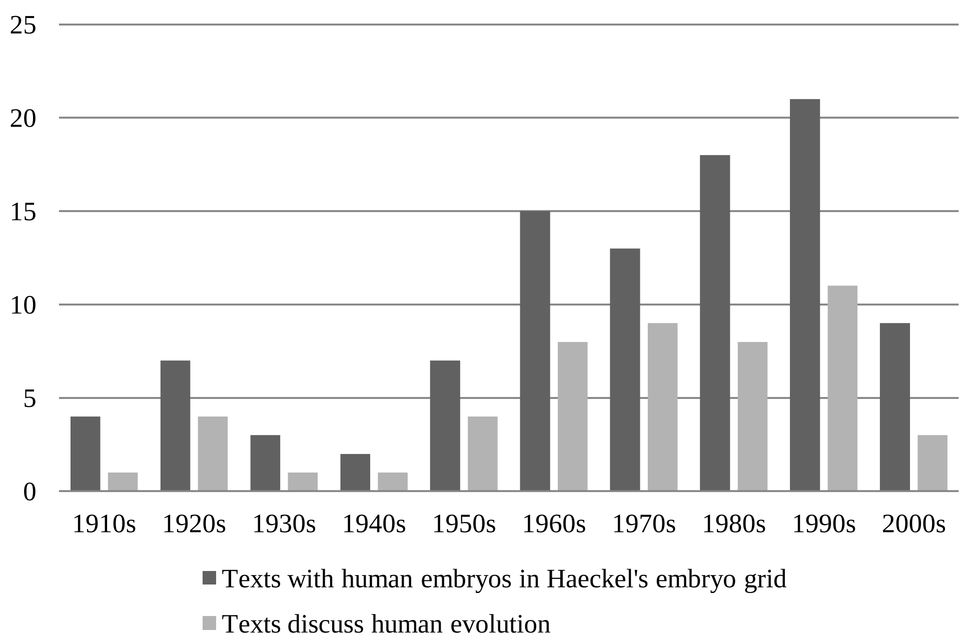


Fig. 39. Prevalence of human embryos in grids and discussion about human evolution.

In the 1950s, a few authors mentioned that human embryos had gill slits, which is evidence of common ancestry with fish. One author, Cyril Bibby, took a more progressive stance and his text is one of the first to mention humans, monkeys, and evolution in relation to the text's embryo grid:

> We have yet another reason for believing that evolution has occurred. As embryos grow, they pass through stages when they look rather like simpler living things. For example, at one stage the human embryo has gill pouches, and at another stage is covered with hairs. Perhaps these are reminders of the days when fish-like animals and later, monkey-like animals evolved towards humans. We are never really like fish or monkeys before we are born, but we are rather like the embryos of these and other animals. (Bibby, 1950, p. 119)

In the 1960s through the 1970s, the prevalence of humans in embryo grids and discussion about human evolution rose. One might attribute this to BSCS textbooks and their emphasis on evolution, but I did not find this to be true. While all three early BSCS versions contained embryo grids, only *BSCS Yellow Version* discussed the relatedness of humans and fish. The *BSCS Blue Version* placed its embryo grid in a chapter titled "Development" and the grid sat somewhat apart from the text's discussion about how embryos develop. The *BSCS Green Version* used its embryo grid to discuss Darwin's work (in a single paragraph, no less). That is not to say that human evolution was not discussed somewhere else in these texts. According to Skoog (2005), early BSCS textbooks did give heavy emphasis to human evolution (p. 405), but in my study, this emphasis was not found associated with grids.

In the 1980s, the number of grids with human embryos went up, but discussion of human evolution dropped; perhaps a reflection of the fact that human evolution was not a high school priority during this decade (Skoog, 2005). This trend continued into the 1990s as eleven grids with human embryos discussed human evolution and ten similar grids did not mentioning humans, or even mammals, at all.

In the 2000s, it was not only evolution and common ancestry that disappeared from grid discussions; there was also a significant drop in discussion about human evolution. One reason for the recent drop in the use of humans in embryo grids is the increased use of photographs rather than drawings. Photographs provide more "life" to an embryo grid and it is unlikely that publishers want to show case pictures of dead human embryos, knowing that textbook review committees might be quick to seize upon this fact. For those books with human embryos in grids, there tended to be little, if any discussion about humans in terms of evolution or common ancestry.

Section III. Hunter, Moon, Smith, and BSCS

One problem that can occur with examining such a large sample size is losing track of certain authors who published multiple editions of biology textbooks over several decades. Knowing this, I wanted to see if tracing a particular author's work would reveal any changes in the way that he or she used embryo grids. I chose four text series based primarily on longevity, but other factors also led me to select certain authors.

I chose George W. Hunter for several reasons. First, he is one of the authors who Philip Pauly discusses in his research about early American high school biology classrooms. Hunter is also the author of *Civic Biology*, which was at the center of the Scopes Trial in 1925, and he published a variety of texts, some written for rural high school students and others marketed to urban high school students. Would these texts for different audiences show changes in the use or even presence of embryo grids?

Truman J. Moon's *Modern Biology* is the longest running high school biology text in the U.S. *Modern Biology* first appeared as *Biology for Beginners* in 1921 and Moon was removed from the masthead of *Modern Biology* in the 1960s (even though he died in

1946). I felt that *Modern Biology*, published by a single publisher (Holt) over a long period of time, would provide me with a large number of texts to examine changes in secondary evolution education.

Ella T. Smith's *Exploring Biology* deserves attention for several reasons. First, Smith's texts are cited by Ladouceur as the first to include discussion about the evolutionary synthesis. Ladouceur also goes to bat for Smith's work, declaring it progressive rather than dull and drab as the BSCS liked to refer to all texts in the 1950s. With *Exploring Biology* published from 1938 through 1966, the opportunity arose to examine a well-selling text published after notable authors like Hunter and Gruenberg, had retired from writing school texts.

My last selection included all three of the original BSCS textbooks. Unlike most of the texts that I examine in Section III, BSCS texts were written by committees of writers. However, the literature is so rich with examinations of BSCS materials that I would be remiss if I too, did not examine these highly popular texts designed to reform biology education.

George W. Hunter and assorted texts.

Unlike Smith, Moon, and BSCS authors, who primarily published multiple editions of texts with the same title, Hunter presents a different situation. Starting in 1907 with *Elements of Biology*, Hunter then wrote six other differently titled biology texts, some with multiple editions, up to the year 1955 (see Table 6). Early biology textbooks written by other authors also show a similar pattern of writing different texts with different titles. This is partly explained by the fact that publishers did not want to lose rural markets and advocated for different biology books for different audiences (Shapiro, 2013, p. 76).

If all fourteen Hunter texts that I examined had had different embryo grids, it would have led to a difficult analysis, but this was not the case. In Hunter's early publications, such as his 1911 and 1923 *New Essentials of Biology* text, there is little, if any discussion about evolution. These texts introduced students to botany, physiology, health, and a progressive look at animals starting with single-celled organism and finishing with chapters on "man." In a chapter titled "Man, a Mammal" Hunter briefly discussed the evolution of humans, but only in how modern humans progressed from earlier humans (Hunter, 1911, pp. 319–320). There was no biological explanation of evolution and thus, no embryo grids.

Table 6

George W. Hunter's Text Titles and Publication Dates

Publication Date	Title
1907	*Elements of Biology*
1911	*New Essentials of Biology*
1914	*A Civic Biology*
1923	*New Essentials of Biology (2nd ed.)*
1926	*New Civic Biology*
1928	*New Essentials of Biology (3rd ed.)*
1931	*Problems in Biology*
1935	*Problems in Biology (2nd ed.)*
1937	*Biology: The Story of Living Things*
1939	*Problems in Biology (3rd ed.)*
1940	*Problems in Biology (4th ed.)*
1941	*Life Science: A Social Biology*
1949	*Biology in our Lives*
1955	*Biology in our Lives (2nd ed.)*

With Hunter's 1926 text, *New Civic Biology*, one paragraph was devoted to natural selection with information that "descendents can vary and a new species of plant or animal fitted for that special place, will be gradually formed" (Hunter, 1926, p. 383). Discussion of Darwin appeared at the end of the book in a chapter devoted to the men of science. Although Hunter described Darwin as a "great naturalist," there was no discussion of Darwin's theory of evolution by natural selection. Unsurprisingly, there were no Haeckel embryo grids in this text.

1937: Biology–The Story of Living Things.

In 1937, Hunter co-wrote *Biology: The Story of Living Things* with Herbert E. Walter, a Brown University biology professor, and George W. Hunter III, his son and professor of biology at Wesleyan University. This text provides tremendous attention to evolution. Compared to Hunter's earlier texts with only one or two paragraphs about natural selection, the 1937 text devotes over 45 pages to evolution in a chapter titled "The Epic of Evolution."

Hunter, Brown, and Hunter provided evidence of evolution from embryology by showing four invertebrates: *Daphnia*, *Sacculina* and *Balanus* barnacles, and a lobster (see Figure 40). The authors explained that although the four crustaceans were morphologically diverse in adult form, they appeared quite similar in their embryonic stages. The intent was to show students that embryologists look at similarities in embryos to see relationships that might otherwise not be apparent. Hunter's use of crustaceans is reminiscent of Fritz Müller's work with larval stages of a wide range of crustaceans. The larval stages appeared so similar to Müller's that the zoologist argued that the larval stage represented an adult common ancestor to the present-day crustaceans.

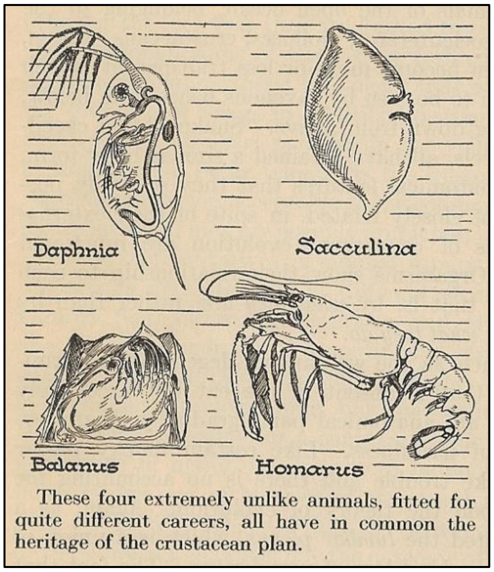


Figure 40. Hunter used crustacean larval forms to explain common ancestry in crustaceans. From *Biology: The Story of Living* Things (p. 500). By G. W. Hunter, H. E. Walter, & G. W. Hunter, 1937, New York: American Book.

Hunter et al. devoted several pages to recapitulation, using language similar to that found in de Beer's 1930 text, *Embryology and Evolution*. Hunter identified Haeckel as the originator of the Biogenetic Law and explained that Haeckel's idea of recapitulation had limitations. Certainly, Hunter proclaimed, "it is too much to ask of a hen's egg, which can develop into a chick in three weeks, to rehearse word for word a phylogenetic story that has required a million years to accomplish" (Hunter, Walter, & Hunter, 1937, p. 501).

Surprisingly, Hunter did not use Haeckel embryo drawings to illustrate recapitulation. He did however, utilize a large number of line drawings in this chapter, leaving me puzzled about the absence of an embryo grid. I include discussion about this text here though, because much like Gruenberg, Hunter capitalized on criticisms of recapitulation, taking critiques from the inner circle of scientists, in this case Garstang and de Beer in the 1920s and 1930s, to the external circle of lay people and students.

Hunter et al. further their evolution discussion with von Baer's observation that "the more nearly the adults of two groups resemble each other, the longer their embryonic development follows an identical path" (p. 502). Hunter compared Haeckel's idea of recapitulation to Morgan's "Repetition Theory" with the aid of two line diagrams (see Figure 41). With Morgan's theory, the embryonic stages run along parallel lines rather than run through the adult stages of lower organisms, reminiscent of von Baer's view of embryogenesis where for example, the development of a mammal runs parallel with that of the fish, and therefore it is likely that resemblances are to be expected.

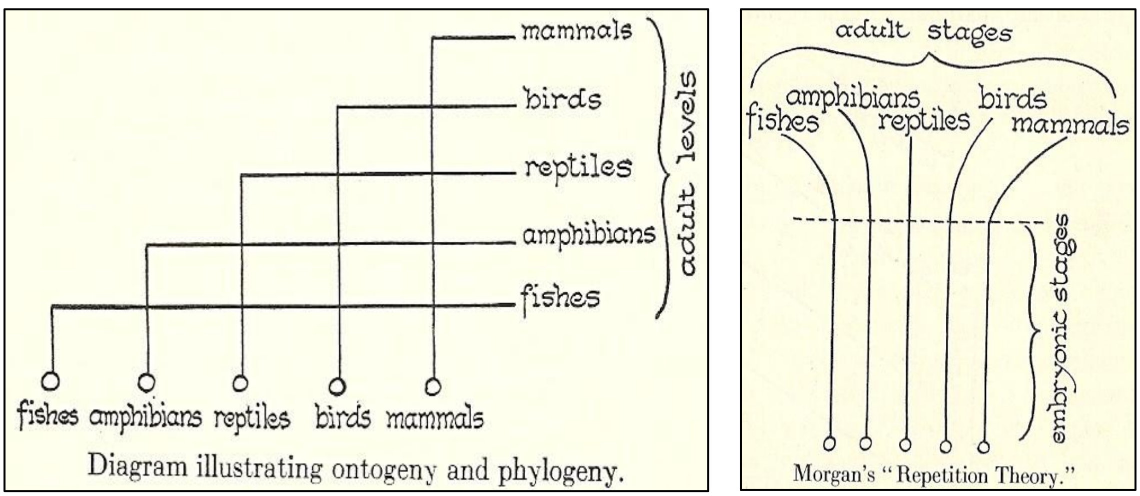


Diagram illustrating ontogeny and phylogeny.

Morgan's "Repetition Theory."

Figure 41. Hunter in 1937. Hunter used the schematic on the left to represent recapitulation while the diagram on the right represents Morgan's Repetition Theory. From *Biology: The Story of Living Things* (p. 502, left & p. 503, right). By G. W. Hunter, H. E. Walter, & G. W. Hunter Jr., 1937, New York: American Book.

Hunter also described C. Herbert Hurst's Divergence Theory, where the further one traces back an organism's ontogeny, the greater the resemblance to other organism's lines of development (see Figure 42). Hurst believed that Morgan's parallel lines of embryonic development should show more divergence and less parallelism. Hurst was a late 1800s opponent of Haeckel's Biogenetic Law and it is interesting to see Hunter discuss embryos from the viewpoints of Haeckel's opponents in a high school biology text.

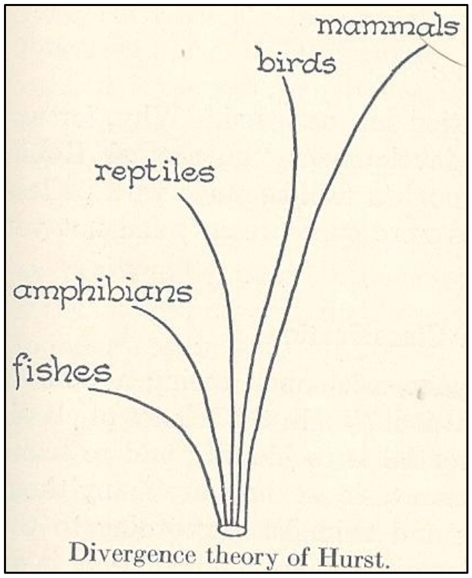


Figure 42. Hurst's Divergence Theory. From *Biology: The Story of Living Things* (p. 503). By G. W. Hunter, H. E. Walter, & G. W. Hunter, 1937, New York: American Book.

Hunter et al. end their discussion of embryology by referencing the work of Oscar Hertwig (1849–1922), a former student of Haeckel's at the University of Jena. An accomplished embryologist in his own right, Hertwig gave special criticism to his former mentor's recapitulation ideas in the early 1910s (Churchill, 1998). Hertwig was convinced that different species' eggs possessed certain "possibilities" that other eggs did not have. To Hertwig, evolution did not wait for embryos to pass through developmental stages of ancient ancestors—evolution had already occurred in the egg and different organisms attained different levels of possibility because of this fact.

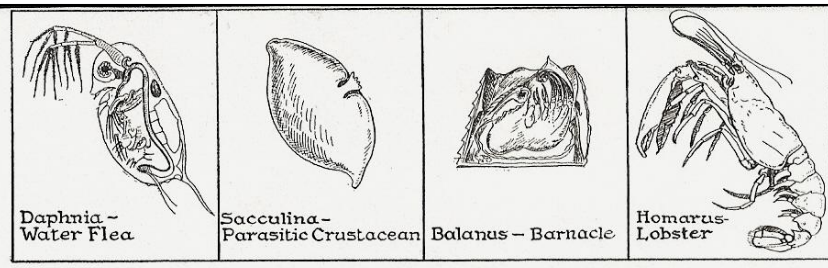
Even though Hunter pointed out differences in how scientists thought embryonic development should support evolution, he advised readers that even with all of these "speculations," the similarities exhibited by different vertebrates in embryogenesis suggested relationships even between very dissimilar adult forms, and these relationships implied evolution.

Hunter ended his section on embryology by asking critics of evolution, "Why, for example, should a mammal in its development, go around Robin Hood's barn in order to pass through a fishlike stage with useless gill pouches, unless such structures were once present, and not yet discarded, in ancestral fishes (Hunter et al., 1937, p. 504).

The thorough and detailed attention given to embryos by Hunter in this text was rarely seen in any biology textbook written in the 1930s. This text is the only book I examined that identified and described the ideas of Haeckel, von Baer, Morgan, Hurst, and O. Hertwig. The figures accompanying Hunter's discussion about recapitulation appeared only in this single edition 1937 textbook.

Hunter's later editions.

In 1941 Hunter published another biology text with only one publication run. With *Science: A Social Biology*, Hunter used the same four crustaceans that he used in his 1937 text to provide evidence for organic evolution. This time though, the adult organisms were arranged linearly in a grid-like fashion with a caption stating that although the organisms appeared differently as adults, they all showed relationships during embryological development (see Figure 43). The text accompanying the invertebrate embryo grid stated that the crustaceans were close relatives due to their embryonic similarities. Hunter then explained that vertebrate embryos appear similar early in development, but change with time, showing that "each animal in its development climbs its own ancestral tree" (Hunter, 1941, p. 515).



Here are four animals that are quite unlike as adults, but which show relationships through their embryological development.

Figure 43. Hunter used invertebrates in his “embryo” grid to provide evidence for evolution in 1941. From *Life Science: A Social Biology* (p. 514). By G. W. Hunter, 1941, New York: American Book.

The only Hunter text with a vertebrate embryo grid is *Biology in our Lives*, co-written with Hunter’s son in 1949. A second edition, published in 1955, used the same grid. Figure 44 shows the uncredited, but Romanes-like embryo grid appearing in a chapter subsection titled “Living Things are Alike yet Unlike.” The grid’s caption indicates that higher vertebrate embryos, like pigs (humans are noticeably absent from the grid) are similar in the development of embryos of lower vertebrates. The deictic text explained that there is a morphological relationship between human embryos and lower vertebrate embryos, namely gill slits., which provides evidence of common ancestry from embryology. The term “evolution” was not discussed in relation to the embryo grid.

In general, Hunter’s early texts reflect the tone of other early biology textbooks. Here, the concern was not focused on big idea or theories, but on practical applications of biology to the lives of students. Thus, keeping clean and healthy trumped Darwin’s ideas of evolution and Haeckel’s recapitulation work. It is not surprising to see an absence of Haeckel’s embryos in early 1910s and 1920s texts. There was no difference between Hunter’s urban texts (e.g., *A Civic Biology*) and his rural texts (e.g., *New Essentials of* Biology) in terms of embryo grids because there weren’t any.

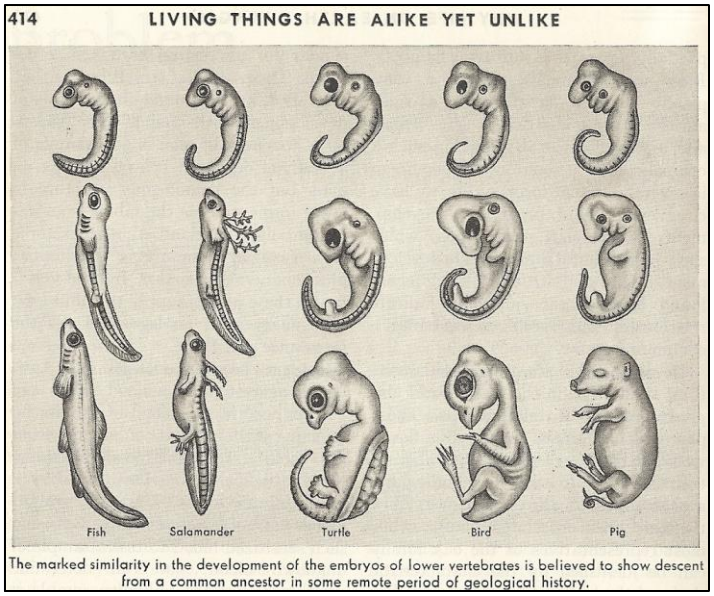


Figure 44. Hunter’s only vertebrate embryo grid. From *Biology in our Lives* (p. 414). By G. W. Hunter & F. R. Hunter, 1949, New York: American Book.

After examining Hunter’s texts, I remain amazed at his extensive discussion of recapitulation in the 1930s. Hunter addressed recapitulation far more than other authors did, but he still did not use an embryo grid. It is not until 1949 that a vertebrate embryo grid was incorporated into one of Hunter’s schoolbooks. With more embryo grids appearing in the early 1940s, Hunter’s long-time publisher, American Book, may have decided to simply join the cause.

Truman J. Moon and *Modern Biology.*

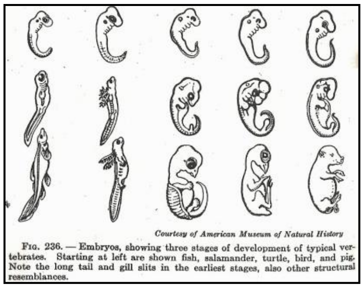
There is no other high school biology text series that has used Haeckel’s embryo grid more than *Modern Biology.* Table 7 represents the *Modern Biology* textbook series, beginning in 1921 with Truman J. Moon’s first text, *Biology for Beginners*. Moon wrote four editions of *Biology for Beginners,* with Paul Mann joining Moon to help write the third and fourth editions. In 1947, Moon’s text changed its name to *Modern Biology* and that title has remained unchanged ever since. The longevity of *Modern Biology* is even more remarkable by the fact that Holt remains its only publisher.

Table 7

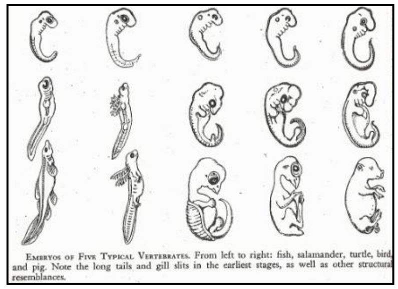
Truman J. Moon and Modern Biology Publication Dates

Publication Date	Title and Principle Author(s)
1921	*Biology for Beginners* (Moon)
1926	*Biology for Beginners (2nd ed.)* (Moon)
1933	*Biology for Beginners (3rd ed)* (Moon & Mann)
1938	*Biology for Beginners (4th ed.)* (Moon & Mann)
1947	*Modern Biology* (Moon, Mann, & Otto)
1951	*Modern Biology (2nd ed.)* (Moon, Mann, & Otto)
1956	*Modern Biology (3rd ed.)* (Moon, Mann, & Otto)
1960	*Modern Biology (4th ed.)* (Moon, Otto, & Towle)
1963	*Modern Biology (5th ed.)* (Moon, Otto & Towle)
1965	*Modern Biology (revised)* (Otto & Towle)
1969	*Modern Biology (6th ed.)* (Otto & Towle)
1973	*Modern Biology (7th ed.)* (Otto & Towle
1977	*Modern Biology (8th ed.)* (Otto & Towle)
1981	*Modern Biology (9th ed.)* (Otto & Towle)
1985	*Modern Biology (10th ed.)* (Otto & Towle)
1989	*Modern Biology (11th ed.)* (Towle)
1991	*Modern Biology (12th ed.)* Towle)
1993	*Modern Biology (13th ed.)* (Towle)
1999	*Modern Biology (14th ed.)* (Standafer)
2002	*Modern Biology (15th ed.)* (Alcamo)
2006	*Modern Biology (16th ed.)* (Postlethwait)
2009	*Modern Biology (17th ed.)* (Postlethwait)

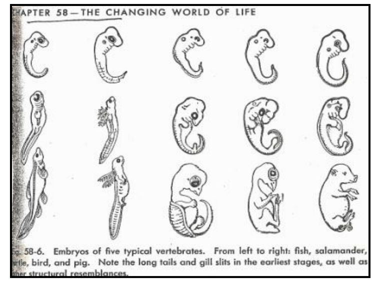
Other than the first two editions of *Biology for Beginners*, all subsequent 20 editions used a variety of embryo grids to support evolution. The variability includes large and small grids, grids with and without humans, illustrations of embryos and photographs of embryos, and black-and-white embryos and color embryos. These grids are chronologically arranged in Figure 45.



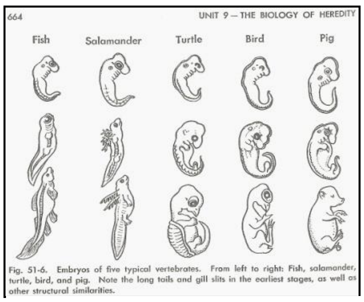
1933 and 1938



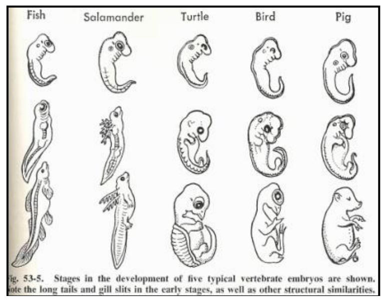
1947



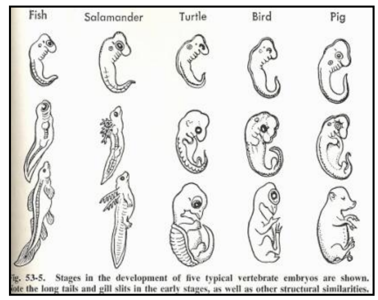
1951



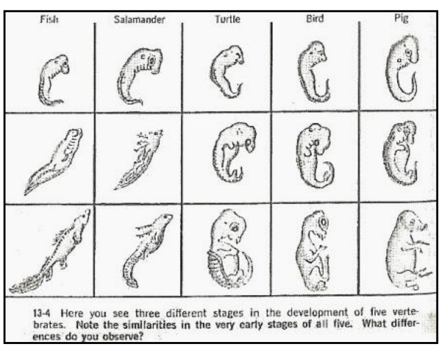
1956



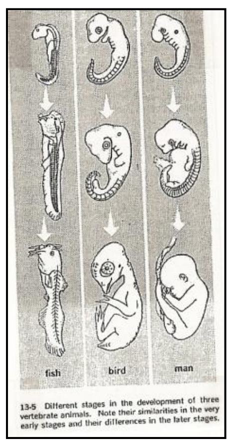
1960



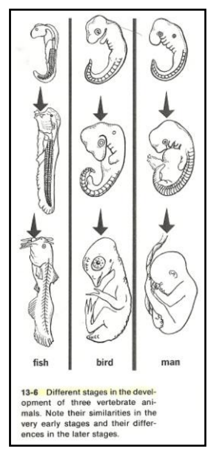
1963



1965



1969



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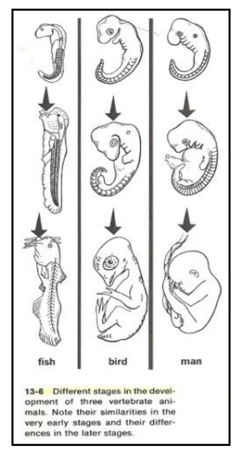

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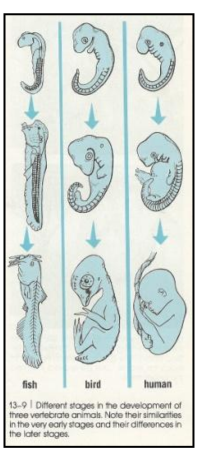

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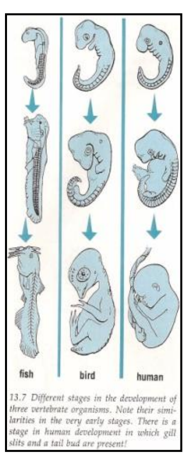

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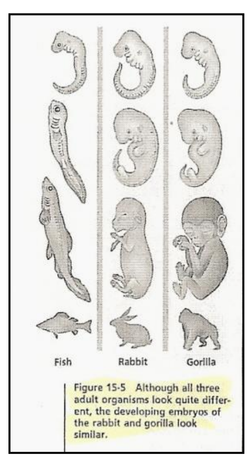
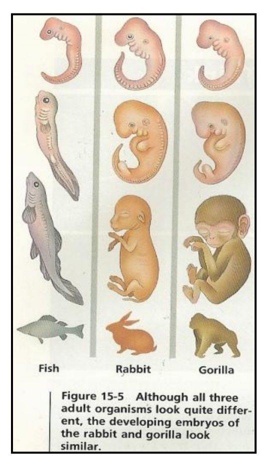
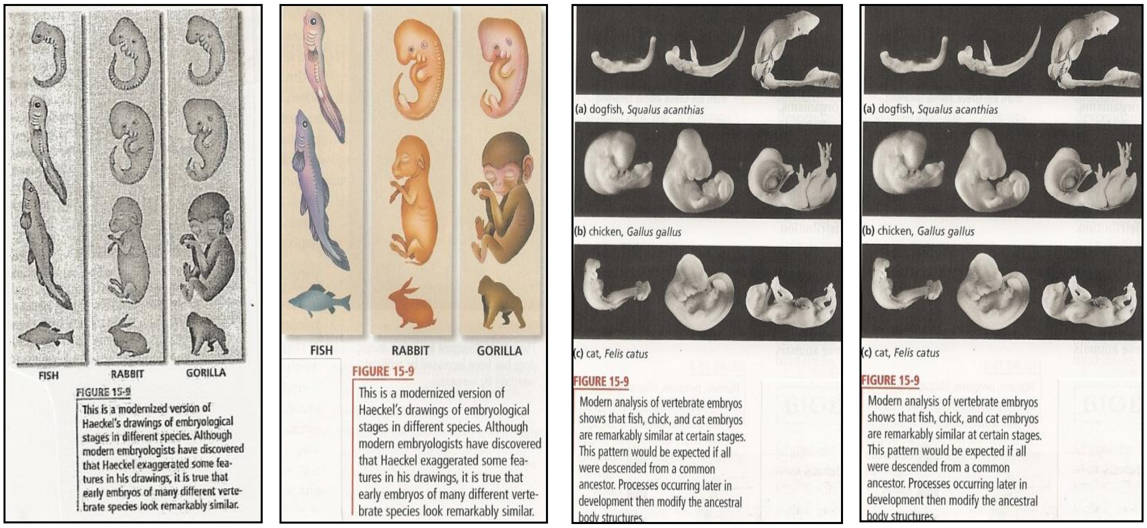
1989



1991



1993



1999 2002 2006 2009

Figure 45. Embryo grids in *Modern Biology* from 1933 to 2009. From *Modern Biology* and *Biology for Beginners* (see Appendix for full references).

Early Moon texts.

The third and fourth edition of *Biology for Beginners* (1933 and 1938) and the five editions of *Modern Biology* immediately following, used the same 5 x 3 grid of fish, salamander, turtle, bird, and pig embryos. In 1933 and 1938 the grid was credited to the American Museum of Natural History but thereafter, no credit for the drawing appears. The caption for these early grids remained the same: students were to note the long tail and gill slits in the earliest stages. A tail is usually easy to make out, but Moon does not label the gill slits, making students take a best guess where gill slits are located.

The deictic text accompanying the six embryo grids in these early books is as consistent as the embryo drawings themselves. Aided by two short paragraphs, the embryo grid shows gills slits and tails as evidence of common ancestry. Tails and two-chambered hearts all add up to "each animal in its individual development passes through stages which resemble its remote adult ancestors. The similarity of vertebrate embryos shows relationship through common ancestry" (Moon & Mann, 1938, p. 517). *Modern*

Biology described recapitulation as a developmental process that embryos underwent, thus lending evidence to the concept of common ancestry, even into the mid-1960s.

1965.

Perhaps motivated by the publication of BSCS texts in 1963, *Modern Biology* published a "revised edition" in 1965 to compete with the new BSCS texts that were cutting into *Modern Biology's* market. It is worth noting that the 1965 *Modern Biology* text, with an evolution chapter titled "The History of Man," was used by high school biology teacher Susan Epperson at Central High School in Little Rock, Arkansas. Epperson challenged the Arkansas law banning the teaching of evolution—the first challenge of an antievolution law since the trial of John Scopes in 1925. In 1968, the Supreme Court ruled unanimously in *Epperson vs. Arkansas* that banning the teaching of evolution violated the Due Process Clause of the Fourteenth Amendment and the Establishment Clause of the First Amendment to the Constitution (Moore, 2002).

In the 1965 edition, the embryo grid continued to use fish, salamanders, turtles, birds, and pigs, but there were noticeable changes. The embryo drawings seemed a bit cruder and horizontal and vertical lines were now part of the grid. The addition of lines appeared to make the embryos permanent in their placements. Since the fluidity of the grid is lost, I wonder if students had trouble recognizing that the development of embryos moved linearly, from left to right. The caption of the 1965 embryo grid no longer told students to note tails and gill slits. Rather, students were to note the similarities and differences in the very early stages of all five vertebrates.

The 1965 text continued using an embryo grid to show that "the evidence from embryology seems to indicate that each animal in its individual development passes through stages which resemble those of its remote ancestors" (Otto & Towle, 1965, p. 183) or in other words, recapitulation. For the first time, *Modern Biology* explained that not only were early stage embryos similar in form, but there was also a marked similarity in their function: "For instance, all organisms (including embryos) produce nucleic acids, especially DNA, and all use ATP in energy transfer" (p. 184). The commonalities that embryos possessed in terms of their biochemistry provided more embryological evidence for common ancestry.

1969–1990s.

Coming in late to biology's modern evolutionary synthesis, genes finally entered *Modern Biology's* embryo grid in 1969. The sixth edition of *Modern Biology* explains that embryos are similar because "all of these animals received, from some remote common ancestor, genes that control development for a time. Later, other genes take over and cause the fish, bird, and mammal to develop in different ways" (Otto & Towle, 1969, p. 187).

Not only does the 1969 discussion about embryos change, but there is also a makeover for the embryo grid. Starting in 1969 and continuing to 2002, each grids' embryos were arranged vertically and flipped so that they were all looking left, instead of right, and the number of organisms in each grid dropped from five to three. Surprisingly, published shortly after *Epperson vs. Arkansas*, a human embryo appears for the first time in *Modern* Biology in 1969 and stayed in the grid until 1985. In 1989, *Modern Biology* replaced the human embryo with that of a gorilla embryo. The gorilla remained in the embryo grid until 2002.

Also in 1969 and continuing through 1985, arrows appeared in the grid to show directionality. The arrows guided the student to start at the top of the grid where the youngest embryos were, and to continue downward to the most mature embryos (or, in the case of the human, a fetus). The horizontal lines seen with the grid in 1965 were removed, but vertical lines remained to separate the organisms from each other.

The chick embryo now showed more detail and was drawn in a different development stage. The fish embryo also changed, no longer appearing like one of Haeckel's original drawings, but looking more like a catfish. In 1989, *Modern Biology* placed adult forms in the embryo grid, resulting in a larger 3 x 4 grid. This practice of including adult forms continued until 1999.

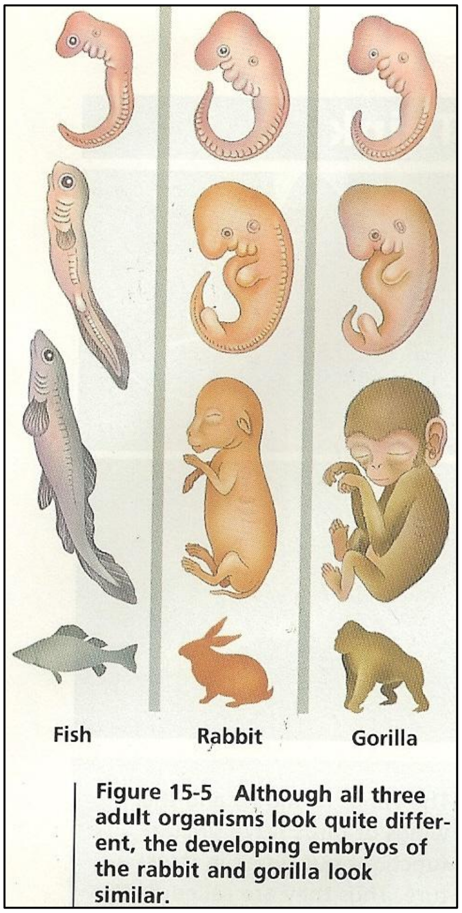
In 1999, in response to Richardson's study and the subsequent statements made by the intelligent design community about Haeckel, *Modern Biology* apparently felt obliged to mention Haeckel for the first time:

> The German zoologist Ernst Haeckel who was also struck by these similarities declared that "ontogeny recapitulates phylogeny." This statement can be translated to "embryological development repeats evolutionary history." We now know that this is a bit of an exaggeration. For example, during no stage of development does a gorilla look like an adult fish. In the early stages of development, all vertebrate embryos are similar, but those similarities fade as development proceeds. Nevertheless, the similarities in early embryonic stages of vertebrates can be taken as yet, another indication that vertebrates share a common ancestry. (Standafer, 1999, pp. 290–291)

Haeckel is also referred to in the 2002 version of *Modern Biology*, but later editions appeared to possess enough distance from the late 1990s uproar against Haeckel, and recapitulation's most famous proponent was not mentioned again in this text series.

Modern Biology in the 2000s.

The 2002 embryo grid (see Figure 46) is a bit smaller than previous grids, showing only two development stages and an adult form stage. The earliest stage from previous grids is missing, resulting in an early fish embryo that looks nothing like the rabbit or gorilla early stage embryos. With this embryo grid, the authors used rabbit and gorilla embryos to show that the more organisms are related, the longer embryos will look like each other during embryogenesis.



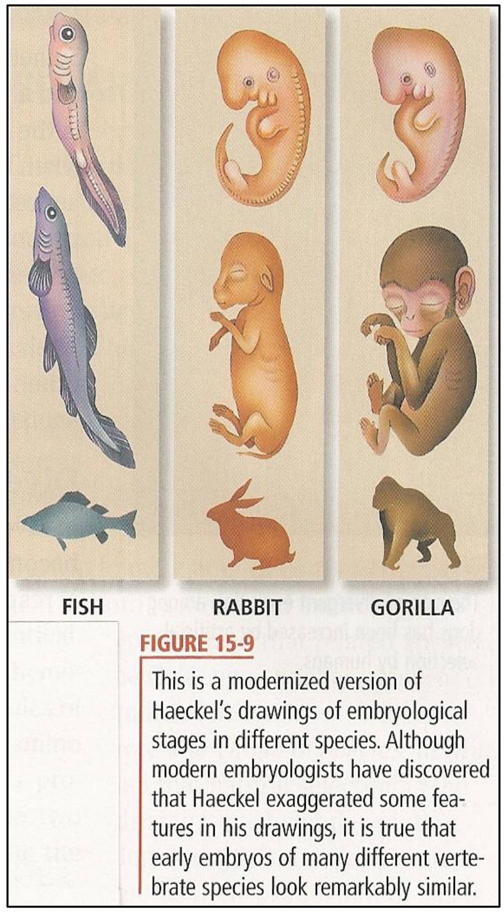


Figure 46. A comparison of *Modern Biology's* 1993 grid (left) to its 2002 grid (right). Note that the earliest stage in the 1993 grid is absent in the 2002 version. Haeckel is mentioned in the 2002 caption, but not in the 1993 caption. From *Modern Biology* (p. 224). By A. Towle, 1993, Austin, TX: Holt, Rinehart, & Winston (left) and *Modern Biology* (p. 291). By E. Alcamo & S. Feldkamp, 2002, Austin, TX: Holt, Rinehart, & Winston.

In 2006, *Modern Biology* changed its embryo grid again. The text's long history of using embryo drawings appeared over, as *Modern Biology* joined with Miller and Levine to use photographs of embryos instead. These embryo photographs were from a series of pictures credited to Ronan O'Rahilly of the Embryological Department of the Carnegie Institution of Washington.

The new *Modern Biology* text no longer placed oldest embryos at the bottom of the grid, but reverted back to a horizontal grid with the oldest organisms in the grid's rightmost column. The grids are identical in the 2006 and 2009 versions of *Modern Biology*, as are the grids' captions. Here, students read that embryos in *certain* stages are similar and that such similarities would be expected if organisms descended from a common ancestor. No longer does the caption state that *early* stage embryos are similar. The question I have with the grid, shown in Figure 47, is that none of the organisms seem at all similar in any of the developmental stages. Other than the middle-staged chicken and cat embryos, it appears as if the authors have gone out of their way to show that these embryos organisms do *not* have a common ancestor.

Modern Biology has been the source of criticism by science education researchers who point out the text's long running chapters on eugenics (Selden, 2007), its reluctance to use the word evolution in many of its editions (Skoog, 1979), and its dull and descriptive portrayal of biology (Ladouceur, 2008). However, the text series has always discussed evolution, although after the Scopes trial, the word "evolution" remained absent for several years. If you look closely though, natural selection, Darwin, and Haeckel's embryo grids are in all of the *Modern Biology* texts. Using a von Baer description, all of the embryo grids show students how early stage embryos are similar. In texts editions running from 1933 until 1963, gill slits and tails served as evidence for common ancestry. After 1963, the relationship of these structures and evolution was not discussed again, as gill slits were replaced by genes and heredity.

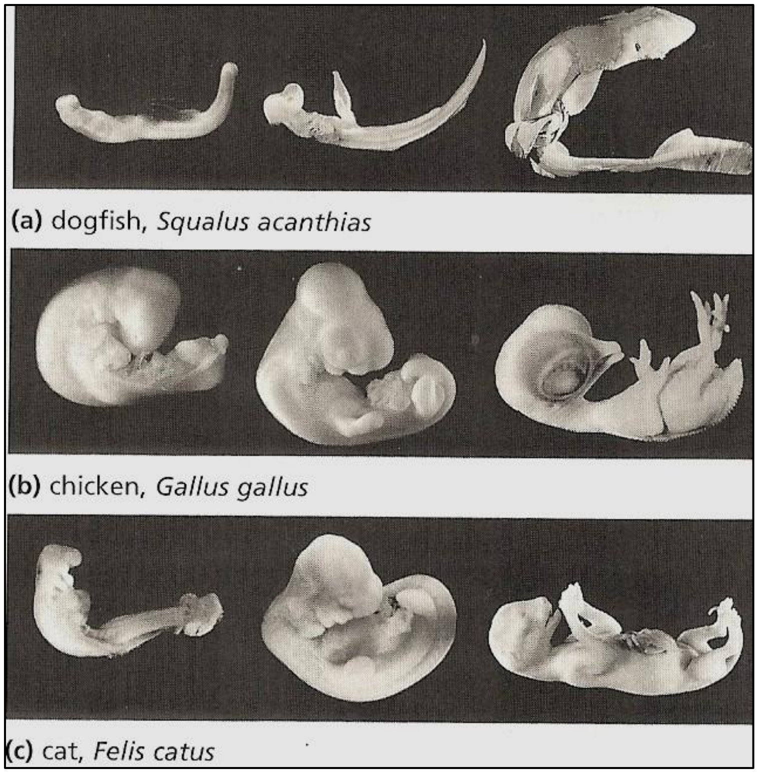


Figure 47. Embryo grid from 2006 and 2009 editions of *Modern Biology*. From *Modern Biology* (p. 306). In J. H. Postlethwait & J. L. Hopson, 2006, Austin, TX: Hold, Rinehart, & Winston.

Ella T. Smith and *Exploring Biology*.

Smith wrote high school biology texts over a 24-year period, beginning in 1938 with the publication of *Exploring Biology.* This text ran through nine editions with its final publication in 1966 (see Table 8). Smith's first two editions (1938 and 1942) did not use an embryo grid, but beginning in 1943 and continuing through the next four editions, the same 4 x 3 grid is seen and credited to the American Museum of Natural History. Clearly, the drawings of the fish, salamander, tortoise, and chick are copies made from Haeckel or more likely, Romanes' drawing.

Captions accompany all of Smith's embryo grids. In the 1943 and 1947 editions, the captions asked students to note, in von Baer fashion, how embryos are similar in their earliest stages. In 1949, the use of the term "progressive stages of development" was dropped from the caption, and in 1949 and 1952, the caption only identified the organisms in the grid (see Figure 48). In 1954, the last edition of *Exploring Biology* to use an embryo grid, the caption once again asks students to note the early similarities of embryos.

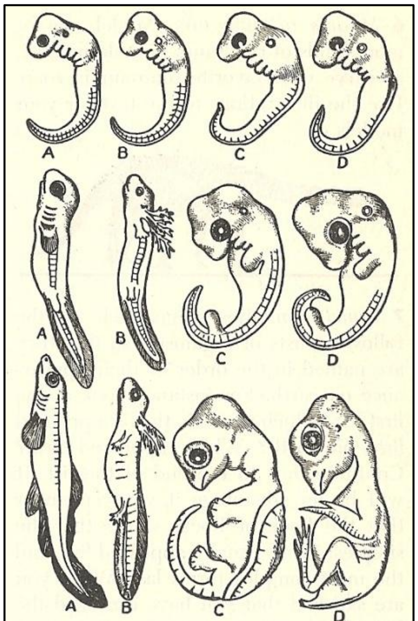
Table 8

Ella T. Smith and Exploring Biology Publication Dates

Publication Date	Title
1938	*Exploring Biology*
1942	*Exploring Biology (2nd ed.)*
1943	*Exploring Biology (3rd ed.)*
1947	*Exploring Biology (4th ed.)*
1949	*Exploring Biology (5th ed.)*
1952	*Exploring Biology (6th ed.)*
1954	*Exploring Biology (7th ed.)*
1959	*Exploring Biology (8th ed.)*
1966	*Exploring Biology (9th ed.)*

Smith used her embryo grids in several ways. In all grid-containing editions except for 1952, gills slits provided evidence that animals (she never refers to human embryos or human development) descended from fish and amphibians. In only one edition does Smith use the word "evolution" with the statement, "The study of the embryology of vertebrates certainly supports the idea of evolution as revealed by fossils (Smith, 1947, p. 541).

Smith also used the embryo grid to allude to the idea of recapitulation. She did not use the term "recapitulation" but she did discuss how stages in development briefly repeat past ancestry. For example, in 1949's *Exploring Biology*, Smith made a short statement supporting von Baer, “similar stages occur in the growth of all vertebrates” (p. 405). She then compares stages in chicks to probable ancestors of all birds. Students read that the



369 *Vertebrate embryos.* A, *fish;* B, *salamander;* C, *tortoise;* D, *chick. The drawings compare the embryos at progressive stages of development. Note how similar they are in the first stage shown.* (*American Museum of Natural History*)

Figure 48. Smith’s Haeckel-like embryo grid in *Exploring Biology.* From *Exploring Biology* (p. 540). By E. T. Smith, 1943, Chicago: Harcourt, Brace.

fertilized chick egg is similar to a one-celled animal, followed by the segmented stage of chick embryos, which is representative of segmented worms. The gill slit stage of the chick represents a fish ancestor and the three-chambered heart stage resembles an amphibian stage. In all, the worm, fish, and amphibian stages seem to repeat briefly the past ancestry of birds (p. 465). Even though most biologists at this time did not support recapitulation, Smith’s textbooks and others like hers continued to give the impression that Haeckel’s ideas were current and relevant to the study of biology.

BSCS and changes to the embryo grid.

The Biological Sciences Curriculum Study and its production of textbooks and teacher ancillary materials have provided a rich resource of study materials for science educators, historians of science, and educational researchers. The topic of evolution has proven particularly resilient in BSCS texts, causing both praise and condemnation.

Early BSCS writing committees focused on making evolution a continuous thread though all of biology and set a goal of publishing texts that were dramatically different from anything else available in the early 1960s. Knowing that embryo grids were in BSCS texts, I was particularly interested to see if BSCS made changes to the embryo grids themselves and how the grids were used to support evolution.

Analyzing all 24 editions of BSCS texts (see Table 9) can be messy because BSCS did not originally publish just one textbook, but three, all with a slightly different focus and all with different publishers. *BSCS Yellow Version* focused on cellular biology, *BSCS Blue Version* centered on molecular biology and biochemistry, and *BSCS Green Version* concentrated on ecology and biological communities. The blue and green versions continue publication, but BSCS stopped publication of the yellow version in 1980.

Early BSCS textbooks.

Three versions of BSCS texts appeared on the market in 1963, with second editions published in 1968, and third editions published in 1973. During this time, the materials were copyrighted by BSCS, which meant that BSCS maintained ownership of the materials and no changes could be made by the publisher without consent of the BSCS. The first editions all sported embryo grids and indeed, the grids were different from other textbook grids in two ways (see Figure 49). First, BSCS placed two additional early embryo stages at the top of the grids. Haeckel never included any drawings of early embryogenesis (i.e., cleavage, blastomeres, gastrulation, or early neurulation) in his embryo grids. Second, the BSCS grids now included adult forms, including “man,” and in the case of the blue and green version grids, chimpanzees were placed next to humans.

Table 9

BSCS Text Titles and Publication Dates

Publication Date	Title	Publisher
1963	*Blue Version*	Houghton-Mifflin
1963	*Green Version*	Rand McNally
1963	*Yellow Version*	Harcourt, Brace
1968	*Blue Version (2nd ed.)*	Houghton-Mifflin
1968	*Green Version (2nd ed.)*	Rand McNally
1968	*Yellow Version (2nd ed.)*	Harcourt, Brace
1973	*Blue Version (3rd ed.)*	Houghton-Mifflin
1973	*Green Version (3rd ed.)*	Rand McNally
1973	*Yellow Version (3rd ed.)*	Harcourt, Brace
1978	*Green Version (4th ed.)*	Rand McNally
1980	*Blue Version (4th ed.)*	Heath
1980	*Yellow Version (4th ed.)*	Harcourt, Brace
1982	*Green Version (5th ed.)*	Houghton-Mifflin
1985	*Blue Version (5th ed.)*	Heath
1987	*Green Version (6th ed.)*	Kendall-Hunt
1990	*Blue Version (6th ed.)*	Heath
1992	*Green Version (7th ed.)*	Kendall-Hunt
1996	*Blue Version (7th ed.)*	Heath
1998	*Green Version (8th ed.)*	Kendall-Hunt
2001	*Blue Version (8th ed.)*	Glencoe/McGraw-Hill
2002	*Green Version (9th ed.)*	Kendall-Hunt
2004	*Blue Version (9th ed.)*	Glencoe/McGraw-Hill
2006	*Green Version (10th ed.)*	Kendall-Hunt
2006	*Blue Version (10th ed.)*	Glencoe/McGraw-Hill

The yellow version's grid used fewer organisms and appeared less conventional by mixing up its four embryos so that man was on the left side, next to pigs, followed by salamanders and chickens, perhaps to challenge Haeckel's idea of evolutionary progress. The embryo grids in each of the yellow versions remained relatively unchanged through 1987. By 1987, the yellow version had already ceased publication and the blue and green versions were on different publication schedules.

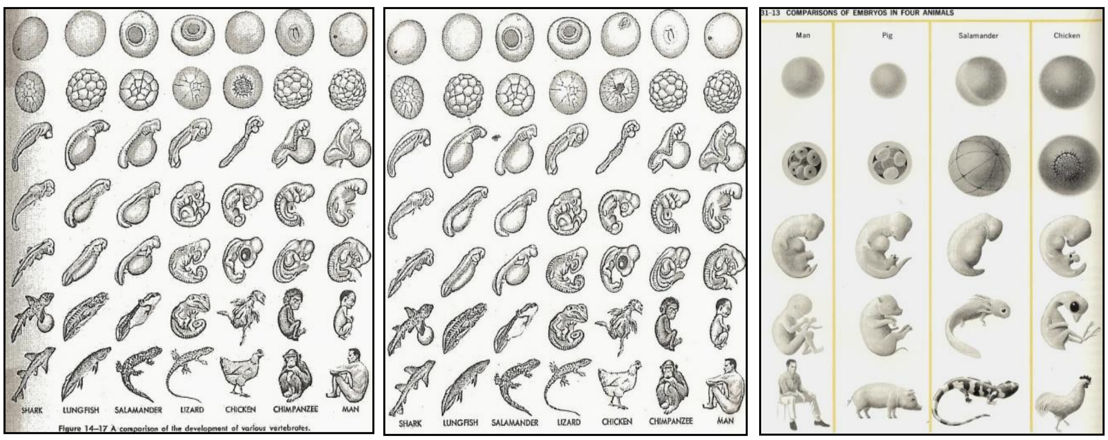


Figure 49. BSCS first edition embryo grids. All three first editions of BSCS Blue (left), Green (center) and Yellow (right) used an embryo grid with earlier embryo stages than previous textbook grids and adult forms. In the Blue and Green versions, embryo development progressed from left to right; in the Yellow version, development progressed from top to bottom (see Appendix for references).

***BSCS Molecules to Man: The Blue Version*.**

With different goals for each of the BSCS textbooks, I examined each version separately for embryo grid changes. I reviewed all ten editions of the *BSCS Blue Version*, noting that two new editions were published about every decade. The blue version underwent three publishing changes. The first three editions were published by Houghton-Mifflin. The next four editions were published by Heath, and the last three editions were published by Glencoe/McGraw-Hill.

Early blue versions placed embryo grids in chapters about development rather than evolution. Because of this, the embryos did not provide evidence of early ancestry. In 1973, the embryo grid disappeared from the blue version and did not reappear until the ninth edition, published in 2001. The 2001 embryo grid is the same as the embryo grid found in the 2002 *BSCS Green Version*. The blue version's recent editions continue to place embryo grids in chapters dealing with animal growth and development but there is now more discussion about the grid itself, compared to the 1960's versions. In the 2000s editions, embryos and development were condensed in a short paragraph identifying Darwin as one of the first biologists to compare embryos to help determine relationships between organisms. Molecular biology and genes seem to "prove Darwin right" in that similar genetic programs point towards a common ancestor.

BSCS An Ecological Approach: The Green Version.

Like the *BSCS Blue Version*, the more ecologically focused *BSCS Green Version* is currently in its tenth edition. The 1963 first edition displayed a large embryo grid, much larger than what most textbooks used at that time. The 7 x 7 grid used shark, lungfish, salamander, lizard, chicken, chimpanzee, and "man" embryos. The same grid was used in the 1968, 1973, and 1978 editions. The 1978 grid showed two changes: the introduction of horizontal lines and replacing the word "man" with the word "human." In 1987 the grid shrunk slightly as the shark embryo disappeared. In 1992, the grid shrunk even more as the lungfish and lizard were also removed from the grid. The resulting 4 x 7 grid, with salamander, chicken, chimpanzee, and human embryos continued up to the most recent edition in 2006 (see Figure 50).

Unlike the other two BSCS versions, the green version emphasizes Darwin with its embryo grid discussions. Students read that Darwin recognized that the structures of organisms might hold clues to the structures of their ancestors. And so, Darwin studied anatomy and embryology and became an expert on barnacles. The text does not actually refer to the embryo grid so the grid's caption becomes important. Here, the caption explains that the drawings represent the comparative embryology of some vertebrates. There is little in the way of descriptive text to inform students why the grid might contain important evidence for evolution.

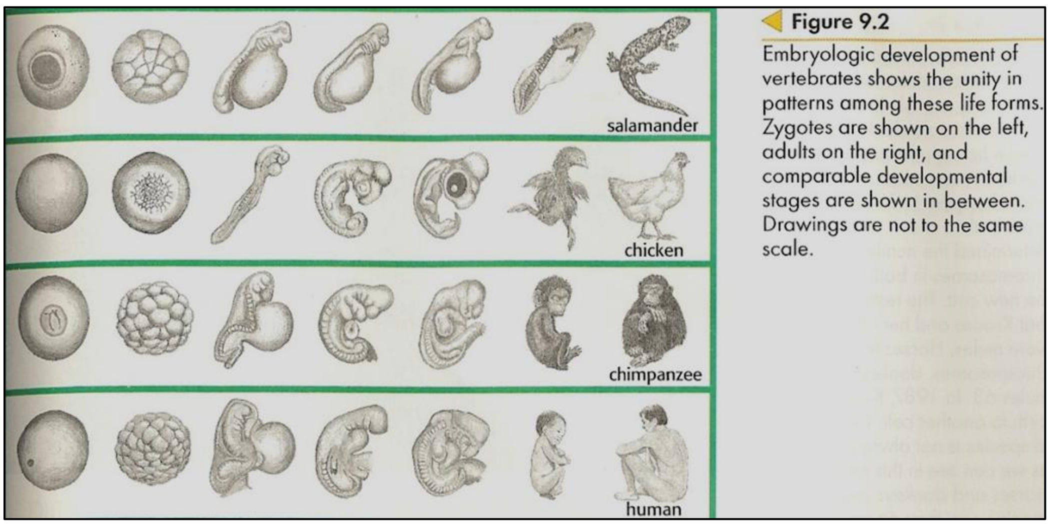


Figure 50. This *BSCS Green Version* grid appeared in its more recent editions. From *BSCS Green Version* (p. 235). By BSCS, 2006, Dubuque, IA: Kendall-Hunt.

In 1992, 1998, 2002, and 2006 green version editions, the embryo grid received more attention with, "as Figure 9.3 shows, for several vertebrates, the early stages of embryologic development are remarkably alike. These similarities do not mean that a human passes through fish, amphibian, or reptile stages during development. Rather, the similarities show that the same fundamental processes occur in the development of many different structures found in vertebrates" (BSCS, 1992, p. 216). The embryos are described in von Baer fashion and the text now explains that recapitulation, without mentioning the word, is defunct. One might conclude that the text changed to accommodate critics of Haeckel who became vocal after the 1997 Richardson study. However, this language appeared first in 1992, several years before publication of the Richardson et al. study.

BSCS An Inquiry into Life: The Yellow Version.

With only four editions, the *BSCS Yellow Version* is the only BSCS text series that is no longer in print. The editions, published by Harcourt, Brace in 1963, 1968, 1973, and 1980, use the same 4 x 5-embryo grid in a chapter titled “Darwinian Evolution.” The organisms in the grid never varied—students always saw chickens, salamanders, pigs and humans. The 1980 edition was the first (and only that I could find) text to use a female adult form in its embryo grid, and like the blue and green versions, the yellow version also included early embryo stages that resembled fertilized eggs and blastulas.

The 1963 text accompanying the embryo grid explained two things: that embryos were similar and that at one time in the latter half of the nineteenth century, “studies led to the conclusion that the embryonic development of the individual repeated the evolutionary history of the race.” Authors did not identify Haeckel, but they did mention his work with the statement that “so great was the desire on the part of some to strengthen this idea, that a classic series of drawing showing embryonic similarities was produced in which the resemblances of the embryos of fish and man were remarkable. They were so remarkable, in fact, that further investigation showed that overzealous artistry had indicated a few resemblances that did not quite exist” (p. 608). Students read that while a certain amount of recapitulation had merit, the idea that humans pass through fish, amphibian, and reptile stages was not correct.

Unlike the 1963 edition, the 1968, 1973, and 1980 editions of *BSCS Yellow Version* did not discuss Haeckel's drawings, but authors continued to inform that recapitulation was not scientifically correct. A deeper nature of science approach, explaining why Haeckel's recapitulation process was at first considered "right" and then "wrong" was not discussed. Nonetheless, the *BSCS Yellow Version* counters those claims made by Gould (2000) that textbook authors and publishers dumb down students by recklessly placing Haeckel's embryos in books. If one were to read these particular BSCS editions, he or she would agree that BSCS cautiously attempted to use the embryo grid to show similarities. The texts clearly state that embryos cannot be used to trace the evolutionary history of a species as Haeckel believed.

Overall, BSCS helped bring Haeckel's embryo grid back into textbook prominence. Over time, the BSCS grids were downsized, but human embryos were always present, in all versions and in all decades. The yellow version used its grid as evidence of evolution while the green and blue versions associated their grids with "adaptation" and "growth and development," respectively.

Summary of the four textbook series.

George Hunter's biology texts represent early 1900s views of biology education. Students memorized facts and numbers to help improve their daily lives, mainly in terms of good health and wise use of natural resources. Living things were not ignored either—organisms were described and discussed in an orderly progression. For example, Hunter has chapters on protozoa, mollusks, vertebrates, and finally, man. With no evolution chapters until the 1930s, Haeckel's embryo grid was not a good fit for Hunter.

Hunter wrote many biology texts and I was surprised that only one text, *Biology in our Lives* (1949; 1955) used a Haeckel embryo grid. Even with the modern synthesis well underway, Hunter treated the grid similar to that of pre-1940s authors: gill slits and early stage embryos provide evidence of evolution. I was unable to find any differences in Hunter's texts for rural students and his texts for urban students, as Hunter's formula for writing about evolution appeared the same for both audiences. By the late 1930s, when the idea of different texts for different students based on geographic location fell out of favor, Hunter increased his discussion about evolution by devoting several chapters to evolution and inclusion of the embryo grid.

Modern Biology has consistently discussed evolution. In the early 1920s through the 1940s, Truman J. Moon and co-authors scattered the concept of evolution here and there, and replaced the term "evolution" with chapters titled "The Facts of Racial Development through the Ages," (1938) or "The Changing World" (1947). From 1933 to the mid-1960s, the long-running textbook series provided many embryo grids that were unchanged and non-controversial. One of the reasons that Moon's early grids remained uncontroversial was their lack of human embryos and a simple statement that told students to note similarities in early stages and differences in later stages. This was hardly alarming to any anti-evolutionists since Moon did not explain how embryos provided evidence for evolution and common ancestry.

In 1969, *Modern Biology* added humans to the grid, perhaps influenced by BSCS texts with their redrawn and expanded embryo grids. Even with growing anti-evolution sentiment in the U.S., human embryos in grids remained in *Modern Biology* until 1989. The publication of *Modern Biology* in 1989 signified a change in authorship and organisms in the grid. James Otto, a long-time evolutionist who died in 1972 was finally removed from the masthead and authorship fell to Albert Towle. Perhaps with a new direction and mounting controversy about the teaching of evolution in public schools, Towle and Holt Publishing decided to avoid confrontation (and decreasing sales) by removing the grid's human embryo and replacing it with a gorilla. That is, students were instructed to note similarities, without having to think of one's self-relatedness to rabbits and fish.

Modern Biology also reflects a change in the visual representation of grid embryos. Publishers began using photographs of embryos to make grids "more real." I find it unlikely that grids will continue to use human embryos, if and when, publishers convert their drawings of embryos to photographs of embryos. With embryo grids already under scrutiny by religious groups, pictures of human embryos or fetuses may add another layer of controversy.

Ella T. Smith's work has received recent praise by Ronald Ladouceur and evolutionary biologist Rudolf A. Raff for incorporating evolution into biology textbooks at a time when most authors avoided the troublesome concept. Raff also praises Smith for her incorporation of human evolution in texts (Raff, 2012, p. 60) and Ladouceur (2008) compliments Smith for staying up-to-date with biology. However, out of the five editions of *Exploring Biology* that used embryo grids, evolution was mentioned only once in reference to the grid. Without this key concept, it undoubtedly was difficult for students to see the link between embryology and evolution.

Like George Hunter, Smith avoided using humans in her embryo grids. While human embryos did appear in grids prior to the 1960s, it was not a common occurrence. Smith's grids appear to follow the norm of her times, one in which pig and rabbit embryos were deemed fit for students, but not human embryos.

No matter which edition I examined, *Exploring Biology's* embryo grids and accompanying text were essentially the same. Whether all of Smith's texts presented such repetitiveness is beyond the scope of this study, but her predictable writing about embryology and evolution could not have helped her when it came to BSCS's cursory examination and critical report of the antiquated nature of 1950's biology texts.

Smith and Hunter's texts read similarly in terms of "same content, different editions," but I would not attribute this to lackadaisical work habits or that science in the earlier 1900s was static. Rather, I think it is reflection of the difficulties that single authors face when updating his or her texts in a rapidly changing world. Writing textbooks was not the sole occupation of Smith or Hunter—teaching high school students took up much of their days and they most probably did not have the time to research new findings and rewrite texts to reflect how rapidly biology was changing.

The BSCS texts provided me with a good look at how embryo grid narratives differed depending on the focus of a textbook. While it is true that all three BSCS versions used embryo grids, the grids were not the same in appearance, nor in description. The green version, with its focus on ecology, briefly discussed the embryo grid in terms of Darwin's discoveries. In 1978, the green version's grid also supported common ancestry. In 1992, the same version hinted that recapitulation was no longer accepted by scientists but that embryos went through stages of similar development, which provided evidence of common ancestry. The yellow version discussed embryo grids in the most detail, pointing out as early as 1963 that human embryos did not go through stages resembling adults of ancient ancestors. In addition, the yellow version always used its grid to show how embryo similarities supported evolution.

The blue version's earliest grid appeared in a chapter titled "Animal Growth and Development," and not in the chapter devoted to evolution. The diagram provided evidence that vertebrates develop similarly, but the authors did not elaborate further on how embryos provide evidence for common ancestors or evolution. This changed in 2001, when the blue version authors kept the grid in the development chapter, but now wrote about embryos providing evidence for common ancestry.

Discussion about the BSCS grids left me a bit underwhelmed. The grids themselves were noticeably bigger, with more stages and more organisms, but the authors seemed to let the grids do the talking, rather than the text. Few of the BSCS texts addressed the embryo grids in context of Haeckel's ideas or embryology in the late 1800s. The yellow and some of the green versions told students that human embryos never pass through fish or amphibian stages, but the statements seemed oddly placed, with no discussion about why scientists would have supported such a notion in the first place.

SUMMARY AND CONCLUSIONS

> We should therefore not be surprised that Haeckel's drawings entered nineteenth Century textbooks. But we do, I think, have the right to be both astonished and ashamed by the century of mindless recycling that has led to the persistence of these drawings in a large number, if not a majority, of modern textbooks!

Stephen Jay Gould, 2000

> Haeckel's inaccurate drawings and inaccurate claims about invertebrate embryos keep appearing in textbooks, and this inaccurate material is being used for the purpose of overstating the evidence for evolution. The evidence should be presented accurately and these drawings and other inaccurate claims should be removed.

Steve Olson, *Evolution News and Views*, 2011

Ernst Haeckel's embryo drawings represent a visual image of a scientific idea, and because scientific images have the capacity to say more or less than what the illustrator intended, Haeckel's embryo grids possess the capacity to raise a great deal of interest. Whether presented to Haeckel's public audiences, argued over by Haeckel's adversaries like Wilhelm His, criticized by Stephen J. Gould and Michael Richardson, or, as evidenced by Steve Olson's quote above, attacked by creationists and intelligent design followers, the little grid of embryos remains a showcase of visual ambiguity and controversy.

I entered this research with a head-scratching question—if Ernst Haeckel's embryos are no longer viewed by scientists as evidence of recapitulation, why then are Haeckel's embryos and their facsimiles still used in high school biology textbooks? After examining a large number of texts, I know that (a) no other textbook illustration is more prevalent and resilient than Haeckel's comparative embryology illustrations, and (b) authors use embryo grids in ways other than discussing recapitulation.

With biology textbooks published from 1907 to 2010, the most common use of embryo grids is to illustrate similarities and differences between vertebrate embryos, much like von Baer's descriptions. That is, authors use embryo grids to show that, while adults of different vertebrates look different from one another, their embryos go through developmental stages in which they strongly resemble one another. More recent textbook use of embryo grids describe the stage where embryos most resemble each other—the phylotypic stage. During this time, vertebrate embryos exhibit common characteristics: notochords and a dorsal nerve cord, gill slits, tails, and somites. Although von Baer and his colleagues knew nothing about genes in the mid-1880s, the best available interpretation today is that the phylotypic stage is the period of gene expression by Hox and other genes to establish the vertebrate body plan.

Similarities though, are not the only narrative that accompanies embryo grids. In the 1940s, embryo grid use skyrocketed. With the modern synthesis well underway, was the increase in grids a reflection of a society that suddenly became more tolerant of evolution? We know that not to be true. The main reason for an increase in grids at this time is simply that there were many new authors. Textbook publishers inevitably copy each other so it is not surprising to see many more textbooks, all displaying the same types of embryo grids.

It is also no secret that publishing is expensive. Once a certain format for a text is set in place, similar illustrations will repeatedly appear in newer editions. This was evidenced by the similarities of 1940s and 1950s texts written by the same author and is one reason why BSCS committee members railed so much against pre-1960's textbooks.

The 1990s represent a time when Haeckel's work was again brought into question. The number of embryo grids in texts at this time however, do not reflect the controversy—embryo grid use actually went up. It would be easy to say that authors banded together and decided to put up a unified fight to promote embryo grids, but the reason most probably falls in line with a "safety in numbers" approach. That is, if enough authors used embryo grids, it was ok for other authors to follow suit.

The decrease in embryo grids in the early 2000s is likely a reflection of two things–a decrease in the number of texts published and an increase in anti-evolution rhetoric. Authors either dropped grids or modified them in ways that made it difficult to use the embryo drawings or photographs for comparison purposes. Haeckel used many different vertebrates to show the relatedness of organisms and in a sense, that the animal kingdom itself was an organic "individual." It was indeed possible that by simply looking Haeckel's embryo grid, the notion of common ancestry and relatedness was conveyed to Haeckel's audience without the grid having to call much attention to itself. Perhaps embryo grids have a silent narrative all to themselves, but I argue that the grids need to be large in order to make this inference. This was definitely not the case in the early 2000s. Discussion of evolution and common ancestry dropped and the grids that were left to do the "talking" were too small to allow students to recognize any relationship building between embryology and evolution, let alone visualize Haeckel's original idea.

If you want to compare the morphology of embryos, logic tells you to line them up in a way that you can view and compare all of the embryos quickly and simply. Using a grid becomes a logical choice. So, what is all of the fuss about Haeckel's embryo grids? Embryo grids, in all of their many shapes and sizes imply common ancestry and the theory of evolution by natural selection. Therefore, it does not matter that I was unable to find an actual grid of Haeckel's in any of these textbooks. All embryo grids are suspect to anti-evolutionists since Haeckel is most associated with this way of comparing embryos. However, it seems unfair to condemn a textbook for using the most logical manner to make a valid point: similarities in structure are evidence for common ancestry.

Proponents of intelligent design are correct, to some extent, when they state that biology textbooks use Haeckel's embryos to support a now-defunct scientific idea. My study indicates that critics need to replace the word "use" with the past tense "used." I did find texts, even in the 1940s and 1950s, using grids to support Haeckel's idea of recapitulation, although this was not common practice for that time period. Authors such as Ruth Dodge, James Otto, and Albert Towle apparently were unable to give up on Haeckel's recapitulation even though the idea had fallen out of scientific favor many years prior. In my survey, the most recent text stating that each individual embryo passes through stages of adult remote ancestors was Moon and Mann's rather ironically titled *Modern Biology*, published in 1965. In most textbooks however, Haeckel's idea of recapitulation had parted company with embryo grids long before 1965. Contrary to what intelligent design websites would lead the public to believe, embryo grids are no longer trying to resurrect recapitulation.

One of my driving questions was how tangled up have Haeckel's embryos become as a consequence of socio-political influences on the teaching of evolution in high school biology classes. I found no instances of Haeckel's grid coming under attack in textbooks until the late 1990s. Evolution as a teachable concept though, certainly experienced periods in which textbook discussion about evolution decreased. This was most evident in the 1920s and 1930s where wrangling over evolution saw a decrease in textbook evolution topics, and with it, a limited use of embryo grids.

After 1940, embryo grids became common in textbooks although the use of human embryos in the grid was severely curtailed. As long as the embryo grid served a scientific purpose and excluded human development, embryo grids were of little concern. The 1960s through 1990s saw embryo grids seemingly immune to the effects of religious fundamentalists' call for either equal time in the teaching of creationism in biology or the ability of school districts to opt out of teaching evolution in entirety. One reason why embryo grids remained in texts is that after the 1960s, no authors discussed recapitulation.

The relative non-controversy of embryo grids ended in the late 1990s with the culmination of (a) Michael Richardson's study, (b) Jonathan Wells' publications, (c) an increase in internet sites condemning Haeckel and textbook authors by the intelligent design community, and (d) an American public that remained conflicted over evolution.

Late 1990s and early 2000s biology textbooks reflect when the politicization of Haeckel's embryos occurred. Several textbook authors seemingly went out of their way to include disclaimers about Haeckel and "ontogeny recapitulates phylogeny." References to embryo grids now included the admission that human embryos never were, and would never be part fish, amphibians, reptiles, or birds. None of the texts stated that humans were never monkeys or gorillas during development either, but you could argue that it was implied. The sudden appearance of disclaimers made it seem as if scientists had either only recently discovered that Haeckel's Biogenetic Law was not correct, or that scientists had "covered up" Haeckel's work and allowed the idea of recapitulation to survive for many years in student's books.

Human embryos cause concern for religious fundamentalists, intelligent designers, and members of certain political parties. Embryologists may argue that an embryo is an embryo, but to much of society, a human embryo is different, and this difference affects whether human embryos remain in textbook grids. Before the 1960s, humans in grids were not common and if present, little attention was given to them by authors. One can argue that having human embryos present was a quiet way to infer human evolution—nothing more needed to be said.

It is fair to say that BSCS textbooks in the 1960s helped put humans back in the grid. Placing humans in an embryo grid assumes that humans are vertebrate animals. By removing humans, the assumption is that we deserve a category all to ourselves. A recent poll found that 46 per cent of Americans reject evolution as an explanation of human origins (NCSE, 2012). This number has not changed significantly in thirty years, which makes me think that science education has not made much of an impact. Publishers know these poll numbers, and despite national science standards to increase treatment of evolution in public high school textbooks, removing humans from the grid, noticeably evident in the 2000s, represents a negotiated middle ground, where comparing embryos of other vertebrates is acceptable, but treating human embryos in the same fashion is not.

When it comes to Haeckel and his modern critics, the issue isn't simply about comparative embryology, but trust. Not just Haeckel, but the trust of evolutionists and perhaps science in general. With growing anti-science and anti-intellectualism sentiment in the U.S., Haeckel is an easy target. If the forgeries of Haeckel are seemingly upheld by scientists and authors, what else about evolution are scientists holding back on? Is the whole of evolution based on false premises, mistakes, and hoaxes?

It was under this swirling uncertainty that textbook authors in the 2000s appeared unsure of exactly what to do with the embryo grid. Their grids shrunk and with it, an understanding of the history of comparative embryology. It was common to see genes, evolution, gills slits, and common ancestry in texts before the 2000s, but the inclusion of these topics in the early 2000s' texts was reduced or removed. Authors took a non-confrontational route by changing the narrative, mentioning that embryos are similar, but omitting how those similarities fit in with evolution and universal common descent.

Overall, while narratives about Haeckel's embryos have changed and grids have undergone redrawing, resizing, and revamping, there is still something obviously appealing, yet recently problematic about Haeckel's embryo grids. The predominance of the embryo grid in chapters about evolution elevates this illustration to an icon status. Even though a good part of my study examined the narratives accompanying embryo grids, one can argue that the powerful image, simply by itself, subliminally implies evolutionary development, regardless of what is written about it. Generations of biology students took the message home that fish, turtles, and monkeys were close relatives, especially when grids included chimpanzees and humans. Another subtle idea was captured simply from examining where human embryos were placed, usually at either the top row, or the right-most column of the grid. Here, any student could trace the embryos with his or her finger and surmise that humans represented the end-all for progressive evolution. Because the very nature of content-laden textbooks limit how much authors can write about specific topics, the embryo grid serves to provide its own descriptions to students just by having them analyze the grid.

The persistence of the embryo grid is not simply due to the attractiveness of the grid itself, but also due to how textbooks examine evolution. Since the early 1900s, evolution narratives have remained relatively unchanged, focusing on evidences for evolution. A compelling line of evidence has always been embryo development. While there is a current movement in biology education to shift discussion away from lines of evidence and to move towards more discussion about evolution's explanatory and predictive powers (Allchin, 2013), comparative embryology has always accompanied evolution and grids have provided an empirical seriousness to the field of evolution.

What I found, however, was that this "empirical seriousness" was rather static. It seems as if many authors treated embryo grids as throwbacks of a different and earlier era. This was especially noticeable when the grids highlighted the idea of recapitulation, but even when recapitulation dropped out of the picture in the 1960s, most texts did not capitalize on new genetic and biochemistry research to “update” their grids. This is not to say that new genetic and molecular biology research was not present elsewhere in textbooks, but newer lines of embryological evidence for evolution were clearly lacking in discussions about embryo grids. Here, discussion about gill slits and tails continued as it had for decades and did little to show embryology as an ever-changing and serious scientific field of study.

Implications for Biology Education and Further Study

Science textbooks often present science as ahistorical. One reason for this is that textbook authors write in a linear manner that makes the most sense to students. Showing science as complicated, imperfect, and messy probably will not sell. From my examination of embryo grids, I argue that while some may complain that the grid’s embryos are trying to do too much (an overreach to provide evidence for evolution), many of the textbook embryo grids that I examined, did too little. The current grids are now so overgeneralized and underutilized that their use as evidence for common ancestry or evolution is lost. However, since overgeneralization is a common fault of textbooks where breadth of the subject matter is more important than depth, it is difficult to accuse authors of only skimming over this particular content.

One reason for emotionally charged accusations against Haeckel, embryo grids, and evolution, might surprisingly lead us back to the BSCS program. With more scientist oversight in the 1960s, there was heavy emphasis placed on the scientific method and empirical evidence. This emphasis managed to instill the conception of the scientific method into a large number of people (Depew, 2009, p. 361), but with unintended consequences. Where does evolution fit in with the scientific method? Evolution is not a "simple fact" and does not fit with other well-confirmed things in science. Thus, it seems uncertain to the point that if something in a science textbook is questionable, students will assume that it will probably turn out to be wrong. It also appears as if evolutionists will accept any shoddy evidence (in this case anti-evolutionists will argue, an embryo grid) as long as it supports evolution.

One might think that if the embryo grid has the potential to cause controversy, then we should discuss Haeckel's work in the context of 1800's embryology and evolution. That is, give the embryos more depth. However, you then have a problem. One characteristic of textbook narratives is their rarity of complications. By signaling that controversy surrounds Haeckel and if that is the only thing in the textbook noted as controversial, authors imply that everything else in their text is firmly grounded in "textbook science" (Bauer, Magnoli, Alvarez, Chang-Van Horn, & Gomes, 1981).

By highlighting only Haeckel, evolution is viewed as that part of biology that still warrants critical examination and that evolution stands on shaky ground. In this manner, when Haeckel's drawings and subsequently, comparative embryology is treated as a "failure," evolution is viewed as "frontier science," in which evidence still needs to be established because the theory has a narrow range of acceptance. On the other hand, if Haeckel's work is not shown to be historically complicated (at least more complicated than any textbook story), than Haeckel appears as some type of strange Darwinist ghost haunting our public understanding of evolution.

I have yet another concern with writing about embryo grids in the context of the history of science and that is the potential for inaccuracy. I noted errors when textbook authors attempted to give the grid a bit of an historical insight. Several times von Baer became the originator of the Biogenetic Law, or authors blended the works of Haeckel and von Baer together for a more sanitized use of the grid. Worse yet was when the history was correct, but since Haeckel's work was not placed in the context of the nature of science (i.e., disputes and controversies in biology are considered to be a good thing), Haeckel comes off looking like a buffoon, making an easy target for anti-evolutionists.

Given the undue attention to Haeckel's embryos, why not just drop the grid entirely? In the short term that action might provide relief for publishers, but in the end, such action simply provides "more evidence" that biologists covered up the controversy about Haeckel and recapitulation. This is odd given the number of scientists who wrote articles and gave talks dismissing recapitulation in the late 1800s and early 1900s, but the general public probably does not know this history. Removing embryo grids entirely also diminishes the robustness of the nature of science by implying that the history of science (at least in textbooks) includes no failures.

How could high school textbooks improve their presentations of comparative embryology? The most obvious improvement is to lengthen discussion of embryology to show that one of the functions of science is the formation of explanations. Unfortunately, textbooks often state, but rarely explain. A second enhancement is to stop using embryos strictly for evidence of evolution and to involve grids with evolution's explanatory and predictive powers. Third, use photographs of embryos rather than drawings, but do so with great care. I saw that simply replacing a drawing with a photo, with no consideration of selecting embryos in the same stage or aligning them correctly led to comparison problems. The question that authors should ask themselves is, should changes be undertaken to appease critics at the expense of student understanding?

Additionally, all texts by this point should discuss the 1983 discovery of master developmental control genes (Hox genes), developmental genetics, and evolutionary developmental biology. In my examination of texts, only Miller and Levine's 2000 *Biology* discussed Hox genes in relation to embryo grids:

> The similarities of vertebrate embryos show that similar genes are at work. The genes that control an animal's basic body plan—its head and tail, its right and left, and even the positions of its limbs—are strikingly similar. In fact, a particular group of genes, known as the Hox cluster, establishes the basic pattern of organs and structures arranged from an animal's head to its tail. The common patterns of embryonic development we see in vertebrates occur because all these animals share the same basic control mechanism. (Miller & Levine, 2000, p. 283)

Surprisingly, Miller and Levine's later editions did not use embryo grids to discuss Hox genes. Perhaps the authors described Hox genes in other chapters of their texts, but with no combined discussion of genetic expression and embryo grids, this reflects the neglect given to developmental biology during these two decades. The lag time between the discovery and acceptance of Hox genes by the scientific community, to when that information made its way to the public in the form of secondary biology textbooks is significant, and serves as another question worth investigating.

Examining the topic of embryo grids leads me to the conclusion, which others have undoubtedly also expressed, that scientists and science textbooks are not the same. I am intrigued with how the idea of recapitulation, falling out of scientific favor beginning in the late 1800s and certainly denounced by the entire scientific community by the 1930s, continued to be presented in some textbooks as an accepted biological phenomenon.

How is it that the denunciation of recapitulation in the internal circle of science took so long to be accepted by the external circle of textbook authors? One reason is that scientists in the first half of the twentieth century were rarely involved with reviewing textbooks and provided little oversight to what high school students were learning. This seemingly dual world of science, the inner circle and the external circle, is an area that warrants further study, especially when the inner "scientist" and external "science writer" circles moved close together in the 1960s with the BSCS program. What happened after the 1960s to make these circles drift away, and are they still moving apart?

The story of Haeckel's embryo grids is certainly not over. By 2010, a shift was well underway to simplify the grid and to change its narrative, moving Haeckel's embryos from their original scientific issue focus to that of a social issue. I entered this study with a head-scratching question about why I continued to see Haeckel's embryos in textbooks. I left the study with another head-scratching question: what will the contestable space of embryo grids look like in the future? This leaves me interested in examining texts in the 2010s. Embryo grid use in the 2000s appeared a bit schizophrenic, with some grids showing only one developmental stage and others showing four stages of development. Some grids used drawings and some used photographs. Some grids no longer discussed human evolution, let alone discussed any evolution at all. Will biology texts eventually sort embryo grids out and explain them again in terms of evolutionary development or will the trend of quasi-Haeckel embryo grids continue with the narrative "to be determined?" Might embryo grids disappear? If they do disappear, an important course of action will be to determine who made that decision, who influenced that decision, and what were the reasons for the decision to let Haeckel's embryo grids go.

References

Abbott, H. P. (2003). Unnarratable knowledge: The difficulty of understanding evolution by natural selection (pp.143–162). In D. Herman (Ed.). *Narrative theory and the cognitive sciences*. Stanford, CA: Center for the Study of Language and Information.

AIBS. (2014). AIBS state news on teaching evolution. In *Public Policy*, from *http://www.aibs.org/public/evolution_state_news.html*

Alcamo, E., & Feldkamp, S. (2002). *Modern biology.* Austin, TX: Holt, Rinehart and *Winston.*

Allchin, D. (2013). Contextualizing creationists. *American Biology Teacher, 75*, 144–147.

Allen, G. E. (1975). *Life science in the twentieth century.* New York: John Wiley.

Amundson, R. (2005). *The changing role of the embryo in evolutionary thought. Roots of evo-devo.* Cambridge, MA: Cambridge University Press.

Armon, R. (2010). Beyond Darwinism's eclipse: Functional evolution, biochemical recapitulation and Spencerian emergence in the 1920s and 1930s. *Journal of General Philosophy of Science, 41*: 173–194.

Atwood, W. H. (1922). *Civic and economic biology.* Philadelphia: Blakiston's.

Atwood, W. H. (1927). *Biology*. Philadelphia: Blakiston's.

Baker, A. O., & Mills, L. H. (1933). *Dynamic biology.* New York: Rand McNally.

Barnes, R. D. (1987). *Invertebrate zoology* (5th ed.). Philadelphia: Saunders.

Bauer, P. H., Magnoli, M. A., Alvarez, A., Chang-Van Horn, D., & Gomes, D. T. (1981). *Experiences in biology*. River Forest, IL: Laidlaw Bros.

Behe, M. (1998). Embryology and evolution. [Letter to the editor]. *Science, 281*(5375): 348–349.

Benedict, R. C., Knox, W. W., & Stone, G. K. (1938) *High school biology* (1st ed.). New York: Macmillan.

Benson, K. R., & Quinn, C. E. (1990). The American Society of Zoologists, 1889–1989. A century of integrating the biological sciences. *American Zoologist, 30*(2), 353–396.

Berkman, M., & Plutzer, E. (2010). *Evolution, creationism, and the battle to control America's classrooms.* Cambridge, MA: Cambridge University Press.

Bibby, C. (1950). *An active human biology*. London: William Heinemann.

Bigelow, M. A., & Bigelow, A. N. (1911). *Applied biology.* New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1913). *Introduction to biology.* New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1922). *Introduction to biology: An elementary textbook and laboratory guide.* New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1925). *Applied biology.* New York: Macmillan.

Biggs, A., Hagins, W. C., Kapicka, C., & Lundgren, L., Rillero, P., Tallman, K. G., & Zike, D. (2004). *Biology: The dynamics of life.* New York: McGraw-Hill/Glencoe.

Biggs, A., Hagins, W. C., Kapicka, C., & Lundgren, L., Rillero, P., Tallman, K. G., & Zike, D. (2006). *Biology: The dynamics of life.* New York: McGraw-Hill/Glencoe.

Biggs, A., Kapicka, C., & Lundgren, L. (1998). *Biology: The dynamics of life* (3rd ed.). New York: Glencoe.

Blackwell, W. H. (2001). Don't heckle Haeckel so much. [Letter to the editor]. *American Biology Teacher, 63*(8), 550–554.

Bowler, P. J. (1983). *The eclipse of Darwinism. Anti-Darwinism evolution theories in the decades around 1900.* Baltimore: Johns Hopkins University Press.

Bowler, P. J. (1996). *Life's splendid drama. Evolutionary biology and the reconstruction of life's ancestry 1860–1940*. Chicago: University of Chicago Press.

Bowler, P. J. (2007). *Monkey trials and gorilla sermons. Evolution and Christianity from Darwin to intelligent design.* Cambridge, MA: Harvard University Press.

Breidbach, O. (2006a). The conceptual framework of evolutionary morphology in the studies of Ernst Haeckel and Fritz Müller. *Theory in Biosciences*, *124*, 265–280.

Breidbach, O. (2006b). *Visions of nature: The art and science of Ernst Haeckel*. London: Prestel.

Brown, J. (2002). *Charles Darwin. The power of place*. Princeton, NJ: Princeton University Press.

BSCS. (1963). *Biological science: An ecological approach* (1st ed.). Chicago: Rand McNally.

BSCS. (1963). *Biological science: An inquiry into life* (1st ed.). New York: Harcourt, Brace.

BSCS. (1963). *Biological science: Molecules to man* (1st ed.). Boston: Houghton-Mifflin.

BSCS. (1968). *Biological science: An ecological approach* (2nd ed.). Chicago: Rand McNally.

BSCS. (1968). *Biological science: An inquiry into life* (2nd ed.). New York: Harcourt, Brace.

BSCS. (1968). *Biological science: Molecules to man* (2nd ed.). New York: Houghton-Mifflin.

BSCS. (1973). *Biological science: An ecological approach* (3rd ed.). Chicago: Rand McNally.

BSCS. (1973). *Biological science: An inquiry into life* (3rd ed.). New York: Harcourt, Brace.

BSCS. (1973). *Biological science: Molecules to man* (3rd ed.). New York: Houghton-Mifflin.

BSCS. (1978). *Biological science: An ecological approach* (4th ed.). Chicago: Rand McNally.

BSCS. (1980). *Biological science: An inquiry into life* (4th ed.). New York: Harcourt, Brace.

BSCS. (1992). *Biological science: An ecological approach* (7th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (1998). *BSCS biology: An ecological approach* (8th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2001). *BSCS biology: A molecular approach* (8th ed.). New York: McGraw-Hill/Glencoe.

BSCS. (2002). *BSCS biology: An ecological approach* (9th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2006). *BSCS biology. An ecological approach* (10th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2006). *BSCS biology: A molecular approach* (10th ed.). New York: McGraw-Hill/Glencoe.

Burrow, J. W. (2000). *The crisis of reason: European thought, 1848–1914.* New Haven, CT: Yale University Press.

Campbell, N. A., Reece, J. B., Mitchell, G. M., & Taylor, M. R. (2003). *Biology: Concepts and connections.* San Francisco: Benjamin Cummings.

Churchill, F. B. (1991). The rise of classical descriptive biology. In S. G. Gilbert (Ed.), *Developmental biology: A comprehensive synthesis. Vol. 7. A conceptual history of modern embryology* (pp. 1–29). New York: Plenum Press.

Churchill, F. B. (1998). The modern evolutionary synthesis and the biogenetic law. In. E. Mayr and W. B. Provine (Eds.). *The evolutionary synthesis* (pp. 112–122). Cambridge, MA: Harvard University Press.

Churchill, F. B. (2007). Living with the biogenetic law: A reappraisal. In M. D. Laubichler and J. Maienschein (Eds.), *From Embryology to evo-devo: A history of developmental evolution* (pp. 37–82). Cambridge, MA: MIT Press.

Clark, C. A. (2008). *God or gorilla—images of evolution in the jazz age*. Baltimore: Johns Hopkins University Press.

Clausen, C. (2012). Left, right, and science. *The Wilson Quarterly, 36*(2), 16–21.

Coleman, W. (1971). *Biology in the nineteenth century. Problems of form, function, and transformation.* New York: Cambridge University Press.

Coleman, W. (1973). Limits of the recapitulation theory: Carl Friedrich Kielmeyer's critique of the presumed parallelism of earth history, ontogeny, and the present order of organisms. *Isis, 64*(3), 341–350.

Coyne, J. A. (2001). Creationism by stealth. [Review of the book *Icons of evolution: Science or myth? Why much of what we teach about evolution is wrong*, by J. Wells]. *Nature*, *410*, 745–746.

Cunningham, J. T. (1897). Recapitulation. *Science Progress, 1*(4), 483–510.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1934). *Biology for today.* Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1940). *Everyday biology* (1st ed.). Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1943). *Everyday biology* (3rd ed.). Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1946). *Everyday biology* (2nd ed.). Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1953). *Everyday biology* (3rd ed.). Chicago: Ginn.

Curtis, F. D., & Urban, J. (1949). *Biology in daily life.* New York: Ginn.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. London: Murray.

De Beer, G. R. (1930). *Embryology and evolution.* London: Clarendon Press.

De Beer, G. R. (1940). *Embryos and ancestors* (1st ed.). London: Clarendon Press.

De Beer, G. R. (1954). *Embryos and ancestors* (2nd ed.). London: Clarendon Press.

De Beer, G. R. (1958). *Embryos and ancestors* (3rd ed.). London: Oxford University Press.

Depew, D. J. (2009). Darwinian controversies: An historiographical recounting. *Science & Education, 19*, 323–366.

Dodge, R. A. (1952). *Elements of biology*. Boston: Allyn & Bacon.

Dodge, R. A. (1959). *Elements of biology*. Boston: Allyn & Bacon.

Dodge, R, A. (1964). *Elements of biology*. Boston: Allyn & Bacon.

Doolittle, F. W., & Bapteste, E. (2007). Pattern pluralism and the tree of life hypothesis. *Proceedings of the National Academy of Sciences, 104*(7), 2043–2049.

Doumont, J.-L. (2002). Verbal vs. visual: A word is worth a thousand pictures, too. *Technical Communication, 49*, 219–224.

Durkin, D. (1992). *Teaching them to read* (6th ed.). Boston: Allyn & Bacon.

Engleman, L. (2002).*The BSCS story: A history of the biological sciences curriculum study.* Colorado Springs, CO: BSCS.

Freeman, B. (2001a). Haeckel's forgeries. [Letter to the editor]. *American Biology Teacher, 63*(4), 230.

Freedman, B. (2001b). The myth of the "biogenetic law." [Letter to the editor]. *American Biology Teacher*, *63*(2), 84.

Garstang, W. (1922). The theory of recapitulation: A critical restatement of the biogenetic law. *The Journal of the Linnean Society of London, 35*(232), 81–101.

Gilbert, S. F. (1997). *Developmental biology* (5th ed.). Sunderland, MA: Sinauer.

Gilbert, S. F. (2003). The morphogenesis of evolutionary developmental biology. *International Journal of Developmental Biology, 47*, 467–477.

Gilbert, S. F. (2014). *Developmental biology* (10th ed.). Sunderland, MA: Sinauer.

Glanz, J. (2001, April 18). Biology text illustrations more fiction than fact. *New York Times*. Science Section.

Glass, B. (1945). Exploring biology. [Review of the book *Exploring biology* by E. T. Smith]. *The Quarterly Review of Biology, 20*(2), 169.

Glass, B. (1948). Modern biology [Review of the book *Modern biology* by T. J. Moon, P. B. Mann, and J. H. Otto]. *The Quarterly Review of Biology, 23*(1), 44–45.

Glass, B. (1949). Exploring Biology 3rd ed. [Review of the book *Exploring biology* by E. T. Smith]. *The Quarterly Review of Biology, 24*(3), 227.

Glass, B. (1988). Biology for living [Review of the book *Biology for living* by B. Wallace and G. M. Simmons]. *The Quarterly Review of Biology, 63*(1), 64.

Gliboff, S. (2008). *H. G. Bronn, Ernst Haeckel, and the origins of German Darwinism*. Cambridge, MA: MIT Press.

Gould, S. J. (1977). *Ontogeny and phylogeny*. Cambridge, MA: Belknap.

Gould, S. J. (1989). *Wonderful life*. New York: Norton.

Gould, S. J. (2000). Abscheulich! (Atrocious). *Natural History, 109*(2), 42.

Gould, S. J. (2002). *The structure of evolutionary theory*. Cambridge, MA: Belknap.

Grabiner, J. V., & Miller, P. D. (1974). Effects of the Scopes trial. Was it a victory for evolutionists? *Science, 185*(4154), 832–837.

Green, L. A. (2012). *Science for survival: The modern synthesis of evolution and the Biological Sciences Curriculum Study* (Doctoral Dissertation, University of California, Riverside). Retrieved from http://www.escholarship.org/uc/item/8fs4c6nc

Gruenberg, B. C. (1919). *Elementary biology*: *An introduction to the science of life*. New York: Ginn.

Gruenberg, B. C. (1924). *Elementary biology*: *An introduction to the science of life* (2nd ed.). New York: Ginn.

Gruenberg, B. C. (1925). *Biology and human life.* New York: Ginn.

Gruenberg, B. C. (1929). *The story of evolution*. Garden City, NY: Garden City Publishing.

Gruenberg, B. C., & Bingham, N. E. (1944). *Biology and man.* New York: Ginn.

Haeckel, E. (1866). *Generelle morphologie der organismen*. Berlin: Reimer.

Haeckel, E. (1868). *Natürliche schöpfungsgeschichte*. Berlin: Reimer.

Haeckel, E. (1874). *Anthropogenie*. Leipzig: Engelmann.

Hall, B. K. (2000). Balfour, Garstang and de Beer: The first century of evolutionary embryology. *American Zoologist, 40*, 718–728.

Hall, B. K. (2010). Charles Darwin, embryology, evolution, and skeletal plasticity. *Journal of Applied Ichthyology, 26*(2), 148–151.

Halpern, M. K., & Rogers, H. S. (2013). Inseparable impulses: The science and aesthetics of Ernst Haeckel and Charley Harper. *Leonardo*, *46*(5), 465–470.

Hardy, A. C. (1951). Introduction. In W. Garstang, *Larval forms and other zoological verses*. Chicago: University of Chicago Press.

Heie, N. (2008). Ernst Haeckel and the redemption of nature (Doctoral Dissertation, Queen's College). Retrieved from https://qspace.library.queensu.ca.bitstream.1974/1016/Heie_Nolan_D_200801_PhD.pdf

Heiss, E. D., & Lape, R. H. (1961). *Biology: A basic science* (2nd ed.). New York: Van Nostrand.

Holland, N. D. (2011). Walter Garstang: A retrospective. *Theory in Biosciences 130*, 247–258.

Hopwood, N. (2006). Pictures of evolution and charges of fraud: Ernst Haeckel's embryological illustrations. *Isis, 97*(2), 260–301.

Hopwood, N. (2007). A history of normal plates, tables, and stages in vertebrate embryology. *International Journal of Developmental Biology, 51*(1), 1–26.

Hopwood, N. (2009). Embryology. In P. J. Bowler & J. V. Pickstone (Eds.), *The modern biological and earth sciences: Vol. 6. The Cambridge history of science* (pp. 285–315). doi:10.1017/CHOL9780521572019.017

Horder, T. (2010). History of developmental biology. In *Encyclopedia of life sciences* (p.1–12). Chichester: Wiley. doi:10.1002/9780470015902.a0003080.pub2

Hunter, G. W. (1907). *Elements of biology: A practical text-book correlating botany, zoölogy, and human physiology.* New York: American Book.

Hunter, G. W. (1911). *New essentials of biology: Presented in problems.* New York: American Book.

Hunter, G. W. (1914). *A civic biology*: *Presented in problems.* New York: American Book.

Hunter, G. W. (1923). *New essentials of biology*. New York: American Book.

Hunter, G. W. (1926). *New civic biology*. New York: American Book.

Hunter, G. W. (1941). *Life science. A social biology.* New York: American Book.

Hunter, G. W., & Hunter, F. R. (1949). *Biology in our lives.* New York: American Book.

Hunter, G. W., & Hunter, F. R. (1955). *Biology in our lives* (2nd ed.). New York: American Book.

Hunter, G. W., Walter, H. E., & Hunter, G. W. (1937). *Biology: The story of living things.* New York: American Book.

Hurd, P. D. (1961). *Biological education in American secondary schools 1890–1960. Bulletin No.1.* Baltimore, MD: American Institute of Biological Sciences.

Hurst, C. H. (1893a). The recapitulation theory. *Natural Science, 2*(15), 195–200.

Hurst, C. H. (1893b). The recapitulation theory; a rejoinder. *Natural Science, 2*(15), 364–369.

Icons of Evolution [Advertisement]. (2001, March). *American Biology Teacher, 63*(3), 175.

Irie, N., & Kuratani, S. (2011). Comparative transcriptome analysis reveals vertebrate phylotypic period during organogenesis. *Nature Communications 2*, 248 doi:10.1038/ncomms1248.

Irmscher, C. (2013). *Louis Agassiz. Creator of American science*. New York: Houghton Mifflin.

Keibel, F. (1897). *Normal plates of the development of the vertebrates.* Jena: Fischer.

Kelly, A. (1981). *The descent of Darwin. The popularization of Darwinism in Germany, 1860–1914*. Chapel Hill, NC: University of North Carolina Press.

Kimball, J. W. (1965). *Biology* (1st ed.). Reading, MA: Addison-Wesley.

Kimball, J. W. (1969). *Biology* (2nd ed.). Reading, MA: Addison-Wesley

Kimball, J. W. (1974). *Biology* (3rd ed.). Reading, MA: Addison-Wesley.

Kimball, J. W. (1978). *Biology* (4th ed.). Reading, MA: Addison-Wesley.

Kimball, J. W. (1994). *Biology* (6th ed.). Dubuque, IA: Wm C. Brown.

Kinsey, A. C. (1926). *An introduction to biology*. Chicago: Lippincott.

Kraus, D., & Perkins, O. E. (1969). *Concepts in modern biology*. New York: Cambridge University Press.

Kraus, D. (1984). *Concepts in modern biology* (5th ed.). New York: Globe.

Kraus, D. (1993). *Concepts in modern biology*. Englewood Cliffs, NJ: Globe.

Kraus, D. (1999). *Concepts in modern biology.* Upper Saddle River, NJ: Globe.

Ladouceur, R. P. (2008). Ella Thea Smith and the lost history of American high school textbooks. *Journal of the History of Biology, 41*(3), 435–471.

Larson, E. J. (1997). *Summer for the Gods. The Scopes trial and America's continuing debate over science and religion.* New York: Basic Books.

Larson, E. J. (2003). *Trial and error. The American controversy over creation and evolution.* NY: Oxford University Press.

Lazarowitz, R. (2007). High school biology curricula development: Implementation, teaching, and evaluation from the twentieth to the twenty-first century. In S. K Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp.561–598). Mahwah, NJ: Lawrence Erlbaum.

Levine, J. S., & Miller, K. R. (1994). *Biology: Discovering life.* Lexington, MA: Heath.

Lienesh, M. (2012). Abandoning evolution: The forgotten history of antievolution activism and transformation of American social science. *Isis, 103*(4), 687–709.

Lowery, L. F., & Leonard, W. H. (1978). A comparison of questioning styles among four widely used high school biology textbooks. *Journal of Research in Science Teaching, 15*(1), 1–10.

Ludwig, D. (2013). Mediating objects: Scientific and public functions of models in nineteenth-century biology. *History and Philosophy of the Life Sciences, 35*(2), 139–166.

Lynch, M. (1990). The externalized retina: Selection and mathematization in the visual documentation of objects in the life science. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 153–186). Cambridge, MA: MIT Press.

Mayer, W. V. (1989). 20 years of progress 1966–1985: A presidential view. *The American Biology Teacher, 51*(7), 402–407.

Mayr, E. (1959). Agassiz, Darwin, and evolution. (Harvard Library Bulletin). *13*, 165. Harvard University.

Mayr, E. (1982). *The growth of biological thought. Diversity, evolution, and inheritance.* Cambridge, MA: Harvard University Press.

McLaren, J. E., Rotundo, L., & Gurley-Dilger, L. (1991). *Heath biology.* Lexington, MA: Heath.

Meyer, A. W. (1935). Some historical aspects of the recapitulation idea. *The Quarterly Review of Biology, 10*(4), 379–396.

Miller, K. R., & Levine, J. (1997). Haeckel and his embryos. In *High School Textbooks,* retrieved from http://www.millerandlevine.com/km/evol/embryos/Haeckel.html

Miller, K. R., & Levine, J. (1998). *Biology: The living science.* Upper Saddle River, NJ: Prentice Hall.

Miller, K. R., & Levine, J. (2000). *Biology* (5th ed.). Upper Saddle River, NJ: Prentice Hall.

Miller, K. R., & Levine, J. (2002). *Biology* (6th ed.). Upper Saddle River, NJ: Prentice Hall. Needham, MA: Pearson.

Miller, K. R., & Levine, J. (2008). *Biology* (7th ed.). Upper Saddle River, NJ: Pearson/Prentice Hall.

Moody, D. E. (1996). Evolution and the textbook structure of biology. *Science Education, 80*(4), 395–418.

Moon, T. J. (1921). *Biology for beginners* (1st ed.). New York: Ginn.

Moon, T. J. (1926). *Biology for beginners* (2nd ed.). New York: Ginn.

Moon, T. J., & Mann, P. B. (1933). *Biology for beginners* (3rd ed.). New York: Holt.

Moon, T. J., & Mann, P. B. (1938). *Biology, a revision of biology for beginners.* New York: Holt.

Moon, T. J., Otto, J. H., & Towle, A. (1960). *Modern biology* (4th ed.). New York: Holt

Moon, T. J., Otto, J. H., & Towle, A. (1963). *Modern biology* (5th ed.). New York: Holt.

Moore, J. A. (1987). Science as a way of knowing: Developmental biology. *American Zoologist, 27*(2), 415–573.

Moore, J. A. (1993). *Science as a way of knowing: The foundations of modern biology*. Cambridge, MA: Harvard University Press.

Moore, R. (1998a). Creationism in the United States: I. Banning evolution from the classroom. *American Biology Teacher, 60*(7), 486–507.

Moore, R. (1998b). Creationism in the United States: II. The aftermath of the Scopes trial. *American Biology Teacher, 60*(8), 568–577.

Moore, R. (2002). *Evolution in the courtroom: A reference guide.* Santa Barbara, CA: ABC-CLIO.

Morgan, M., & Morrison, M. (1999). *Models as mediators.* Cambridge, MA: Cambridge University Press.

Müller, F. (1869). Facts and arguments for Darwin (W. S. Dallas, Trans.). London: Murray.

Myers, G. (1990). Every picture tells a story: Illustrations in E. O. Wilson's *Sociobiology*. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 231–267). Cambridge, MA: MIT Press.

National Center for Science Education. (2012). The latest Gallup poll on evolution. National Center for Science Education. Retrieved frohttp://ncse.com/news/2012/06/latest-gallup-poll- evolution-007431

Needham, J. (1926). The energy-sources in ontogenesis: II. The ammonia content of the developing avian egg and the theory of recapitulation. *Journal of Experimental Biology*, *4*: 145–154.

Needham, J. (1959). *A history of embryology.* New York: Abelard-Schuman.

Nelkin, D. (1977). *Science textbook controversies and the politics of equal time*. Cambridge, MA: MIT Press.

Nunn, C. L. (2011). *The comparative approach in evolutionary anthropology and biology.* Chicago: University of Chicago Press.

Numbers, R. L. (1998). *Darwinism comes to America*. Cambridge, MA: Harvard University Press.

Nyhart, L. K. (1995). *Biology takes form. Animal morphology and the German universities, 1800–1900.* Chicago: University of Chicago Press.

Nyhart, L. K. (2009). Embryology and morphology. In M. Ruse & R. J. Richards (Eds.), *The Cambridge companion to the Origin of Species* (pp. 194–215). Cambridge: University of Cambridge Press.

Oppenheimer, J. M. (1959). Embryology and evolution: Nineteenth century hopes and twentieth century realities. *The Quarterly Review of Biology*, *34*(4), 271–277.

Oram, R. F. (1973). *Biology: Living systems.* (1st ed.). Columbus, OH: Merrill.

Oram, R. F. (1979). *Biology: Living systems* (3rd ed.). Columbus, OH: Merrill.

Oram, R. F. (1994). *Biology living systems*. Columbus, OH: Glencoe/McGraw-Hill.

Oram, R. F., Hummer, P. J., & Smoot, R. C. (1986) *Biology living systems* (5th ed.). Columbus, OH: Merrill.

Otto, J. H., & Towle, A. (1981). *Modern biology* (10th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1965). *Modern biology* (6th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1969). *Modern biology* (7th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1985). *Modern biology* (10th ed.). New York: Holt.

Pauly, P. J. (2000). *Biologists and the promise of American life.* Princeton, NJ: Princeton University Press.

Pennisi, E. (1997). Haeckel's embryos: Fraud rediscovered. *Science*, *277*(5331), 1435.

Peterson, J. (2012). Glimpses of animal life: Nature films and the emergence of classroom cinema. In D. Orgeron, M. Orgeron, and D. Streible (Eds.), *Learning with the lights off*: *Educational film in the United State* (pp. 145–167). New York: Oxford University Press.

Pickett, K. M., Wenzel, J. W., & Rissing, S. W. (2005). Iconoclasts of evolution: Haeckel, Behe, and the ontogeny of a fraud. *American Biology Teacher*, *67*(5), 275–282.

Pietsch, T. W. (2012). *Trees of life. A visual history of evolution*. Baltimore: Johns Hopkins University Press.

Popenoe, P. (1955). In memoriam: Maurice A. Bigelow. *Biodemography and Social Behavior*, *2*(1), 7–8.

Postlethwait, J. H., & Hopson, J. L. (2006). *Modern biology* (14th ed.). Austin, TX: Holt, Rinehart, & Winston.

Postlethwait, J. H., & Hopson, J. L. (2009). *Modern biology* (15th ed.). Austin, TX: Holt, Rinehart, & Winston.

Preston, C. E. (1939). Exploring biology. [Review of the book *Exploring biology* by E. T. Smith]. *The High School Journal*, *22*(7), 304.

Prud'homme, B., & Gompel, N. (2010). Genomic hourglass. *Nature*, *468*, 768–769.

Raff, R. A. (1983). *Embryos, genes, and evolution.* New York: Macmillan.

Raff, R. A. (2012). *Once we all had gills: Growing up evolutionist in an evolving world*. Bloomington, IN: Indiana University Press.

Rasmussen, N. (1991). The decline of recapitulation in the early twentieth-century biology: Disciplinary conflict and consensus on the battleground theory. *Journal of the History of Biology*, *24*(1), 51–89.

Reid, J. M. (1969). *An adventure in textbooks, 1924–1960*. New York: R. R. Bowker.

Richards, R. J. (1992). *The meaning of evolution. The morphological construction and ideological reconstruction of Darwin's Theory.* Chicago: University of Chicago Press.

Richards, R. J. (2008). *The tragic sense of life: Ernst Haeckel and the struggle over evolutionary thought.* Chicago: University of Chicago Press.

Richards, R. J. (2009). Haeckel's embryos: Fraud not proven. *Biology and Philosophy, 24,* 147–154.

Richards, R. J. (2013). The German reception of Darwin's theory, 1860–1945. In M. Ruse (Ed.). *The Cambridge encyclopedia of Darwin and evolutionary thought* (pp. 235–242). New York: Cambridge University Press.

Richardson, M. K., Hanken, J., Gooneratne, M. L., Pieau, C., Raynaud, A., Selwood, L., & Wright, G. M. (1997). There is no conserved embryonic stage in the vertebrates: Implications for current theories of evolution and development. *Anatomy and Embryology*, *196*(2), 91–106.

Richardson, M. K., Hanken, J., Selwood, L., Wright, G. M., Richards, R. J., & Pieau, C. (1998). Haeckel, embryos, and evolution. [Letter to the editor]. *Science*, *280*, 983–984.

Richardson, M. K., & Jeffery, J. E. (2002). Editorial: Haeckel and modern biology. *Theory in Biosciences, 121*(3), 247–251.

Richardson, M. K., & Keuck, G. (2001). A question of intent: When is a 'schematic' illustration a fraud? *Nature*, *410,* 144.

Richardson, M. K., & Keuck, G. (2002). Haeckel's ABC of evolution and development. *Biological Review, 77*(4), 495–528.

Riddle, O. (1954). High schools and biological literacy in the United States. *American Biology Teacher, 16*(7), 179–184.

Ritchie, J. W. (1941). *Biology and human affairs* . New York: World Book.

Ritchie, J. W. (1948). *Biology and human affairs*. New York: World Book.

Romanes, G. J. (1892). *Darwin, and after Darwin*. London: Open Court.

Rosenthal, D. B. (1985). Evolution in high school biology textbooks: 1963–1983. *Science Education 69*, 637–648.

Rudolph, J. L. (2002). *Scientists in the classroom. The cold war reconstruction of American science education.* New York: Palgrave.

Russell, E. S. (1916). *Form and function—A contribution to the history of animal morphology*. London: Murray.

Schwab, J. J. (1963). *The biology teacher's handbook. Biological Sciences Curriculum Study*. New York: Wiley.

Schwartz, J. S. (1999). Robert Chambers and Thomas Henry Huxley, science correspondents: The popularization and dissemination of nineteenth century natural science. *Journal of the History of Biology, 32*(2), 343–383.

Scott, E. C. (2001). Stanley Weinberg, NCSE Founder, Dies. *Reports of the National Center for Science Education, 21*(3–4): 11–13.

Sedgwick, A. (1894). On the law of development commonly known as von Baer's law; and on the significance of ancestral rudiments in embryonic development. *The Quarterly Review of Microscopical Science 36*, 35–52.

Seldon, S. (1999). *Inheriting shame: The story of eugenics and racism in America.* New York: Teachers College Press.

Selden, S. (2007). Biological determinism and the narrative of adjustment: The high school biology textbooks of Truman Jesse Moon, c. 1921–1963. *Curriculum Inquiry, 37*(2), 159–169.

Shapiro, A. R. (2008). Civic biology and the origin of the school antievolution movement. *Journal of the History of Biology, 41*(3), 409–433.

Shapiro, A. R. (2013). *Trying biology. The Scopes trial, textbooks, and the antievolution movement in American schools.* Chicago: University of Chicago Press.

Shumway, W. (1932). The recapitulation theory. *The Quarterly Review of Biology, 7*(1), 93–99.

Skoog, G. (1979). Topic of evolution in secondary school biology textbooks: 1900–1977. *Science Education, 63*(5), 621–640.

Skoog, G. (2005). The coverage of human evolution in high school biology textbooks in the 20th century and in current state science standards. *Science and Education, 14,* 395–422.

Slack, J. M. H., Holland, P. W. H., & Graham, C. F. (1993). The zootype and the phylotypic stage. *Nature, 361,* 490–492.

Smith, E. T. (1938). *Exploring biology* (1st ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1942). *Exploring biology* (2nd ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1943). *Exploring biology* (3rd ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1947). *Exploring biology* (4th ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1949). *Exploring biology* (5th ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1954). *Exploring biology* (7th ed.). Chicago : Harcourt, Brace.

Sommerey, C. (2011, November). Resilient recapitulation: Ernst Haeckel and the public understanding of evolution. Paper presented at the Society for Social Studies of Science, Cleveland, OH.

Sonleitner, F. J. (2001). Pharyngeal arches in question. [Letter to the editor]. *American Biology Teacher, 63*(6), 392.

Standafer, E., & Wahlgren, W. (1999). *Modern biology*. New York: Holt.

Tauber, A. I. (2013). Ilya Metchnikoff. From evolutionist to immunologist, and back again. In O. Harmand & M. D. Dietrich (Eds.), *Outsider scientists: Routes to innovation in biology* (pp. 259–274). Chicago: University of Chicago Press.

Tobin, G. A., & Ybarra, D. R. (2008). The trouble with textbooks. New York: Lexington Books.

Towle, A. (1989). *Modern biology*. (11th ed.). New York: Holt.

Towle, A. (1991). *Modern biology.* (12th ed.). New York: Holt.

Tyson-Bernstein, H. (1988). *A conspiracy of good intentions: America's textbook fiasco.* Washington, DC: Council for Basic Education.

Wallace, B., & Simmons, G. M. (1987). *Biology for living.* Baltimore: Johns Hopkins.

Webb, G. E. (1994). *The evolution controversy in America.* Lexington, KY: University of Kentucky Press.

Webb, H. A. (1948). George William Hunter (1873–1948). *Science Education*, *32*(3), 131–134.

Weinberg, S. L. (1966). *Biology: An inquiry into the nature of life* (1st ed.). Boston: Allyn & Bacon.

Weinberg, S. L. (1971). *Biology: An inquiry into the nature of life* (2nd ed.). Boston: Allyn & Bacon.

Weinberg, S. L. (1974). *Biology: An Inquiry into the nature of life* (3rd ed.). Boston: Allyn & Bacon.

Weinberg, S. L. (1977). *Biology: An inquiry into the nature of life* (4th ed.). Boston: Allyn & Bacon.

Weiss, K. M. (2007). The Scopes Trial. *Evolutionary Anthropology 16*, 126–131.

Wells, J. (1999). Haeckel's embryos and evolution: Setting the record straight. *The American Biology Teacher*, *61*(5), 345–349.

Wells, J. (2000). *Icons of evolution. Science or myth?* Washington, D.C.: Regnery.

Woodruff, L. L. (1922). *Foundations of biology.* New York: Macmillan.

Woodruff, L. L. (1927). *Foundations of biology* (3rd ed.). New York: Macmillan.

Woodruff, L. L. (1930). *Foundations of biology* (4th ed.). New York: Macmillan.

Yager, R. E. (1982). The crisis in biology education. *American Biology Teacher, 44*(6), 328–334.

Zuckerkandl, E., Jones, R. T., & Pauling, L. (1960). A comparison of animal hemoglobins by tryptic peptide pattern analysis. *Proceedings of the National Academy of Sciences*, *46*(10), 1349–1360.

APPENDIX

BIBLIOGRAPHY OF BIOLOGY TEXTBOOKS

1900–1919

Bailey, L. H., & W. M. Coleman. (1917). *First course in biology.* New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1911). *Applied biology.* New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1913). *Introduction to biology*. New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1916). *Applied biology.* New York: Macmillan.

Gruenberg, B. C. (1919). *Elementary biology*: *An introduction to the science of life*. New York: Ginn.

Hodge, C. F, & Dawson. J. (1918). *Civic biology: A textbook of problems, local and national, that can be solved only by civic cooperation.* Boston: Ginn.

Hunter, G. W. (1907). *Elements of biology: A practical text-book correlating botany, zoölogy, and human physiology.* New York: American Book.

Hunter, G. W. (1911). *New essentials of biology: Presented in problems.* New York: American Book.

Hunter, G. W. (1914). *A civic biology*: *Presented in problems.* New York: American Book.

Peabody, J. E., & Hunt, A. E. (1912). *Elementary biology: Animal and human.* New York: Macmillan.

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1916). *Practical biology.* Boston: Allyn & Bacon.

1920–1929

Atwood, W. H. (1922). *Civic and economic biology.* Philadelphia: Blakiston's.

Atwood, W. H. (1927). *Biology*. Philadelphia: Blakiston's.

Bigelow, M. A., & Bigelow, A. N. (1922). *Introduction to biology* (2nd ed.). New York: Macmillan.

Bigelow, M. A., & Bigelow, A. N. (1925). *Applied biology*. New York: Macmillan.

Clement, A. G. (1924). *Living things: An elementary biology.* Syracuse, NY: Iroquois Publishing.

Gruenberg, B. C. (1924). *Elementary biology*: *An introduction to the science of life* (2nd ed.). New York: Ginn.

Gruenberg, B. C. (1925). *Biology and human life.* New York: Ginn.

Hunter, G. W. (1923). *New essentials of biology presented in problems.* New York: American Book.

Hunter, G. W. (1926). *New civic biology*. New York: American Book.

Hunter, G. W. (1928). *New essential of biology presented in problems* (2nd ed.). New York: American Book.

Kinsey, A. C. (1926). *An introduction to biology*. Chicago: Lippincott.

Kline, N. S. (1925). *A concise biology for high schools*. New York: Oxford.

Linville, H. R. (1923) *The biology of man and other organisms.* New York: Harcourt, Brace.

Mandl, M. M. (1925). *Biology*. New York: Oxford.

Moon, T. J. (1921). *Biology for beginners*. New York: Henry Holt.

Moon, T. J. (1926) *Biology for beginner* (2nd ed.). New York: Holt and.

Peabody, J. A., & Hunt, A. E. (1926). *Biology and human welfare.* New York: Macmillan.

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1920). *Biology for high schools*. Boston: Allyn & Bacon

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1924). *New biology* (1st ed.). Boston: Allyn & Bacon.

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1929). *New general biology.* New York: Allyn & Bacon.

Trafton, G. H. (1923). *Biology of home and community: A textbook for high schools.* New York: Macmillan.

Woodruff, L. L. (1922). *Foundations of biology.* New York: Macmillan.

Woodruff, L. L. (1926). *Foundations of biology* (2nd ed.). New York: Macmillan.

Woodruff, L. L. (1927). *Foundations of biology* (3rd ed.). New York: Macmillan.

1930–1939

Baker, A. O., & Mills, L. H. (1933). *Dynamic biology.* New York: Rand McNally.

Baker, A. O., & Mills, L. H. (1938). *Dynamic biology* (2nd ed.). New York: Rand McNally.

Benedict, R. C., Knox, W. W., & Stone, G. K. (1938) *High school biology* (1st ed.). New York: Macmillan.

Corwin, W., Corwin, M. J., & Miller, C. (1934). *Living things: A high school biology.* Philadelphia: P. Blakiston's Son & Co.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1934). *Biology for today.* Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1939). *Biology for today.* Chicago: Ginn.

Heiss, E. D., Obourn, E. S., & Manzer, J. G. (1936). *Our world of living things: A high school biology.* St. Louis: Webster.

Hunter, G. W. (1931). *Problems in biology* (1st ed.). New York: American Book.

Hunter, G. W. (1935). *Problems in biology* (2nd ed.). New York: American Book.

Hunter, G. W. (1939). *Problems in biology* (3rd ed.). New York: American Book.

Hunter, G. W., Walter, H. E., & Hunter, G. W. (1937). *Biology: The story of living things.* New York: American Book.

Kinsey, A. C. (1933). *New introduction to biology* (1st ed.). Chicago: Lippincott.

Kinsey, A. C. (1938). *New introduction to biology* (2nd ed.). Chicago: Lippincott.

Meier, W. H. D., & Meier, L. (1931). *Essentials of biology.* New York: Ginn.

Meier, W. H. D., & Shoemaker, L. M. (1938). *Essentials of biology* (2nd ed.). New York: Ginn.

Moon, T. J., & Mann, P. B. (1933). *Biology for beginners*. New York: Holt.

Moon, T. J., & Mann, P. B. (1938). *Biology, a revision of biology for beginners.* New York: Holt.

Peabody, J. E., & Hunt, A. E. (1933). *Biology and human welfare* (1st ed.). New York: Macmillan.

Peabody, J. E., & Hunt, A. E. (1938). *Biology and human welfare* (2nd ed.). New York: Macmillan.

Pieper, C. J., Beauchamp, W. L., & Frank, O. D. (1936). *Everyday problems in biology*. New York: Scott, Foresman.

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1934). *New biology.* Boston: Allyn & Bacon.

Smallwood, W. M., Reveley, I. L., & Bailey, G. A. (1937). *New biology.* Boston: Allyn & Bacon.

Smith, E. T. (1938). *Exploring biology* (1st ed.). Chicago: Harcourt, Brace.

Wood, G. C., & Carpenter, H. A. (1938). *Our environment: The living things in it.* New York: Allyn & Bacon.

Woodruff, L. L. (1930). *Foundations of biology* (4th ed.). New York: Macmillan.

1940–1949

Baker, A. O., & Mills, L. H. (1948). *Dynamic biology today*. New York: Rand McNally.

Bayles, E. E., & Burnett, R. W. (1942). *Biology for better living* (2nd ed.). New York: Silver Burdett.

Bayles, E. E., & Burnett, R. W. (1944). *Biology for better living* (3rd ed.). New York: Silver Burdett.

Bayles, E. E., & Burnett, R. W. (1946). *Biology for better living* (4th ed.). New York: Silver Burdett.

Benedict, R. C. (1941). *Life science based on high school biology*. New York: Macmillan.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1940). *Everyday biology* (2nd ed.). Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1943). *Everyday biology* (3rd ed.). Chicago: Ginn.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1946). *Everyday biology* (4th ed.). Chicago: Ginn.

Curtis, F. D., & Urban, J. (1949). *Biology in daily life.* New York: Ginn.

Gruenberg, B. C., & Bingham, N. E. (1944). *Biology and man.* New York: Ginn.

Hunter, G. W. (1940). *Problems in biology* (4th ed.). New York: American Book.

Hunter, G. W. (1941). *Life science. A social biology.* New York: American Book.

Hunter, G. W., & Hunter, F. R. (1949). *Biology in our lives.* New York: American Book.

Moon, T. J., Mann, P. B., & Otto, J. H. (1947). *Modern biology* (1st ed.). New York: Holt.

Ritchie, J. W. (1941). *Biology and human affairs* (1st ed.). New York: World Book.

Ritchie, J. W. (1948). *Biology and human affair*. (2nd ed.). New York: World Book.

Smallwood, W. M., Reveley, I. L., Bailey, G. A., & Dodge, R. A (1948). *Elements of biology*. Boston: Allyn & Bacon.

Smith, E. T. (1942). *Exploring biology* (2nd ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1943). *Exploring biology* (3rd ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1947). *Exploring biology* (4th ed.). Chicago: Harcourt, Brace.

Smith, E. T. (1949). *Exploring biology* (5th ed.). Chicago: Harcourt, Brace.

Vance, B. B., Miller, D. F., & Teeters, W. R. (1946). *Biology for* you (1st ed.). Chicago: Lippincott.

Weymouth, C. G. (1941). *Science of living things.* New York: Holt.

Woodruff, L. L. (1941). *Foundations of biology* (5th ed.). New York: Macmillan.

1950–1959

Baker, A. O., & Mills, L. H. (1953). *Dynamic biology* (3rd ed.). New York: Rand McNally.

Baker, A. O., Mills, L. H., & Tanczos, J. (1959). *New dynamic biology*. New York: Rand McNally.

Bibby, C. (1950). *An active human biology*. London: William Heinemann.

Curtis, F. D., Caldwell, O. W., & Sherman, N. H. (1953). *Everyday biology*. Chicago: Ginn.

Curtis, F. D., & Urban, J. (1955). *Biology in daily life*. Boston: Ginn.

Curtis, F. D., & Urban, J. (1958). *Biology: The living world*. Boston: Ginn.

Dodge, R. A. (1959). *Elements of biology*. Boston: Allyn & Bacon.

Fenton, C. L., & Dambly, P. E. (1953). *Basic biology for high schools* (2nd ed.). New York: Macmillan.

Gillespie, D. K. (1957). *Better biology for high school*. New York: Vantage Press.

Grant. C., Cady, H. K., & Neal, N. A. (1952). *High school biology* (2nd ed.). New York: McGraw-Hill.

Heiss, E. D., & Lape, R. H. (1958). *Biology: A basic science* (1st ed.). New York: Van Nostrand.

Hunter, G. W., & Hunter, F. R. (1955). *Biology in our lives.* New York: American Book.

Jean, F. C., Harrah, E. C., & Herman, F. L. (1952). *Man and his biological world.* Boston: Ginn.

Kroeber, E., Wolff, W. H., & Weaver, R. L. (1957). *Biology*. Boston: Heath.

Lauby, C. J., Silvan, J. C., & Mork. G. M. A. (1958). *Biology*. New York: American Book.

Moon, T. J., Mann, P. B., & Otto, J. H. (1951). *Modern biology* (2nd ed.). New York: Holt.

Moon, T. J., Mann, P. B., & Otto, J. H. (1956). *Modern biology* (3rd ed.). New York: Holt.

Moon, T. J., Mann, P. B., Otto, J. H., Kuntz, J. A., & Dury, E. J. (1958). *Modern biology*. (Gregor Mendel Edition). New York: Holt.

Smallwood, W. M., Reveley, I. L., Bailey, G. A., & Dodge, R. A. (1950). *Elements of biology*. Boston: Allyn & Bacon.

Smallwood, W. M., Reveley, I. L., Bailey, G. A., & Dodge, R. A. (1952). *Elements of biology*. Boston: Allyn & Bacon.

Smith, E. T. (1952). *Exploring biology* (6th ed.). Chicago : Harcourt, Brace.

Smith, E. T. (1954). *Exploring biology* (7th ed.). Chicago : Harcourt, Brace.

Smith, E. T. (1959). *Exploring biology* (8th ed.). Chicago: Harcourt, Brace.

Smith, E. T., & Lisonbee, L. (1958). *Your biology*. New York: Harcourt, Brace Science Program.

Vance, B. B., & Miller, D. F. (1950). *Biology for you* (2nd ed.). Chicago: Lippincott.

Vance, B. B., & Miller, D. F. (1954). *Biology for you* (3rd ed.). Chicago: Lippincott.

Vance, B. B., & Miller, D. F. (1958). *Biology for you* (4th ed.). Chicago: Lippincott.

1960–1969

BSCS. (1963). *Biological science: An ecological approach* (1st ed.). Chicago: Rand McNally.

BSCS. (1963). *Biological sciences: An inquiry into life* (1st ed.). New York: Harcourt, Brace.

BSCS. (1963). *Biological science: Molecules to man* (1st ed.). Boston: Houghton-Mifflin.

BSCS. (1968). *Biological science: An ecological approach* (2nd ed.). Chicago: Rand McNally.

BSCS. (1968). *Biological science: An inquiry into life* (2nd ed.). New York: Harcourt Brace.

BSCS. (1968). *Biological science: Molecules to man* (2nd ed.). New York: Houghton-Mifflin.

Dodge, R, A. (1964). *Elements of biology* (2nd ed.). Boston: Allyn & Bacon.

Gregory, W. H., & Goldman, E. H. (1965). *Biological science for high school.* New York: Ginn.

Heiss, E. D., & Lape, R. H. (1961). *Biology: A basic science* (2nd ed.). New York: Van Nostrand.

Kimball, J. W. (1965). *Biology* (1st ed.). Reading, MA: Addison-Wesley.

Kimball, J. W. (1969). *Biology* (2nd ed.). Reading, MA: Addison-Wesley.

Kraus, D., & Perkins, O. E. (1969). *Concepts in modern biology* (1st ed.). New York: Cambridge.

Miller, D. F., and Vance, B. B. (1965). *Science of biology*. Philadelphia: Lippincott.

Moon, T. J., Otto, J. H., & Towle, A. (1960). *Modern biology* (4th ed.). New York: Holt.

Moon, T. J., Otto, J. H., & Towle, A. (1963). *Modern biology* (5th ed.). New York: Holt.

Nason, A., & Goldstein, P. (1969). *Biology: Introduction to life.* Menlo Park, CA: Addison-Wesley.

Otto, J. H., & Towle, A. (1965). *Modern biology* (6th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1969). *Modern biology* (7th ed.). New York: Holt.

Smith, E. T. (1966). *Exploring biology* (9th ed.). Chicago: Harcourt, Brace.

Smith, E. T., & Lisonbee, L. (1962). *Your biology* (2nd ed.). New York: Harcourt, Brace.

Vance, B. B., & Miller, D. F. (1963). *Biology for you* (5th ed.). Philadelphia: Lippincott.

Weinberg, S. L. (1966). *Biology: An inquiry into the nature of life.* Boston: Allyn & Bacon.

1970–1979

Brandwein, P. F., Brovey, D. J., Greenstone, A. W., & Yasso, W. E. (1975). *Life: A biological science* (3rd ed.). New York: Harcourt Brace Jovanovich.

BSCS. (1973). *Biological science: An ecological approach* (3rd ed.). Chicago: Rand McNally.

BSCS. (1973). *Biological science: An inquiry into life* (3rd ed.). New York: Harcourt, Brace.

BSCS. (1973). *Biological science: Molecules to man* (3rd ed.). New York: Houghton-Mifflin.

BSCS. (1978). *Biological science: An ecological approach* (4th ed.). Chicago: Rand McNally.

Kimball, J. W. (1974). *Biology* (3rd ed.). Reading, MA: Addison-Wesley.

Kimball, J. W. (1978). *Biology* (4th ed.). Reading, MA: Addison-Wesley.

Kraus, D, & Perkins, O. E. (1974). *Concepts in modern biology* (2nd ed.). New York: Cambridge.

Levy, C. K. (1978). *Elements of biology* (2nd ed.). Reading, MA: Addison-Wesley.

Morholt, E. L., & Brandwein, P. F. (1976). *Biology: Patterns in living things* (2nd ed.). New York: Harcourt, Brace & Jovanovich.

Oram, R. F. (1973). *Biology: Living systems.* (1st ed.) Columbus, OH: Merrill.

Oram, R. F. (1976). *Biology: Living systems* (2nd ed.). Columbus, OH: Merrill.

Oram, R. F. (1979). *Biology: Living systems* (3rd ed.). Columbus, OH: Merrill.

Otto, J. H., & Towle, A. (1973). *Modern biology* (8th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1977). *Modern biology* (9th ed.). New York: Holt.

Oxenhorn, J. M. (1974). *Pathways in biology.* New York: Globe.

Rahn, J. E. (1974). *Biology: The science of life*. New York: Macmillan.

Smallwood, W. M. (1978). *Challenges to science: Life science*. New York: McGraw-Hill

Smallwood, W. M., & Green, E. R. (1977). *Biology.* Morristown, NJ: Silver Burdett.

Weinberg, S. L. (1971). *Biology: An inquiry into the nature of life* (2nd ed.). Boston: Allyn & Bacon.

Weinberg, S. L. (1974). *Biology: An Inquiry into the nature of life* (3rd ed.). Boston: Allyn & Bacon.

Weinberg, S. L. (1977). *Biology: An inquiry into the nature of life* (4th ed.). Boston: Allyn & Bacon.

Weinberg, S. L., & Stoltze, H. J. (1977). *Action biology.* Boston: Allyn & Bacon.

1980–1989

Bauer, P. H., Magnoli, M. A., Alvarez, A., Chang-Van Horn, D., & Gomes, D. T. (1981). *Experiences in biology* (1st ed.). River Forest, IL: Laidlaw.

Bauer, P. H., Magnoli, M. A., Alvarez, A., Chang-Van Horn, D., & Gomes, D. T. (1985). *Experiences in biology* (2nd ed.). River Forest, IL: Laidlaw.

BSCS. (1980). *Biological science: An inquiry into life* (4th ed.). New York: Harcourt Brace.

BSCS. (1980). *Biological science: Molecules to man* (4th ed.). Lexington, MA: Heath.

BSCS. (1982). *Biological science: An ecological approach* (5th ed.). Boston: Houghton Mifflin.

BSCS. (1985). *Biological science: Molecules to man* (5th ed.). Lexington, MA: Heath.

BSCS. (1987). *Biological science: An ecological approach* (6th ed.). Dubuque, IA: Kendall-Hunt.

Goodman, H. D. (1986). *Biology*. Orlando: Harcourt.

Gottfried, S., Hampton, C. D., Hampton, C. H., Leibel, W., Madrazo, G., Motz, L., Sinclair, D., & Skoog, G. (1983). *Biology*. (1st ed). Englewood Cliffs, NJ: Prentice-Hall.

Gottfried, S., Hampton, C. D., Hampton, C. H., Leibel, W., Madrazo, G., Motz, L., Sinclair, D., & Skoog, G. (1986). *Biology*. (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Gottfried, S., Hampton, C. D., Hampton, C. H., Leibel, W., Madrazo, G., Motz, L., Sinclair, D., & Skoog, G. (1987). *Biology*. (3rd ed). Englewood Cliffs, NJ: Prentice-Hall.

Hanson, E. D., Lockard, J. D., & Jensch, P. F. (1980). *Biology: The science of life.* Boston: Houghton-Mifflin.

Kimball, J. W. (1983). *Biology* (5th ed.). Reading, MA: Addison-Wesley.

Kraus, D. (1984). *Concepts in modern biology* (5th ed.). New York: Globe.

Levy, C. K. (1982). *Elements of Biology* (3rd ed.). Reading, MA: Addison-Wesley.

McLaren, J. E., & Rotundo, L. (1986). *Heath biology* (1st ed.). Lexington, MA: D.C. Heath.

McLaren, J. E., & Rotundo, L. (1989). *Heath biology* (2nd ed.). Lexington, MA: D.C. Heath.

Oram, R. F., Hummer, P. J., & Smoot, R. C. (1983) *Biology living systems* (4th ed.). Columbus, OH: Merrill.

Oram, R. F., Hummer, P. J., & Smoot, R. C. (1986) *Biology living systems* (5th ed.). Columbus, OH: Merrill.

Otto, J. H., & Towle, A. (1981). *Modern biology* (10th ed.). New York: Holt.

Otto, J. H., & Towle, A. (1985). *Modern biology* (11th ed.). New York: Holt.

Rahn, J. E. (1980). *Biology* (2nd ed.). New York: Macmillan.

Schraer, W. D., & Stoltze, H. J. (1983). *Biology: The study of life* (1st ed.). Fairfield, NJ: Cebco.

Schraer, W. D., & Stoltze, H. J. (1987). *Biology: The study of life* (2nd ed.). Newton, MA: Cebco.

Slesnick, I. L., Balzer, L., McCormack, A. J., Newton, D. E., & Rasmussen, F. A. (1980). *Biology*. (1st ed.). Glenview, IL: Scott, Foresman.

Slesnick, I. L., Balzer, L., McCormack, A. J., Newton, D. E., & Rasmussen, F. A. (1983). *Biology*. (2nd ed.). Glenview, IL: Scott, Foresman.

Slesnick, I. L., Balzer, L., McCormack, A. J., Newton, D. E., & Rasmussen, F. A. (1988). *Biology*. (3rd ed.). Glenview, IL: Scott, Foresman.

Towle, A. (1989). *Modern biology*. (11th ed.). New York: Holt.

Wallace, B., & Simmons, G. M. (1987). *Biology for living*. Baltimore: Johns Hopkins.

1990–1999

Balzer, A. L. (1990). *Life science*. Glenview, IL: Scott, Foresman.

Biggs, A., Kapicka, C., & Lundgren, L. (1991). *Biology: The dynamics of life* (1st ed.). New York: Glencoe.

Biggs, A., Kapicka, C., & Lundgren, L. (1995). *Biology: The dynamics of life* (2nd ed.). New York: Glencoe.

Biggs, A., Kapicka, C., & Lundgren, L. (1998). *Biology: The dynamics of life* (3rd ed.). New York: Glencoe.

BSCS. (1990). *Biological science: Molecules to man* (6th ed.). Lexington, MA: Heath.

BSCS. (1992). *Biological science: An ecological approach* (7th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (1996). *Biological science: A molecular approach* (7th ed.). Lexington, MA: Heath.

BSCS. (1997). *BSCS biology: A human approach* (1st ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (1998). *BSCS biology: An ecological approach* (8th ed.). Dubuque, IA: Kendall-Hunt.

Goodman, H. D., Graham, L. E., Emmel, T. C., & Schechter, Y. (1991). *Biology today*. Austin, TX: Holt, Rinehart & Winston.

Gottfried, S. Madrazo, G., Motz, L., Olenchalk, J., Sinclair, D., & Skoog, G. (1990). *Biology*. Englewood Cliffs, NJ: Prentice-Hall.

Johnson, G. B., & Raven, P. H. (1998). *Biology, principles and explorations*. Austin, TX: Holt.

Kimball, J. W. (1994) *Biology* (6th ed.). Dubuque, IA: Wm C. Brown.

Kraus, D. (1993). *Concepts in modern biology.* Englewood Cliffs, NJ: Globe.

Kraus, D. (1999). *Concepts in modern biology*. Upper Saddle River, NJ: Globe.

Leonard, W. H., & Penick, J. E. (1998). *Biology: A community context.* Cincinnati: South-Western Educational Publishing.

Levine, J. S., & Miller, K. R. (1994). *Biology: Discovering life* (2nd ed.). Lexington, MA: Heath.

McLaren, J. E., Rotundo, L., & Gurley-Dilger, L. (1991). *Heath biology.* Lexington, MA: D.C. Heath.

Miller, K. R., & Levine, J. (1991). *Biology* (1st ed.). Upper Saddle River, NJ: Prentice Hall.

Miller, K. R., & Levine, J. (1993). *Biology* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

Miller, K. R., & Levine, J. (1998). *Biology: The living science.* Upper Saddle River, NJ: Prentice Hall.

Oram, R. F. (1994). *Biology living systems*. Columbus, OH: Glencoe/McGraw-Hill.

Oram, R. F., & Hummer, P. J. (1998). *Biology living systems*. New York: Glencoe.

Schraer, W. D., & Stoltze, H. J. (1990). *Biology: The study of life* (3rd ed.). Fairfield, NJ: Cebco.

Schraer, W. D., & Stoltze, H. J. (1993). *Biology: The study of life* (4th ed.). Englewood Cliffs, NJ: Prentice Hall.

Schraer, W. D., & Stoltze, H. J. (1995). *Biology: The study of life* (5th ed.). Englewood Cliffs, NJ: Prentice Hall.

Schraer, W. D., & Stoltze, H. J. (1999). *Biology: The study of life* (6th ed.). Englewood Cliffs, NJ: Prentice Hall.

Standafer, E., & Wahlgren, W. (1999). *Modern biology* (14th ed.). New York: Holt.

Strauss, E., & Lisowski, M. (1998). *Biology the web of life.* Menlo Park, CA: Scott Foresman Addison-Wesley.

Towle, A. (1991). *Modern biology* (12th ed.). New York: Holt.

Towle, A. (1993). *Modern biology* (13th ed.). Austin, TX: Holt, Rinehart, & Winston.

2000–2010

Alcamo, E., & Feldkamp, S. (2002). *Modern biology.* Austin, TX: Holt, Rinehart and Winston.

Biggs, A. (2002). *Biology: The dynamics of life.* New York: McGraw-Hill/Glencoe.

Biggs, A., Daniel, L., Ortleb, E., Rillero, P., & Zike, D. (2008). *Life Science*. New York: McGraw-Hill/Glencoe.

Biggs, A., Hagins, W. C., Kapicka, C., & Lundgren, L., Rillero, P., Tallman, K. G., & Zike, D. (2004). *Biology: The dynamics of life.* New York: McGraw-Hill/Glencoe.

Biggs, A., Hagins, W. C., Kapicka, C., & Lundgren, L., Rillero, P., Tallman, K. G., & Zike, D. (2006). *Biology: The dynamics of life.* New York: McGraw-Hill/Glencoe.

BSCS. (2000). *BSCS biology: A human approach* (2nd ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2001). *BSCS biology: A molecular approach* (8th ed.). New York: McGraw-Hill/Glencoe.

BSCS. (2002). *BSCS biology: An ecological approach* (9th ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2003). *BSCS: A human approach* (3rd edition). Dubuque, IA: Kendall-Hunt.

BSCS. (2004). *BSCS biology: A molecular approach* (9th ed.). New York: McGraw-Hill/Glencoe.

BSCS. (2006). *BSCS biology: A human approach* (3rd ed.). Dubuque, IA: Kendall-Hunt.

BSCS. (2006). *BSCS biology: A molecular approach* (10th ed.). New York: McGraw-Hill/Glencoe.

BSCS. (2006). *BSCS biology: An ecological approach* (10th ed.). Dubuque, IA: Kendall-Hunt.

Campbell, N. A., Reece, J. B., Mitchell, G. M., & Taylor, M. R. (2003). *Biology: Concepts and connections.* San Francisco: Benjamin Cummings.

Campbell, N. A., Williamson, B., & Heyden, R. J. (2004). *Biology: Exploring life.* Boston: Pearson.

Leonard, W. H., & Penick, J. E. (2003). *Biology: A community context* (2nd ed.). New York: Glencoe McGraw-Hill.

Miller, K. R., & Levine, J. S. (2000). *Biology* (5th ed.). Upper Saddle River, NJ: Prentice Hall.

Miller, K. R., & Levine, J. S. (2002). *Biology* (6th ed.). Upper Saddle River, NJ: Prentice Hall. Needham, MA: Pearson.

Miller, K. R., & Levine, J. S. (2008). *Biology* (7th ed.). Upper Saddle River, NJ: Pearson/Prentice Hall.

Miller, K. R., & Levine, J. S. (2010). *Miller and Levine biology.* Boston: Pearson.

Oram, R. F. (2003). *Biology living systems*. Columbus, OH: Glencoe/McGraw-Hill.

Postlethwait, J. H., & Hopson, J. L. (2006). *Modern biology* (14th ed.). Austin, TX: Holt, Rinehart, & Winston.

Postlethwait, J. H., & Hopson, J. L. (2009). *Modern biology* (15th ed.). Austin, TX: Holt, Rinehart, & Winston.

Starr, C, Taggart, R., & Starr, L. (2001). *Biology: The unity and diversity of life.* Pacific Grove, CA: Brooks/Cole.