Haeckel's Embryos

Ernst Haeckel and comparative embryology

Ernst Haeckel (1834–1919) is both a hero and a villain in the biological community. He was a prominent figure in the late nineteenth-century comparative anatomy community and is famous for his phylogenetic trees, anatomical illustrations, support for evolution, and strong personality. He is perhaps as well known, and considerably misunderstood, for his studies in embryology and his dictum that "ontogeny recapitulates phylogeny," called the Biogenetic Law. Haeckel espoused the view that evolution generally proceeds by placing each innovation on top of a previous one, like adding layers on a cake. Therefore, the embryo of an "advanced" organism should pass through ("recapitulate") the *adult* stages of more "primitive" forms as it develops. However, repeated observations of development by other workers (e.g., Wilhelm His, Walter Garstang, Wilhelm Roux, Adam Sedgwick, Gavin de Beer, and others; see Gilbert, 1991, or Gould, 1977 for a detailed history) clearly showed that embryos do not go through adult stages of lower forms; rather, they share many common features in development. No biologist has accepted the biogenetic law for many decades and it may have been a caricature of Haeckel's actual views anyway. Much of Haeckel's developmental work is now considered invalid, and some historians of science have provided reasonable evidence to suggest that he manipulated his drawings to fit his preconceived views about development and evolution. Haeckel's views about the progressive nature of evolution are no longer accepted.

Regardless of Haeckel's accuracy or preconceptions, comparative embryology continues to be central to our understanding of evolution. Comparative embryology shows how different adult structures of many animals have the same embryonic precursors. These shared developmental features suggest that many animals have ancestors in common. Further comparative embryology shows that closely related animals show a unity of developmental pattern, particularly in earlier stages, and have more developmental features in common than do more distantly related organisms. The fact that certain incipient structures such as pharyngeal pouches or arches exist in all vertebrate embryos yet develop into very different adult structures suggests that they all share a common ancestor whose embryo had pharyngeal pouches (at least at some stage in development). In this way, developmental similarities that are inherited from a common ancestor are homologous, just like the patterns of bones in adult limbs.

Developing an argument

Wells's entire chapter on embryology amounts to little more than a misreading of Darwin, Haeckel, and others, combined with a general failure to acknowledge recent work on Haeckel and his embryos by Gould, Richardson, and others. In it, he conflates ideas in history of developmental biology with ideas of contemporary developmental biology. He also fails to recognize close to 60 years of work in developmental biology and thus completely omits any discussion of the real developmental evidence for evolution. It almost seems that Wells's goal is to discredit the entire field of comparative embryology by proxy, employing a bait-and-switch between Haeckel and Darwin. Wells's ploy is reminiscent of a child's false logic proof. It goes like this: Darwin relied on Haeckel, Haeckel was a fraud, therefore Darwin is a fraud.

The charge that Ernst Haeckel intentionally "faked" his drawings is irrelevant. Regardless of his intent, the drawings that Haeckel made are incorrect, especially in what he labeled as the "first stage." But it really does not matter what Haeckel thought or whether his drawings are accurate: modern comparative embryology does not stand or fall on the accuracy of Haeckel any more than modern physics stands or falls on the accuracy of Kepler or Newton. Historically, Wells actively ignores the accurate work of many of Haeckel's predecessors and contemporaries (such as William and Jeffrey Parker, Hans Gadow, Hans Selenka, Heinrich Rathke, Virgil Leighton, Hugo Schauinsland, and Alfred Voeltzkow, to name a few). Haeckel and von Baer were not the only embryologists in nineteenth-century science, but you wouldn't know that from reading Wells. Worse, Wells speciously extends his critique of Haeckel to the present day. Wells implies that textbooks misrepresent the study of developmental programs as evidence for evolution by accusing them of using Haeckel's inaccurate drawings, in effect accusing textbooks that show any embryos of "mindlessly repeating" Haeckel. The important question is whether textbooks, and more importantly developmental biologists, still rely on Haeckel's work. The answer is no, but that doesn't stop Wells from acting as if they do.

Wells sets up a straw man in his bait-and-switch, starting with Darwin's famous assertion that embryology represented the "single strongest class of facts" in favor of his theory. Here Wells misrepresents both early embryology and Darwin's own words. When quoting both Darwin and other historical figures, he quotes them out of context, leaves out important parts of quotes, and even changes the order of their appearance, all to misrepresent their real meaning and intent. Wells also conflates "recapitulation" — that is, that embryos go through the adult stages of their ancestors — with the idea that shared features of embryos give insight into their phylogenetic relationships. Failing to distinguish these allows Wells to avoid dealing with the actual evidence for shared developmental features in various embryos and to dismiss the entire field as based on an outdated and outright refuted claim, one that embryologists know to be false but cling to anyway because of an ideological commitment to evolution. Wells should know better, as the holder of a Ph.D. in cell and developmental biology.

Rewriting history for the greater glory of the Rev. Moon

In the introduction to *Icons*, Wells states that he first became aware of the problems in evolutionary theory when he was "finishing his Ph.D. in cell and developmental biology" (Wells, 2000:xi). He claims that he knew that the drawings of embryos presented in textbooks were false because he was a developmental biologist. Shortly thereafter, he claims, his observation was confirmed by other scientists. Before that seminal event, he says, "I believed almost everything I read in my textbooks" (Wells, 2000:xi). This statement is inconsistent with other claims of Wells's. According to statements made by Wells in a sermon on a Unification Church website (http://www.tparents.org/library/unification/talks/wells/DARWIN.htm), he went to graduate school with the specific intent of attacking evolution: "Father's words, my studies, and my prayers convinced me that I should devote my life to destroying Darwinism" and he believed that its weakest point was developmental biology. "I was convinced that embryology is the Achilles' heel of Darwinism; one cannot understand how organisms evolve unless one understands how they

develop. In 1989, I entered a second Ph.D. program, this time in biology, at the University of California at Berkeley. While there, I studied embryology and evolution." So it was not so much a "revelation" as it was a plan. If Wells is so revisionist about his own history, how can we trust him with the history of science?

Developmental anatomy, Darwin, and evolution

Wells opens the chapter by telling us what Darwin thought about development and evolution. Wells uses about 5 different quotes from the *Origin* in an attempt to show that Darwin was advocating recapitulation in spite of what the data showed. To do this, he distorts the history. Wells tries to connect Darwin to Haeckel so that he can use that to dismiss Darwin. Wells says that Darwin was not an embyrologist and thus he relied on Haeckel (Wells, 2000:81). Anyone familiar with the history of biology knows that this is impossible. Haeckel did not publish his *Anthropogenie* until 1874 (where the much-maligned embryo drawings first appear), *15 years* after the publication of the *Origin*. (It should also be noted that the drawings referred to by Wells [2000] are not from Haeckel but redrawn from the first edition of *Anthropogenie* in a textbook by Romanes [1892; see figure 10a]. In later editions of *Anthropogenie,* Haeckel corrected some of the errors of the first edition drawings [Richardson and Keuck, 2002; personal observation].) Wells quotes Darwin's praise of Haeckel in his sixth and final edition of the *Origin* in such a way as to obscure the fact that Darwin lauds Haeckel for his phylogenies, not his embryology. The quote is not even from the embryology section of the book; rather it comes from the classification section, in the final sentence of which Darwin praises Haeckel for using homologous features (including but not limited to developmental ones) to generate classifications for organisms. Darwin is praising the application of *his* theory by Haeckel.

Although Darwin did not use Haeckel on embryology, he did use von Baer. Recognizing Darwin's use of von Baer, Wells then accuses Darwin of "misusing" von Baer's work, twisting the data to fit his views. But Darwin does not. Wells claims that von Baer's embryological laws are incompatible with Darwin's conclusions, but they are not. Von Baer may have disagreed with Darwin about his conclusions, but his laws do not prohibit development elucidating common ancestry. Darwin came to a different conclusion from the same body of evidence — this is not "distorting" the evidence. Darwin was making a general inductive argument and searched for data that could test the general proposition of common descent; he argued that von Baer's data could be reinterpreted in terms of common ancestry. This was no more a "misuse" of von Baer than was Alfred Wegener's reinterpretations of the data of geology in light of mobile continents. New scientific theories always use previous data. Is Wells implying that evolutionary biology cannot cite any research that predates 1859? Is Wells implying that developmental sequences such as those illustrated by von Baer and others are not data?

That Darwin and all modern evolutionists advocate some form of the "Biogenetic Law" is the central falsehood of this chapter; in fact the entire "resurrecting recapitulation" section does nothing but assert this. But Wells fails to explain fully what recapitulation means. There are a number of meanings for "recapitulation" that Wells conflates in order to tar the entire field of embryology with a biogenetic brush. As he says in a footnote, a "plain reading" of Darwin shows that Darwin was advocating recapitulation — but just what kind? (1) An embryo of an "advanced" form goes through

all the adult stages of all its ancestors. This is a caricature of Haeckelian recapitulation, which is false, and few scientists ever believed it anyway. (2) Evolution proceeds as an "add-on" process so that there is a general progression of embryological stages from "primitive" to "advanced" forms. This more traditional reading of recapitulation is also false and has not been accepted for nearly a century. (3) All closely related organisms go through all the same stages of development and always look similar. This is vague: how closely related is closely related? How are the stages individuated? But however these questions are answered, this reading of recapitulation would generally be agreed to make too sweeping a claim. (4) Some parts of developmental sequences (and some specific characters of them) in closely related animals share more specific similarities (in pattern, sequence, position, etc. of developmental features) with each other than with those of more distantly related animals. That's basically true. All modern biologists recognize that all stages of development are open to modification. This is generally the type of "recapitulation" accepted by the post-Haeckelian embryologists (such as Frank Lillie) cited by Wells, as well as by current embryologists, but Wells treats it derisively as if it were exactly what Haeckel thought. Finally, a "plain reading" of Darwin shows that he was suggesting something between (2) and (3); even though he was not an embryologist, he had a more sophisticated notion of embryology and development than does Wells.

Wells chides Darwin and nineteenth-century embryologists for saying that the "earliest" stages of development are similar when in fact they are not. However, "earliest" is Wells's word, not Darwin's. It does not appear in any of the quotes that Wells uses. Indeed, in the entire section on embryology in the *Origin*, the word "earliest" only appears once, in a quotation from von Baer. Does "earliest" reflect Darwin's belief, or is he merely reporting von Baer's? This is important because numerous scholars have made the mistake of confusing Darwin's reporting of what others thought with his expression of his own views (Padian, 1999). So apparently has Wells. But it really does not matter what Darwin thought: just as modern embryology does not rely on Haeckel, neither does modern evolutionary biology slavishly follow Darwin's beliefs.

It is also important to understand what nineteenth-century scientific workers may have meant by the use of "embryo" and "early stage." For many workers in the nineteenth century, developing organisms weren't called embryos until they reached the tailbud (phylotypic) stage. During earlier stages, they were called "developing ovum" or "developing egg" (see Barry, 1839, or just about any embryology work from 1820 to 1900). What this means is that Haeckel, von Baer, and others, have a different meaning for "early embryo." Yet Wells interprets them using modern definitions.

Wells also criticizes the field of comparative embryology for the way it chooses its data and for its names for embryonic structures. First, Wells emphasizes the disparity of "earliest" developmental stages, accusing biologists of "choosing" taxa (animals) that look most similar for illustrations in textbooks and elsewhere. He criticizes Haeckel for not using animals such as monotremes in his work. But developmental sequences for monotremes were not available in 1874. Monotreme developmental sequences were not known or described until 1884 (Caldwell, 1887; Hughes and Hall, 1998), and it was the developmental features monotremes shared with marsupials that led Caldwell to conclude that monotremes were indeed mammals (Caldwell, 1887). Was the sample of organisms available to Haeckel

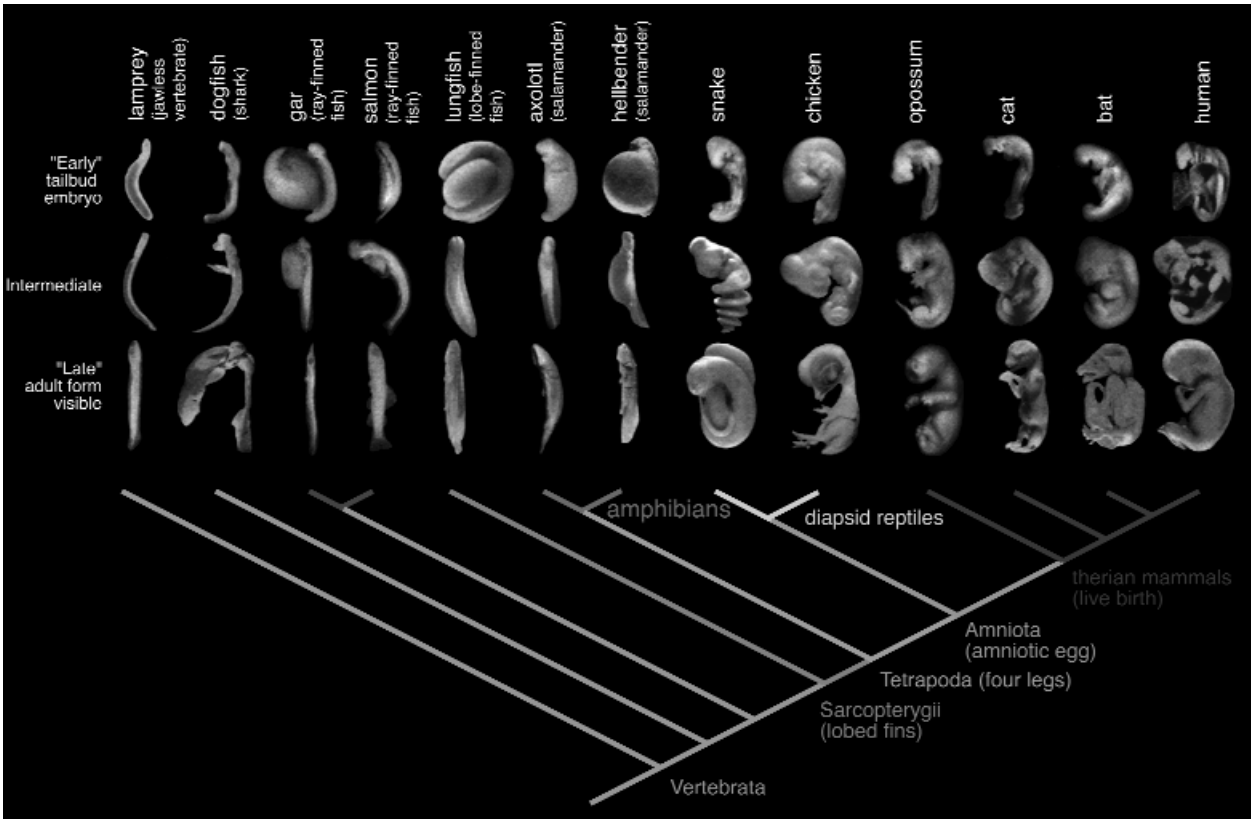

Figure 8. *Developmental sequences of various vertebrates shown in phylogenetic context. Note the shared similarities of some closely related taxa, particularly the amniotes (modified from Richardson et al. 1998).*

biased? Yes, but only in the sense that early embryologists worked with the animals that were available to them. Most specimens of "exotic" animals were shipped to researchers by explorers and received in varying states of decay (Caldwell, 1887). Most nineteenth-century embryologists loved to describe the development of any animal they could. And Haeckel was continually updating and adding new organisms to his embryonic series as they came available. Contrary to what Wells implies, there was no attempt to limit the data, and the sample was not "chosen" for any particular reason.

Today, embryologists work mainly with "model organisms," which were largely chosen for practical reasons such as ready availability, small body size, large litter size, rapid sexual maturity, rapid reproduction, ability for development to occur in the laboratory, and ability to live indoors for several generations (Bolker, 1995). They were not chosen to "support evolution" as Wells implies. In fact, the model organism that is the subject of Wells's own dissertation, *Xenopus*, was not the original "model" amphibian. The discovery that *Xenopus* does not need a breeding season was a boon to embryologists and led to its serendipitous adoption as a model organism (Gurdon and Hopwood, 2000). How Wells knows that "model organisms" were chosen to mislead is unclear, especially given his own use of model organisms later in his chapter. Wells doesn't show developmental sequences for any of the organisms he complains others don't show. Why not? Because there is no evi-

dence for his insinuation that developmental biologists treat their data selectively in order to hide something. The fact that embryologists tend to present, at least in textbooks, developmental sequences for which there is good data does not refute the idea that closely related taxa, should, and do, have more shared similarities in developmental programs than more distantly related taxa (Figures 8, 9). Wells tries to support his claim by using a quote by Darwin in which he states that embryos of the *same* "class" are most similar in their earliest stages. Wells then says that the quote is false, and cites how the *different* "classes" of vertebrates are very different in their "earliest" stages. This is merely a semantic sleight-of-hand, a bait-and-switch. Darwin is not talking about different "classes." Wells leaves out important information, as usual.

In the figures of embryos (Wells, 2000:95, especially stage 4, "gastrulation"), Wells's illustrator resorts to a number of graphic tricks in order to make the embryos appear more different than they are. First, the embryos are not shown from the same rotational angles. The chicken is shown in a different position than the other "Haeckel's first stage" embryos. Second, they are not all scaled the same. In the figure showing the neural crest infolding, the turtle and chicken are shown at a large scale, neglecting the large yolk they sit on, while the human is shown as part of the whole developing ovum, so that the germinal disc and primitive streak formation are shown differently, even though it is shared by all amniotes (Schaunislaund, 1903; Nelson, 1953; Cruz, 1997; Schoenwolf, 1997; Figure 9). Also pictured is a frog embryo, despite its indirect development, which is very different from that of the other vertebrates pictured. Many of the general "differences" in early embryo development that Wells mentions are a result of organization due to the yolk size rather than being specific differences in the basic body-plan of the embryo (Arendt and Nübler-Jung, 1999).

Embryos do reveal phylogenetic information in terms of specific shared features, shared early developmental features such as the formation of a germinal disc and primitive streak in all amniotes or the neural crest cells of all vertebrates. The presence, and sequence of development, of eyes, ears, somites, limbs, guts, nerve cords, tails, organs, etc. are individual features that no one would deny are

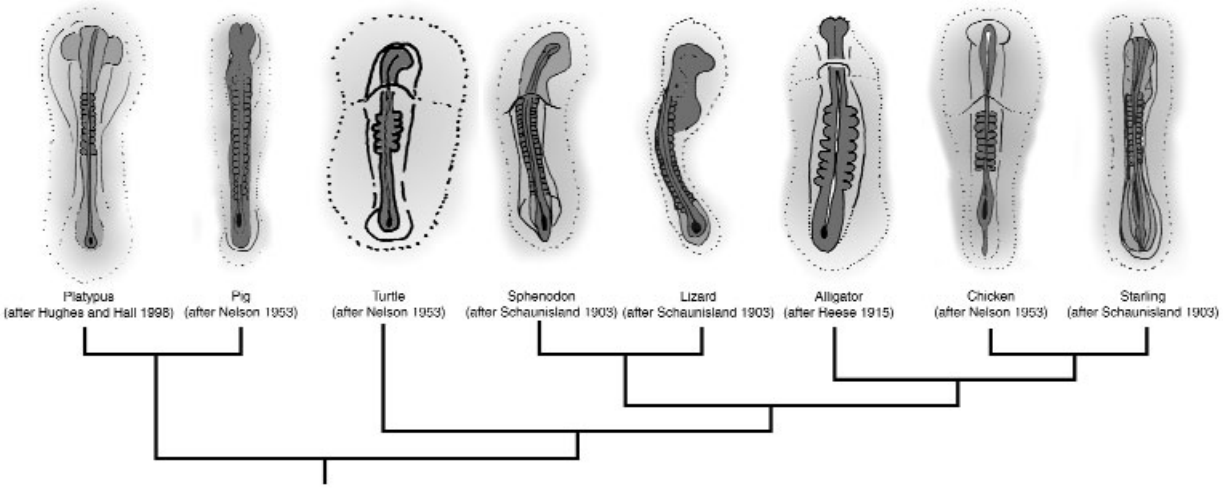

Figure 9. *Embryos of various amniotes shown during somite stage. All amniotes go through the same sequence of development: primitive streak–neural tube–somite formation.*

present in vertebrates and not present in the same way in other animals. These are individual characters whose developmental features are treated as shared features in reconstructing vertebrate evolution; these features do not always have to be in agreement, and some animals can show unusual derived features early in development, such as the snake's tail (Figure 8).

Wells's treatment of comparative embryology is remarkably limited; for example, he never discusses invertebrate development. Yet there are plenty of shared developmental patterns there as well. Despite the very different appearance of echinoderm, hemichordate, and chordate embryos, they all share the deuterostome condition, in which the first cell opening becomes the anus, before they diverge to their adult body plans. Or what about the trochophore larvae of most protostomes and spiral cleavage shared by annelids, arthropods, mollusks (Nielsen, 1995; Fell, 1997)? The nauplius larvae of crustaceans (Gilbert, 1997) or the verliger larvae and development of gastropods, which go through flexure, torsion, and degeneration of muscles on one side of the body, suggestive of their evolutionary history (Nielsen, 1995; Collier, 1997)? These are just a few of the specific similarities of the kind that Wells implies do not exist. Similarities in embryonic sequences are *data* — characters by which we can discover shared similarities among organisms that can be used to reconstruct their relationships. Using such data in phylogeny is not the same as using those characters in any "recapitulationist" way.

Finally, Wells concludes by attacking prominent biologists such as Gould and Futuyma for supposedly not knowing the truth about Haeckel, saying that this is "a confession of ignorance not likely to inspire confidence in the quality of our biology textbooks" (Wells, 2000:107). Wells's own misrepresentations of the letter and spirit of the concepts and authors he presents do little to inspire confidence in what he says about Haeckel or embryology in general. Even if Wells were right about Haeckel's work and Darwin's use of it, what Haeckel and Darwin thought doesn't matter; embryology has moved beyond them. Wells needs to show a lack of *specific* similarities to support his case. Is Wells actually claiming that there are *no* shared features in development at all? That a chicken gets a planula while the duck gets a naupius? If so, he needs to show it, but Wells never gets to specifics — apparently because the specifics aren't there. Innuendo and accusations of fraud do not cut it in science.

What textbooks say

For any textbook to show Haeckel's drawings themselves as unqualified statements of developmental anatomy or to advocate "recapitulation" in a Haeckelian sense would be inexcusable, but none of the textbooks reviewed by Wells appear to do so. Wells gleefully excoriates Futuyma for using Haeckel's drawings (Figure 10a), but apparently in his fit of righteous indignation, he for-

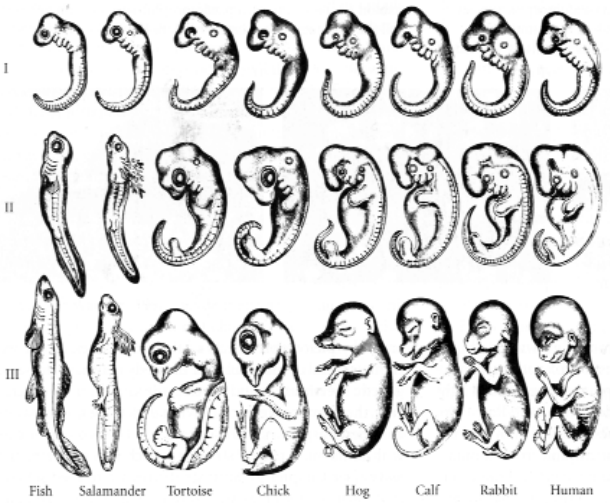

Figure 10a. *Romanes (1892) embryo drawings reproduced in Futuyma (1998:653).*

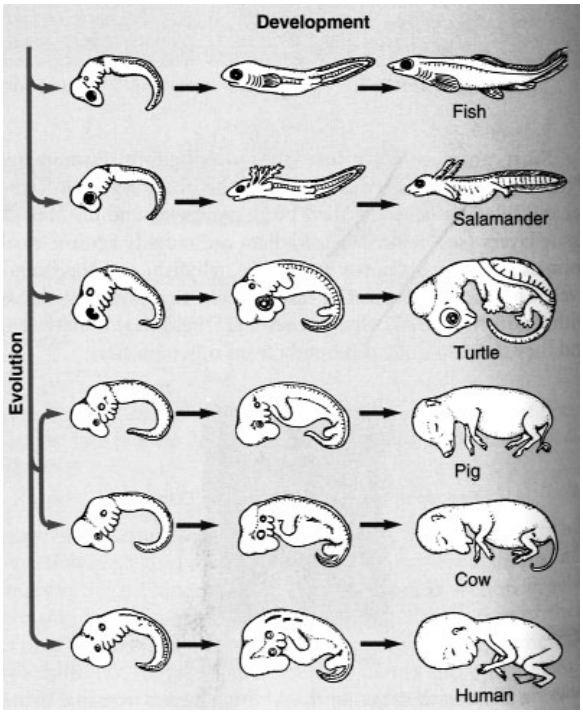

Figure 10b. *Romanes (1892) embryos reproduced and placed in historical context in Guttman (1999:718)*

got to read the text, in which the drawings are discussed in a *historical* context — stating why Haeckel is wrong — and Futuyma has an entire chapter devoted to development and evolution. Guttman (Figure 10b) uses them in an explicitly historical context as well. Wells states that books use "Haeckel's drawings, or redrawn versions of them" (Wells, 2000:255), but this is not true. Figures 10a–j show Haeckel's drawings compared to the drawings in the textbooks reviewed by Wells. It can be clearly seen that a majority of the drawings are not "redrawn." Some textbooks show more

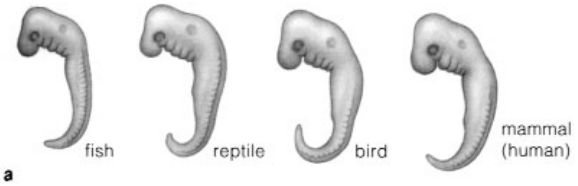

Figure 10c. *Romanes (1892) embryos redrawn in Starr and Taggart (1998:317).*

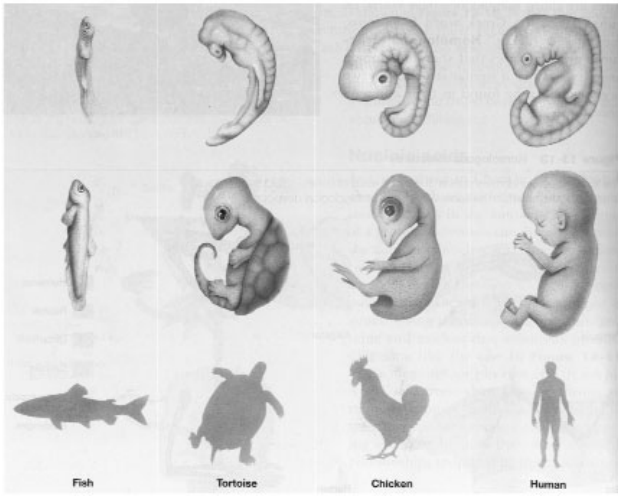

Figure 10d. *Embryos redrawn and somewhat corrected in Raven and Johnson (1999:288).*

accurate drawings (Miller and Levine, Johnson, Biggs, Kapicka and Lundgren; Figures 10f,g,h); some use photos (Campbell, Reese and Mitchell, Mader; Figures 10i,j); only Starr and Taggart (Figure 10c), Raven and Johnson in their development chapter along with accurate drawings and photos; (Figure 10d), and Schraer and Stolze (but redrawn and corrected; Figure 10e) use what could be considered embryos "redrawn" from Haeckel. No textbook discusses embryology in any way

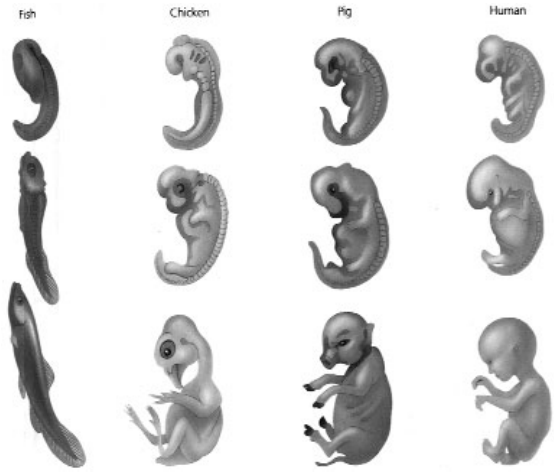

Figure 10e. *Embryos redrawn and corrected in Schraer and Stolze (1999:582)*

that could be considered strongly "recapitulationist." In most textbooks, embryology is presented in just one or two paragraphs, making it hard to discuss all the complexities of development. At a high school level, the aim of the book is to convey some basic concepts of biology, not to confuse students with the complexity of a subject.

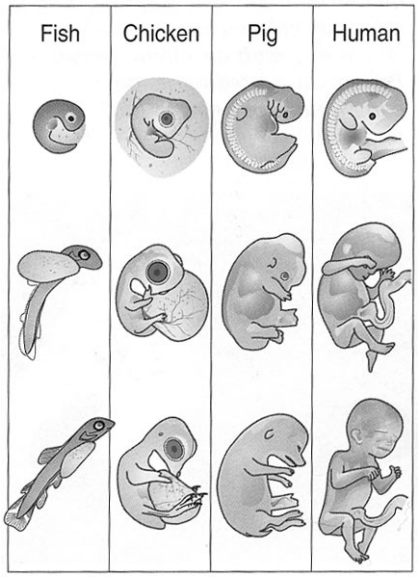

Figure 10f. *Original embryo drawings in Miller and Levine (2000:283).*

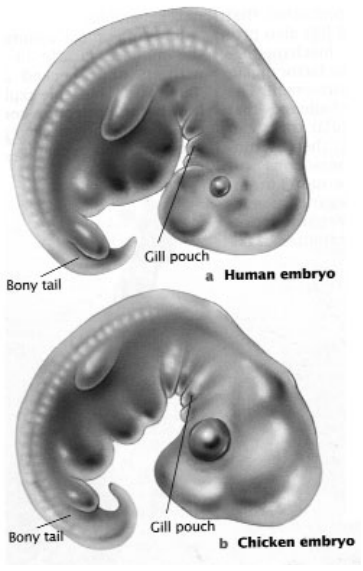

Figure 10g. *Original embryo drawings in Johnson (1998:179).*

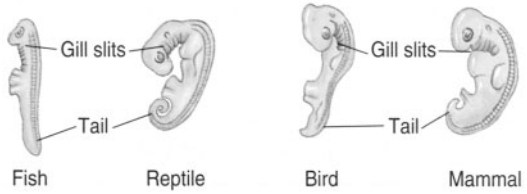

Figure 10h. *Embryo drawings in Biggs et al. (1998:433). Identical drawings appear in the evolution chapter (p.416) of Raven and Johnson (1999).*

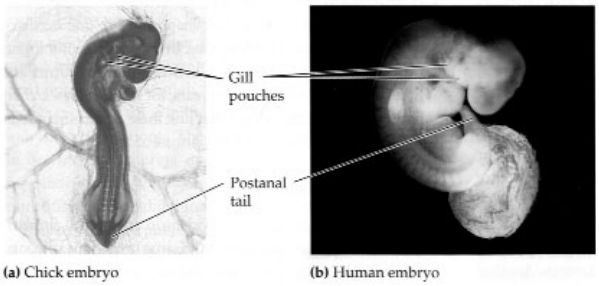

Figure 10i. *Embryo photos in Campbell, Reese, and Mitchell (1999:424).*

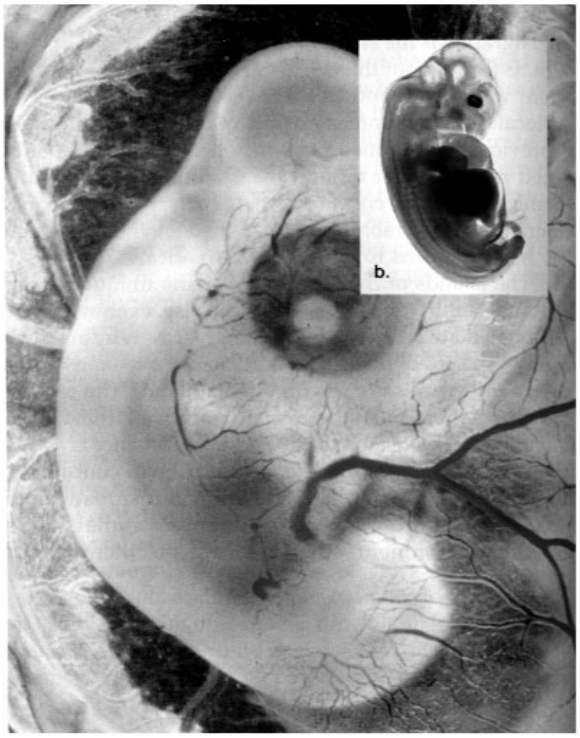

Figure 10j. *Embryo photos in Mader (1998:298).*

WELLS'S "WELL-DEVELOPED" GRADING SCHEME

The grading scheme employed by Wells is designed for failure. This is because Wells assumes all drawings to be "redrawn" from Haeckel and gives *any* book with *a* drawing an F (Figure 11). Wells does not explain how one would determine whether they are simply *redrawn* from Haeckel; in any case none of the books appear to contain mindlessly redrawn figures (Figure 10a–j). Using more accurate pictures only earns a book a D. In order to earn a C or higher, a book must *not use* "misleading drawings or *photos*." This amounts to complaining that textbooks shouldn't allow students to be misled by reality! Wells does not specify what kind of drawings or photos *would not* be misleading. Thus Wells apparently thinks that *all* visual presentations of embryos are misleading, whether they are accurate or not. Wasn't Wells the one complaining about selective use of data? He actu-

Book	Embryology			
	#pages	#words	Embryo representation	Wells's Grade
Schraer, W. D. and H. J. Stolze. 1999. Biology: The Study of Life, seventh edition. Prentice-Hall, Upper Saddle River, NJ. 944p.	1/4	108	redrawn (w/correction)	F
Johnson, G. B. 1998. Biology: Visualizing Life. Holt, Rinehart & Winston, Orlando. 895p.	1/4	78	drawing	F
Biggs, A., C. Kapinka, and L. Lundgren. 1998. Dynamics of life. Glencoe/McGraw Hill, Westerville, OH. 1119p.	1/2	96	drawing	F
Miller, K. R. and J. Levine. 2000. Biology, fifth edition. Prentice-Hall Upper Saddle River, NJ. 1114p.	1	324	drawing	F
Starr, C. and R. Taggart. 1998. Biology: The Unity and Diversity of Life, eighth edition. Wadsworth Publishing Company, Belmont CA. 920p.	1/2	282	redrawn	F
Guttman, B. S. 1999. Biology. WCB/McGraw-Hill, Boston. 1175p.	1/2 +[1]	265	Haeckel/Draw/ photos	F[1]
Mader, S. 1998. Biology, sixth edition. WCB/McGraw-Hill, Boston. 944p.	1/4 +1/3	109 +86	Photo/drawing	D[2]
Raven, P. H. and G. B. Johnson. 1999. Biology, fifth edition. WCB/McGraw-Hill Boston. 1284p.	1/4 +1/3 +1/2	83 +170 +271	photo/ drawing/ redrawn	F
Cambpell, N. A., J. B. Reese, and M. G. Mitchell. 1999. Biology,fifth edition. Benjamin Cummings, Menlo Park, CA. 1175p.	3/4 +[3]	247 +[3]	photos/ drawings	D[3]
Futuyma, D. 1998. Evolutionary Biology. Sinauer Associates, Sunderland, MA. 761p.	26 (1.5)[4]	561[4]	Haeckel (in context)	F[5]

1.Guttman devotes 2 chapters specifically to developmental processes. A nice up to date treatment (Chapter 20, 21 p. 397-441) which discusses some of the "early stage differences" that Wells grade suggests it does not.
2. Mader uses the term "pharyngeal pouches" rather than the much maligned "gill slits." However, the grading scheme does not really have a way to take this into account.
3.This book also contains an entire chapter of developmental biology. (Chapter 47 p.936-960) in which it discusses some of the "earlier stage differences" that Wells grade suggests it does not.
4.Futuyma devotes an entire chapter to "Development and evolution" (Chapter 23 p. 651-676) in which he devotes 1.5 pages to Haeckel, explicitly.
5. Futuyma treatment of Haeckel, is placed in historical context, largely discussing why Haeckel was wrong. Even though the offending diagram is used, it is in historical context. It also clearly states that "gill slits" or "arches" do not develop into gills, and the they never have anything approaching "gills" during their development. Wells grading scheme has to way to take such contextual issues into account.

Figure 11. *Wells's grades for the embryology sections of textbooks.*

ally attacks Mader and Campbell, Reese, and Mitchell, for using "misleading photos" because they show embryos of a chick and a human, which he says "just happen" to have a stronger resemblance than would embryos from any other "classes" of vertebrate. Wells is wrong: a chick embryo at that stage looks much more like an alligator embryo than a mammal embryo (comparisons made from Nelson, 1953, Schaunisland, 1903, and Reese, 1915). This is in accordance with the predictions of evolutionary theory, because an alligator and a chicken share a more recent ancestor with each other than they do with a mammal, and thus should have more similar a developmental program. Wells also chides Mader for saying that embryos "have many features in common" (Wells, 2000:103–104). Does Wells assert that they have *no* features in common? If so, he should document it. Having failed to do this, Wells merely labels anything he does not like "misleading." Wells also takes exception to the colloquial term "gill slits," which is a commonly used non-technical term for pharyngeal pouches. Wells implies that by using this term, biologists and textbooks are saying that all animals' embryos have gills. This is patently false. No textbook reviewed even implies the presence of *gills* in embryos. The question is what these structures are and what they become, not what they are called. Using the terms "gill slits" automatically results in a C even if the textbook contains no images, and regardless of its content. Campbell, Reese, and Mitchell, and Guttman both contain entire chapters devoted to developmental biology in which they *do* discuss some of the "early stage differences" that Wells suggests they do not. They receive no credit for these extensive treatments (Figure 11).

Why we should still teach comparative embryology

Despite changes in how we view the role of developmental programs as reflections of evolutionary history, we can still see how the same embryonic structures develop into different adult structures. We observe the unity of developmental plan in all vertebrates. This is what we see, and no amount of wishful thinking on the part of evolution detractors can change that. There is no reason to let their baseless complaints and character assassination dissuade biology teachers from presenting the evidence to students.

How textbooks could improve their presentations of comparative embryology

Textbooks could largely improve the presentations of embryology by lengthening their discussions of it, and by using photos rather than cartoonish drawings. They could also be more explicit about how embryonic precursors develop into different adult structures. Finally, adding discussions of Hox gene complexes (master developmental control genes) and evolutionary developmental biology would help bring the books up-to-date in their treatment of developmental biology. We are learning more about the evolutionary history and underpinnings of developmental programs every day. We are learning how developmental programs are the source of much of the evolutionary novelty that natural selection shaped. Wells ignores all this. To follow Wells's advice would arrest the development of students' knowledge.

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