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REVIEW ARTICLE

The Evolution of Evolution Theory and Its Controversies

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Keith Thomas. *Before Darwin: Reconciling God and Nature*. New Haven, CT: Yale University Press, 2005. 314 pp, $27.00 hc, ISBN 9780300107937.

Michael Ruse. *Darwinism and Its Discontents*. New York: Cambridge University Press, 2006. 316 pp, $30.00 hc, ISBN 9780521829472.

Marc W. Kirschner and John C. Gerhart. *The Plausibility of Life: Resolving Darwin's Dilemma*. New Haven, CT: Yale University Press, 2005. 314pp., $18.00 pb, ISBN 9780300119770.

Charles Darwin's *On the Origin of Species* was published in 1859. In the nearly 150 years since that landmark publication, evolution theory has been under attack from conservative religionists all over the world, particularly in the United States. Since the Scopes Trial in 1925, anti-evolution movements in the form of "creation science" and "intelligent design theory" have made their way into classrooms and courtrooms across America (Numbers 1998; Pennock 2001; Humes 2007). In 2007 a "museum" dedicated to young earth creationism opened in Kentucky, complete with exhibits featuring dinosaurs and humans "living in harmony." Clearly, there is a huge disconnect between science and contemporary American society for this kind of scenario to continue to thrive in the twenty-first century.

Three recent books (Kirschner and Gerhart 2005; Thomas 2005; Ruse 2006) take different approaches to explain why evolution theory has been so hard for some to accept, or to expand on "classical" evolution theory to put forward a new explanation for the diversity of life on earth. The context of these three tomes is set in an historical overview of the development of evolution theory, discussions on perceived conflicts between religion and science, and contemporary research that builds on existing ideas and pushes evolution theory forward to a more comprehensive explanation for the morphological variation separating genera, families and phyla, or, what some would call, "macroevolution." A parallel theme of the three authors is that the conflict between science and religion, as it relates to evolution theory, is very old and the arguments do not seem to change from one generation to another.

Thomas has written a perspective on the history of science with regard to the development of Darwin's ideas on natural selection as a driving force for speciation. Biographical sketches and the significance of their contributions are provided for, in order of appearance, Charles Darwin, William Paley, Nicolas Copernicus, Galileo Galilei, Isaac Newton, Robert Hooke, René Descartes, Robert Boyle, Erasmus Darwin, John Locke, David Hume, John Toland, John Ray, Robert Plot, Edward Lhwyd, William Smith, Thomas Burnet, John Woodward, William Whiston, Nicolas Steno, James Hutton, Charles Lyell, William Buckland, Jean Baptiste de Lamarck, Philip Henry Gosse, Thomas Huxley, Thomas Malthus, and Samuel Wilberforce. Some of these men were proponents of natural explanations for observed phenomena, others were firmly in the theological camp, and some were torn between the two. *Before Darwin* begins with a section placing the conflict between religion and science in the context of the paradigm of Darwin's time, namely natural theology a la William Paley. At the time of writing *On the Origin of Species*, Darwin had lost his faith as a Christian and thought himself a deist; he died an agnostic and, while we cannot be sure exactly when Darwin first faced the challenges presented to conventional faith by contemporary science, we know that he was well aware of the issues in 1831, because we know what books he read (Thomas 2005, 4).

Darwin, as a student at Cambridge, would have been required to read Paley's *Natural Theology* (1803), and we're informed in the first chapter that Darwin enthusiastically endorsed the ideas presented therein. Darwin's transition from Paley's paradigm occurred slowly, but surely, over the years. To be sure, he was exposed to the idea of mutable species through the writings of his grandfather, Erasmus Darwin, and he was influenced by contemporary thinkers of the era, including Charles Lyell, Thomas Malthus, and a host of others who posed questions about species and diversity of life a century or more before Darwin's first inquiries into the nature of species. Thomas places Darwin's contributions in the context of prior ideas, especially those trying to reconcile fact with Christian dogma. In addition, Thomas discusses the conflicts between science and religion as they relate to the development of evolution theory and the problems of moving away from theological explanations for nature's diversity of pattern and process.

> The dilemma created by the new scientific philosophies was therefore the potential relegation of God from all-powerful to first power only, and the acknowledgement that other scientific (Second) causes drove the world day by day, year by year. The consequent and even greater dilemma was that, once one admitted Second Causes, it was only a simple extrapolation to *all* the processes of life being definable in terms of such causes. In the process, the need for a First Cause would simply fade away. There would be no room—no need—for God at all. (41)

A main theme is that natural explanations inevitably lead to atheism, one of the accusations often made in the contemporary criticism of evolution theory by creationists. Thomas weaves a narrative that builds on the successive steps required to move from theological to scientific explanations for natural phenomena, and then poses the real dilemma of reconciling observations with explanations.

> By the mid-nineteenth century, there were really only three ways in which natural theologians could deal with the growing evidence that the earth was very old, that it was recycling inexorably beneath their feet, and that life on earth had constantly changed over millions of years. They could ignore it, they could accommodate it to the biblical accounts of history by more or less denying the literal truth of Genesis, or they could explain it all away. (223)

On the Origin of Species was a turning point for removing religion from the equation to explain biological diversity. As Thomas also shows, however, it has also been the focus of controversy, beginning with the famous encounter between Thomas Huxley and "Soapy" Samuel Wilberforce at the British Association for the Advancement of Science meeting in 1860 (269–279). In the years after 1859, the watershed date in evolution's respectability, adherents to natural theology increasingly came from more fundamentalist groups, such as the staunchly Calvinist palaeontologist Hugh Miller in Scotland, whose books reached a huge audience. The argument from design, in its elemental version of "irreducible complexity," is today principally favoured by various groups of anti-evolutionists and modern Creationists, offshoots of fundamentalist Protestantism in the USA (261–262).

The societal impact of Darwinism in America in the late 1800s through the twentieth century has been documented by Ronald Numbers (1998). After a lag phase of modest acceptance of Darwin's ideas, a body of work that became modern evolution theory started to build at the turn of the twentieth century with the discovery of Gregor Mendel's studies on inheritance. Adding the mathematical framework provided by Ronald Fisher and Sewell Wright and the collective studies of Theodosius Dobzhansky, J.B.S. Haldane, G. Ledyard Stebbins, George Gaylord Simpson, Bernhard Rensch, Julian Huxley, and Ernst Mayr generated the neo-Darwinian synthesis. Contributions to the theory from the 1940s onward include the discovery of DNA as the currency of inheritance, the structure of DNA, the genetic code, restriction enzymes and the birth of genetic engineering, plate tectonics, advances in systematics methods and analysis, the polymerase chain reaction, and developments in biotechnology. All these advances in modern science spawned growing fields of studies, a key feature of the scientific term "theory" in the robust sense of the word. Science is a heuristic process; queries and answers should lead to additional questions and studies. Unfortunately, the word "theory" is often misused and misconstrued in the criticism of evolution theory. "It's only a theory" is the common degradation one hears in critiques of evolution. This equates "theory" with "wild guess," rather than a body of knowledge that is so robust that it is accepted as the best possible explanation of a phenomenon.

Michael Ruse addresses the misperceptions of evolution theory in *Darwinism and Its Discontents* (2006). Ruse is a philosopher and approaches the defense of evolution theory from this perspective. He begins with an overview of Darwin's contributions to the scientific revolution that shaped modern biology.

> At the risk of damning myself in the eyes both of sound scholarship and of God, let me be categorical. All of the critics of Darwinism are deeply mistaken. Charles Darwin was a good scientist, the biological revolution of the nineteenth century led to genuine understanding, and today's version of the theory is good quality science… Finally, although, like all good science, Darwinism challenges religion, Christianity specifically, it can and should provide a positive and creative stimulus for religious people to think about their faith and move forward in a richer and deeper way. (4)

As in Thomson, Ruse's theme revolves around the conflict between science and religion as it relates to evolution. Evolution theory is perceived as a threat to Christian ideals on creation and biblical dogma, especially where a literal interpretation is a key component to a denomination's beliefs. Conflicts arise with the interpretation of origins—origin of life, origin of species, and origin of humans. Ruse sets the stage in chapter two ("The Fact of Evolution") with a summary of Darwin's arguments in *On the Origin of Species*. He builds on that foundation by bringing in examples from modern biology ranging from classical genetics studies to what molecular studies can tell us about evolution. However, the key question on origins is about the origin of life.

> As we set out to look at the origin of life, at once we encounter a paradox. No self-respecting evolution textbook today avoids the topic, but the truth is that evolutionists are really not at all qualified to talk on the subject—one needs masses of biochemistry and like knowledge really to get involved, far more than that possessed by the average student of life's history. (53)

Origin of life, of course, is not a simple topic, and Ruse begins his discussion by asking the key question, "What is this life that we want to explain?" (53). After a history of science overview from Aristotle to ideas about hypotheses of an RNA world, the discussion turns to the philosophical aspects of the origin of life. Ruse states that the problem is neither insoluble nor a "threat": "It is rather inspiring and exciting. There are Nobel prizes to be won" (71). A book such as this isn't able to address origin of life issues, but Ruse uses the next six chapters to defend evolution theory against criticisms by bringing in examples from morphology through molecules, beginning with the fossil record (chapter four) and a discussion of the historical record of evolution preserved therein. He addresses the patterns observed using examples and then expands on the usual discussion of fossil evidence to include cladistics and molecular methods. Ruse then moves from observed patterns of evolution to discuss "The Cause of Evolution" in chapter five. He begins with an overview of basic genetics and the role genes play in selection as compared to the unit of selection, the organism. Ruse discusses the definition of natural selection in a tongue-in-cheek fashion using biologists and philosophers as examples of organisms that may have different reproductive success rates.

> At least part of the problem (if that is what it is) seems to stem from the fact that so simple a mechanism supposedly does so much. People cannot believe that mere differential reproduction can create the incredibly complex living world that we have around us. It is just not plausible that the hand and the eye—let alone the brain—are the end result of something like selection. At the very least, the feeling is, the cause should be as complex as the result, and that means that whatever it was that made the brain should be on a par with advanced quantum mechanics, totally opaque to those without a doctoral degree in the subject, and preferably rather more. So the sense is that selection must be simply redescribing what is going on, rather than providing genuine empirical insight. (110–111)

Ruse then describes numerous examples of selection, starting with convergences among marine animals with regard to body shape and appendages and then examples from artificial selection. This latter strategy was used to good effect by Darwin in *Origin of Species* when he described examples from the domestication of animals, but Ruse adds new information from genetic research studies on the common fruit fly to illustrate how much farther our knowledge base has grown since Darwin's time. A discussion on speciation and adaptation and the role selection plays in these processes comes back to the fossil record with an example of reverse engineering a fossil to determine the function of a structure found in a skeleton. The reader, up to this point, of Ruse's book would assume that the entire volume is a celebration of natural selection as the primary driving force in evolutionary change.

> It has always been recognized by evolutionists—certainly from the

> *Origin of Species* on—that however common or ubiquitous adaptation may be, it is only part of the story. The living world is not—cannot be—totally and completely adaptive. In fact, this is one of the strongest points against Paley's God. There is far too much wrong with the world—too many instances of malfunction—to think that a designer has been directly involved with making organisms. (135)

Evolution theory has gone through several periods of growth as our body of knowledge expands with each scientific advance. Some of the growth phases have been contentious as scientists argue amongst themselves as to mechanisms, pattern and process, and analytical methodology. The role of natural selection in evolution has also been a focal point within the field of biology, and the tempo and mode of evolution arguments are discussed in chapter six, "Limitations and Restrictions." It is interesting that critics of evolution theory spend so much time focusing on the arguments biologists make against this or that aspect of evolutionary mechanism (e.g., selection, genetic drift, mutation), but miss the whole picture that although the minute details may differ among phyla, the overall pattern of evolutionary change remains the same. In addition, evolution theory is blamed for many societal ills that have nothing to do with biology.

> In recent years, Darwinism has become the whipping boy of every disgruntled member of society—the root cause of problems from fascism to sexism, from anti-Semitism to capitalism, from cross dressing (I kid you not) to the breakdown of the traditional family. It is argued that Darwinism is no true scientific theory by a mere reflection of the more offensive elements of the society within which it finds itself, at best a social construction—an epiphenomenon of the culture within which it resides—and at worst a secular-religious rival to Christianity—a world picture complete with moral directives and eschatology. (194)

Perhaps it was the setting in which *On the Origin of Species* was published that set up many of the conflicts we've seen in the past 150 years. Darwin's era was during the industrial revolution and the rise of capitalism. Whereas the controversies of scientific advances vs. natural theology were the main themes prior to Darwin (as Thomson shows), after publication of *On the Origin of Species*, the differences among economic classes could be put into the context of the phrase "survival of the fittest," which was coined by Herbert Spencer. Modern critics of evolution focus on aspects of Social Darwinism, accusations of atheism, secular humanism, and their perceived dangers to human society (Ruse 2006, 194–196). However, it's important to remember that evolution theory isn't about any of these topics. Under the umbrella of evolution through natural selection, Darwin brought in just about every area of biology—instinct, paleontology, biogeographical distribution, anatomy, embryology, classification—and showed how they are illuminated by the mechanism and in turn support the mechanism (208).

Since Darwin's time, evolution theory has expanded to include genetics, mathematics, molecular biology, genomics, and bioinformatics. The number of scientific journals dedicated to evolutionary pattern and process studies have increased each decade since the early 1900s. The contributions of evolution theory in the applied sciences with direct benefit to humans (e.g., medicine, agriculture, biotechnology) have also increased each decade since publication of *On the Origin of Species*. Thus, it is puzzling as to why evolution theory is continually under attack from conservative religionists.

> One is tempted to let Christians—believers of any kind—fend for themselves. If they want to accept Darwinism, then it is there to be accepted. If they want to reject it on religious grounds, then that is their option. But many are genuinely puzzled and concerned, and would like an answer that is not just based on the prejudice and ignorance of one side or the other. (276)

Is it possible to accommodate science and religion given the deep divide that has kept the attack on evolution theory in the news headlines? It appears as if Paley's argument from design is still the preferred option for those that cannot accept a scientific explanation for origins. Ruse summarizes the modern "argument from design" here:

> Organisms show design-like features: the hand, the eye, the leaf, the fin, the funny plates on the back of stegosaurus. These "adaptations" function, they work, for the benefit of their possessors. They seem far too complex to have come about by chance. In the real world, things break down and go wrong, rather than build up into working units. So there must be an explanation. And the only reasonable explanation is that there is a designer, an intelligence behind adaptations. (281)

One wonders if the proponents of this view prefer it because they perceive science as being too hard to understand. Given the complexity of modern research involving biochemistry and molecular biology together with mathematics and physics, it's no wonder that many people prefer an easier explanation for the diversity of life and how it came to be. Marc W. Kirschner and John C. Gerhart tackle this subject from a scientific perspective in *The Plausibility of Life* (2005). This book begins with Paley's argument for design based on the complexity of a pocket watch, a common tactic for modern day creationists.

> Paley compared the complexity of the watch, which he could understand, with the complexity of life, which in 1802 he could not, as a measure of their creators. However, such comparisons look different today. Where he would have seen an earthworm and a skylark each as a unique and complex design, we now see underlying similarities; they have the same system of heredity, the same genetic code, the same cellular makeup, the same subcellular components, largely the same metabolism, and many of the same processes of embryonic development. (2)

Kirschner and Gerhart present a new explanation for the diversity of life by expanding evolution theory to include "facilitated variation," which deals with evolutionary development and the timing and location of gene expression in organisms. Thus, the problem of novelty's origin in evolution becomes, How could the eye be created in the first place, or the brain, or wing, or lungs, or limbs? Could they have been plausibly assembled, small piece by small piece, each presupposing a selective advantage? It is this feature of Darwin's theory, the uncertain accounting for novelty, that creationists seize on; meanwhile, evolutionary biologists assert that variation must be sufficient, though they lack a general explanation for the origin of complex novel structures. Answers to these questions affect the plausibility of life's arising by way of evolution (4).

Contemporary arguments for design as presented in "intelligent design theory" a la "irreducible complexity" (Behe 1996) use the vocabulary of molecular biology, but ignore or reject hypotheses from that field of research to explain the origin of biological structures. Kirschner and Gerhart begin with an overview of evolution theory from Darwin through the neo-Darwinian synthesis and then bring the reader up-to-date on recent developments in embryology and evolutionary development (evo-devo). The cardinal issue in evolution is the origin of complex and heritable variation from a limited reservoir of components. Although selection has preoccupied evolutionary biologists, the study of the origin of variation and novelty has idled. Is the organism's capacity to generate heritable variation great enough to supply the succession of variants needed for natural selection to bring forth a circadian clock, or—more challenging—a human being from a single-celled ancestor, all within the time span of the earth? Heritable variation requires mutational change of the genome, but that is only the start of the story.

> What else is required to get an adequate frequency of selectable variants? Mutation only changes what already exists. It does not create new anatomy, physiology, and behavior from nothing, so we need to know how readily one structure can be transmuted into another, particularly when we consider structures of intricate design and interdependent activities. With an understanding of how random genetic change is converted into useful innovation, a theory of novelty can be devised. Darwin's general theory of evolution can then be established at the most fundamental level. (Kirschner and Gerhart 2005, 8–9)

The major point made in the early chapters of *The Plausibility of Life* is that we are only now beginning to understand the big picture of how life on earth diversified from unicellular organisms to the complex multicellular ones represented by animals, plants, and fungi. The emphasis, until recently, has been on attempts to explain the origin of lineages and morphological diversification (i.e., the ill-defined "macroevolution" of the creationist lexicon). A big surprise of modern biology has been conservation—that even distantly related organisms use similar processes for cellular function, development, and metabolism. When a process is conserved, most of its protein components are conserved. Details of metabolism are the same in bacteria and humans; basic cell organization and function are similar between yeast and humans; and developmental strategies in fruit flies are strikingly similar to those in humans. The conservation of key processes in diverse organisms today implies, as we shall see, that we can deduce the basic physiological and developmental processes of organisms in the past (34).

"Facilitated phenotypic variation" expands on classical evolution theory by including the development of organisms in the equation. In addition to the requirement of genetic variation and natural selection, Kirschner and Gerhart argue that novelty in organisms arise "by the use of conserved processes in new combinations, at different times, and in different places and amounts rather than by the invention of new processes" (35).

> Novelty usually comes about by the deployment of existing cell behaviors in new combinations and to new extents, rather than in their drastic modification or the invention of completely new ones. True novelty in the invention of cellular processes is rare. Once such novelty occurs, it may be carried through stably in many lineages. Hence, evolution is divided into epochs of invention of cellular behaviors, interspersed with long periods without invention. (39)

This statement is an interesting twist on the idea of punctuated equilibrium (Eldredge and Gould 1972) where species are stable and relatively unchanged in the fossil record for long periods of time followed by a rapid change and burst of speciation and lineage diversification. Kirschner and Gerhart explain that although all organisms share a large percentage of DNA sequences and genes, morphological and physiological differences arise when cellular changes occurring during development are fixed in lineages. Rather than go through the fossil record to explain evolutionary divergence, the authors discuss "the history of the world according to genes" (45–70). "Core processes have been introduced at rare intervals during evolution (the punctuated part), then are largely unchanged until the present (an equilibrium or stasis)" (45). Diversification is placed in the context of adaptive cell behaviors rather than morphological changes. This historical account of diversification is biased toward the animal kingdom and involves: 1) novel chemical reactions, 2) cell organization and regulation, 3) evolution of multicellularity, 4) origin of body plans, 5) and origin of appendages. Kirschner and Gerhart drive home the point that cellular processes, DNA sequences, gene content, and physiologies are highly conserved from bacteria to animals and yet diversification happens through cellular processes common to all lineages.

> If we follow the path from the bacterium-like ancestor toward humans, we find repeated episodes of great innovation. New genes and proteins arose in each episode. Afterward, the components and processes settled into prolonged conservation. The existence of "deep conservation" is a surprise. To some biologists it is a contradiction of their expectations about the organism's capacity to generate random phenotypic variation from random mutation. To some, it borders on paradox when held against the rampant diversification of anatomy and physiology in the evolutionary history of animals. (67–68)

In chapter three ("Physiological Adaptability and Evolution"), the authors discuss this paradox in terms of previous research on adaptation and phenotypic plasticity (changes in morphology or physiology in response to environmental conditions). Such physical changes in response to environmental stimuli do not contribute to evolutionary change unless the changes are heritable. The authors introduce this concept by giving examples of developmental plasticity where organisms have different morphological outcomes depending on environmental cues. Examples include animals that have very different larval morphologies compared to adult morphologies that go through a series of metamorphoses (insects, ascidians, amphibians), which represent sequential alternative phenotypes. When timing of development is affected, speciation may occur where one species resembles an alternate morphological stage of another species. Alternate adult phenotypes may also occur as a result of environmental cues. For example, the different castes of social insects and alternate sex determination of some reptiles come from temperature differences in egg incubation. Kirschner and Gerhart finish the chapter with a discussion of the evolution of hemoglobins and their role in adaptation of animals to their environments.

> It may seem counterintuitive that mechanisms such as oxygen regulation, which function to maintain the existing phenotype by buffering the effects of variation in the environment, should simultaneously serve as vehicles for creating variation in evolution. This pseudoparadox of stability versus change stands juxtaposed to another of conservation and diversity. How do highly conserved processes like oxygen transport in hemoglobin or determination of sex in mammals lower the barrier for generation of diversity? (107)

In chapter four ("Weak Regulatory Linkage"), Kirschner and Gerhart begin their explanation of facilitated phenotypic variation. "Let us now delve directly into the conserved core processes that are responsible for generating most of the anatomy, physiology, and behavior of the organism" (109). Variation arises through the multiple use of conserved core processes. New combinations of the core processes also occur and "individual core processes are constructed so that new linkages can easily be forged and broken" (110). Timing and regulation of gene expression is a key concept in terms of the evolution of variation.

> Understanding embryonic development is central for explaining phenotypic novelty in animals. It is in the embryo that much of the phenotype is established with all its anatomical and physiological complexity… The implications for evolution are powerful, for if complex development is elicited by simple signals, then changes in complex development may be achieved by changing the amount or the location of these simple signals, rather than by changing a highly integrated and complex process. (111–112)

Kirschner and Gerhart then explain the details of gene expression and regulation in bacteria, eukaryotes and multicellular organisms. This is a precursor to a later discussion on gene expression in embryos and its role in evolution of novel traits. First, however, they come back to one of the criticisms of evolution theory, the difficulty of explaining mechanisms for macroevolution.

> Much of the skepticism over the years about the capacity of random mutation or genetic reassortment to generate phenotypic change has arisen from the assumption that genetic changes must create very specific, multiple, complex phenotypic changes. Our view is that specificity and complexity are already built into the conserved processes, as is the propensity for regulatory coupling. It is not necessary for genetic change to create those characteristics, though they are still needed for heritable change. (142)

Chapter five ("Exploratory Behavior") describes a biological phenomenon common to the development of a cell's cytoskeleton to the organization of the vascular system of mammals and to the behavioral ecology of foraging social insects. Exploratory behavior is described as a critical process in the evolution of novelty, especially with regard to anatomical changes that are perceived as difficult to explain if they originated by a slow stepwise accumulation of mutations (e.g., the eye or different limb anatomies of vertebrates). At each stage an exploratory process could, even without genetic modification, adapt to changes in anatomy. Such highly adaptive processes facilitate the production of significant viable and novel variation on which selection can act (147).

The general effect of exploratory behavior at a cellular level appears to be a buffering one that allows for changes in anatomy without causing lethality. There is a lot of tolerance for variation in getting from point A to point B in the development of an organism as long as the critical functions of metabolic pathways, organs, and structures are intact. Exploratory mechanisms have a dual role in facilitating evolutionary change—which on the surface seems paradoxical. By being globally responsive and adaptive they blunt the effects of mutation and reduce its effect and lethality. In this way they make possible the persistence of novel changes by reducing collateral damage, thus increasing the amount of heritable variation (176).

The first five chapters of Kirschner and Gerhart set the stage for the big explanation of the importance of evolutionary development studies for expanding on classical evolution theory to include a new paradigm of facilitated variation. Chapter six ("Invisible Anatomy") specifically deals with how the conserved core processes of cellular biology relate to embryology and the anatomical differences among animals. The invisible anatomy referred to throughout the chapter is the anatomy of the embryo in terms of specific gene expression patterns and zones of activity.

> When a trait of anatomy changes in evolution, it is really the development of that trait that has changed. Anatomy itself is not inherited, but rather the means to generate the anatomy. The real target of heritable genetic change is the development by which the trait is produced… Therefore, in seeking to explain anatomical change in evolution, biologists have come to understand that what they must explain is the changes in developmental processes. (178)

This, then, is the heart of the subject—how evolutionary development studies contribute to a better understanding of evolutionary pattern and process. An explanation of modern embryology in terms of the "compartment plan" of a young embryo is given:

> Once organized in an advanced multicellular stage, but well before the cells have differentiated into their final cell types, the compartment plan gives each cell its address, its identity, and its location relative to the cells in the rest of the body… We call the compartment plan an "invisible anatomy" because the compartments are only identifiable if one can establish which genes are expressed there. At these early stages, compartments cannot be distinguished by anatomical features. The actual differentiation of the organism will depend not only on the compartments but also on the interactions of cells of one compartment with signals from other compartments. The compartment map is an extensible map: individual compartments can expand and shrink independently while overall neighbor relations are retained. This flexibility occurs not only in development, when certain regions grow relative to others, but also in evolution where there is disproportionate growth—for example the neck of the giraffe relative to the neck of the whale. (183)

The discovery of the compartment plan and the importance of this discovery for understanding evolution make up the bulk of this chapter. The discussion emphasizes the importance of genes conserved across phyla (e.g., *Hox*, transcription factors, selector genes) and their role in embryological development and anatomy. By comparing the invisible anatomy of animals from invertebrates to vertebrates it is possible to understand the differentiation of tissues into structures and organs. By small changes in timing, location, and signaling of gene expression during the early stages of embryo development, the mechanisms for all animal body plans and anatomy are explained.

> A significant implication of the comparison is that compartments are much more stable across evolutionary history than are the anatomical structures developed upon them. Compartments, it seems, are unconstrained in the anatomical structures and differentiated cell types they can support. …
>
> The molecular information is so precise and detailed that the interpolations are nearly unassailable. Between insects and vertebrates the sequence of Hox genes is conserved, the order of Hox genes on the chromosome is conserved, and correspondence of the chromosome order to the anatomical order is conserved. These similarities cannot be accidental or convergent from separate starting points. In combination with an increasingly detailed fossil record that shows maintenance

> of the body plans of almost all phyla for the last 535 million years, the commonality of the basic anterior-posterior patterning is proven far beyond any demonstration possible from fossils and comparative anatomy alone. (197–198)

The authors pull all the information from chapters one to six together in chapter seven to state their theory of facilitated variation. The outline takes five pages of their book, but it can be summarized in their point number six:

> Most evolutionary change in the metazoa since the Cambrian has come not from changes of the core processes themselves or from new processes, but from regulatory changes affecting the deployment of the core processes. These regulatory changes alter the time, place, circumstance and amount of gene expression, RNA availability, or protein synthesis of components of the core processes, or alter the activity and interaction of proteins of the processes by modifying them or by changing their stability. Because of these regulatory changes, the core processes are used in new combinations and amounts at new times and places. Also because of the regulatory changes, different parts of the adaptive ranges of performance of the processes are used in new circumstances. (221–222)

The final chapter of *The Plausibility of Life* focuses on the topic of evolution and its impact on society. First there is a discussion on how their theory of facilitated variation dovetails with existing evolution theory, namely by expanding on the framework of selection, genetics, and the neo-Darwinian synthesis to include a mechanism that explains phenotypic changes in organisms. Kirschner and Gerhart admit that the origins of the core processes remain unresolved currently.

> The theory of facilitated variation opens up a new set of questions about the origins of the conserved core processes that, as we have argued, facilitate the generation of all kinds of anatomical, physiological, and behavioral diversity. There is really no alternative but to think that new core processes, such as those that first arose in eukaryotic cells, were cobbled together from the existing process in prokaryotic cells. The transformations from prokaryotes to eukaryotes or from single-celled to multicellular organisms are profound, and evidence is spare. However, as methods for identifying weakly related DNA sequences have improved, and as more organisms have been sequenced, we can glean hints about these major transitions.

> Core processes may have emerged together as a suite, for we know of no organism today that lacks any part of the suite. (253)

Kirschner and Gerhart express confidence that remaining and new questions will be resolved as research progresses. Scientists, in general, agree that the heuristic process of research is an important hallmark of what makes science a robust endeavor and differentiates it from alternative approaches such as those believed by creationists. Though modern scientists may have questioned the completeness of the theory of evolution, few believed that the fundamental principles of variation and selection would not in the end explain the diversity of life. Certain groups, however, particularly active in the United States, have exaggerated and fabricated weaknesses in evolution theory in order to discredit it. From its beginning, the theory of evolution has caused problems for some traditional religious groups. By depicting human beings as derived from simpler animals, evolutionary theory not only undermined the biblical account of creation, but also seemed to debase human beings by suggesting that they were not of divine origin (264).

And so, we are back to my opening paragraph for this review. It is perfectly clear that evolution theory will continue to be controversial in the United States for many years to come, despite the scientific advances that reinforce the robustness of evolutionary biology. Thomson describes the history of the conflict between science and religion as it relates to origins and evolution theory, Ruse discusses the societal impact and disagreements among segments of society with regard to evolution theory, and Kirschner and Gerhart expand on evolution theory to add some explanation for the diversification of animal lineages. One wonders what scientific research, if any, would be sufficient to convince the masses that evolution has occurred.

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