Evo Edu Outreach (2012) 5:585–588
DOI 10.1007/s12052-012-0454-6

VIEWPOINT

Evolution and the Cumulative Nature of Science

David Zeigler

Published online: 18 October 2012

Abstract One of the characteristics of science is its cumulative nature. As more discoveries are made and more is learned, we progressively come to a more and more complete understanding of the physical universe. Evolutionary biology serves as an excellent example of this progressive trend in knowledge, since we now understand significantly more about the mechanisms and details of the evolutionary process than we did in decades past. It is important to comprehend these progressive changes and communicate them effectively to students of evolutionary biology.

Keywords Nature of science · Cumulative nature of science · Evolutionary biology

> To me, the change from the concept of the gene as a Mendelian factor to the gene as a piece of a chromosome, and thence to the gene as a molecule of DNA, does look like progress in knowing what the world is like. (John Maynard Smith)

> Scientists believe—and have not encountered any reason to believe otherwise—that there is only one physical reality, independent of our only incomplete perception and comprehension of it at any time. The progress of science inexorably brings us closer and closer to that reality. (S. Jonathan Singer)

It is unclear to what extent postmodernism has influenced education, though undoubtedly it has had some effect. Some of the younger faculty I have encountered certainly do seem to partake of postmodernism philosophy—maintaining that no one discipline has a monopoly on truth, and that all viewpoints are worthy of consideration and discussion (lots of discussion!). In particular, a couple of non-science colleagues I recall were definitely angered by E.O. Wilson's book *Consilience* (1999), in which Wilson argued that science could and should assist other disciplines in conforming to what is scientifically known about our world and our species.

Scientists are urged and trained to be open-minded, but this open-mindedness is to always be tempered with a healthy dose of critical skepticism. With our accepted baseline of objective evidence that can usually be confirmed empirically, scientists will not and should not long entertain ideas or statements that lack a strong objective base: real data collected in valid scientific observations, studies, and experiments. It is because of this working philosophy that science can make progress toward increasing our understanding of the world—progress often referred to as "the cumulative nature of science." Most scientists who have read much on the nature of science should be familiar with this wording.

My evolution course is the one course in which I devote considerable time to reviewing the basic nature of science including: what science is, what science is not, the methods of science, the values of science, the implications of the scientific view, etc. One of the points I include is that science is generally cumulative—meaning that as more data is collected and more discoveries are made, science builds toward a more complete and accurate understanding of the physical universe—the goal of science in general that Dennis Flanagan referred to when he wrote: "all modern scientists are traveling toward the same Canterbury: a unified understanding of the universe, including ourselves." (Flanagan 1989)

Evolution and its associated disciplines provide excellent examples of this cumulative process. As the leading quote by John Maynard Smith implies, our increasingly more detailed understanding of genes and inheritance serves as a clear and obvious example of this cumulative nature, with each new discovery increasing our understanding of genes, of inheritance, of genomes, of gene regulation, of the nature, variety, and importance of mutations, etc. This past decade

D. Zeigler (✉)
University of NC at Pembroke,
Pembroke, NC, USA
e-mail: david.zeigler@uncp.edu

or two has encompassed an especially significant growth period in our understanding of all aspects and all levels of DNA-related phenomena, and it would be indeed difficult for any postmodernist to contradict this additive or cumulative growth in our knowledge, and of course this expanding arena of knowledge has made major contributions to our understanding of the evolution.

Likewise, the fossil record has of late been enlarging at a breathtaking pace, with many significant fossil finds having been made in recent decades. Whale evolution from land animals was very poorly known when I was an undergraduate student. Today, we have a dozen or so recently discovered fossil genera that well illustrate this amazing transition of terrestrial vertebrates back to a marine lifestyle—a series that clearly shows the gradual loss of the hind limbs, the relocation of the nostrils to the top of the head—resulting in the "blowhole," the reversal of sacral vertebrae fusion to allow the effective dorso-ventral swimming mode, and the increase in relative head size which is especially obvious in the modern baleen whales. Likewise, the fossil record of bird evolution from dinosaurs is now filled in well enough to be beyond doubt thanks to several exceptional fossil finds from China that illustrate the morphological changes that were underway, and even the presence of feathers in several dinosaurs that clearly were not birds. The fossil record in general seems to be one of the clearest and most easily understood examples of the cumulative nature of science. Basically, every newly discovered fossil is a newly located piece of a large puzzle. Each significant fossil find simply increases our knowledge of the history of life.

The ongoing descriptive work of discovering new extant species obviously adds cumulatively to our knowledge of life on Earth, but also to our understanding of evolutionary history, especially when such discoveries constitute new orders, classes, or phyla—and especially if such groups turn out to be "primitive" or ancestral like the 1981 discovery of the Crustacean Class Remepedia—elongated aquatic crustaceans that illustrate several ancestral morphological traits (Brusca and Brusca 2003). The discovery of species believed long extinct like the rediscovery of living coelacanths likewise allows for major corrections in our knowledge of evolution and the history of life.

Evolutionary biology is in and of itself a strong example of the cumulative nature of science, with our knowledge of many aspects of the process having increased significantly and continually over the past century. Back when I was a new graduate student in biology, my courses in evolution touched on only three mechanisms of evolutionary change, with most of the emphasis going of course to natural selection. Genetic drift accounted for only a couple of lectures, and the new (at that time) idea of neutral evolution was given only passing mention since it was still in its infancy and not supported by many known examples.

Since that time, evolutionary theory has most definitely evolved. The recognized significance of genetic drift and neutral evolution has grown significantly, and many additional mechanisms and processes have recently been added to our understanding. The field has grown more complete and at the same time more complex. Textbooks often fail to bring up to date their coverage of evolution by not incorporating the many more recently recognized and understood factors which have played important roles in evolution. Organisms have evolved due to many influences and mechanisms, and not all have shared exactly the same set of contributing factors. Bear with me in this analogy: The last professional meeting I attended took place in the Regan Center in Washington D.C., and around 900 people attended that meeting. In the 24 hours prior to that meeting, the 900 attendees engaged in several forms of transportation along several assorted routes to arrive at the Regan Center. My 24 pre-meeting hours involved travel by private automobile, Amtrak, Metro, escalators, elevators, and of course—walking. Others, of the 900 attendants, would have had a different list of transportation methods along different routes. Many took planes rather than Amtrak. Some took taxis rather than the Metro. Some who live in D.C. may have relied only on private auto and walking. Almost all involved some walking and at least one other transportation mode.

In a somewhat analogous way, all life forms alive today "arrived" in the present through various evolutionary pathways involving numerous evolutionary mechanisms and influences over a nearly 4,000,000,000-year history—but not all were affected equally by the several possible mechanisms and influences. To enumerate some of these:

- Natural Selection: Certainly all lines of descent have been shaped significantly by this central factor, the one that still best explains the *adaptedness* of each species. Some of the following bullets are examples of factors that in one way or another fall under the wide purview of natural selection, yet they are worth separate consideration in themselves.
- Sexual Selection: Some dioecious species have been significantly shaped by this subcategory of natural selection—think elephant seals, peacocks, and bowerbirds. Of course species that are monoecious like earthworms, or asexual organisms like amoebas and prokaryotes have not been much affected by this potentially powerful evolutionary force.
- Disease and Parasitism: William Hamilton famously argued the case that these ever-present selective forces best explain the origin and maintenance of sex in the many sexual organisms found in nature. They also explain why immune systems evolved and why these immune systems are so diverse (interferon for viruses, antibodies and fever for bacteria, eosinophils for worm parasites, etc.). Disease

factors have certainly had a large role in shaping species and ecosystems, as well as constraining the "perfection" and efficiency of most species—and of course, a great many (the majority) of today's species *are* parasites.

- Lateral Gene Transfer: This process undoubtedly has contributed greatly to the evolution of prokaryotes, but we are now finding more and more gene examples from eukaryotes which strongly suggest the involvement of this process as well. And of course, all eukaryotes have experienced the ancestral lateral gene transfer of some mitochondria DNA into the nuclear DNA. In those lines with chloroplasts, likewise the same kind of process transferred some chloroplast DNA into the nuclear DNA. These were indeed significant contributions to evolution and to biodiversity.
- Genetic Drift: Again, this one is covered along with natural selection in most textbooks, but it can be a more difficult one for students to grasp and appreciate. Some species have undoubtedly been more affected by genetic drift than others. Native island populations of fruit flies, lizards, plants, etc. survived a founder effect involving at least some genetic drift through a "sampling" bottleneck. Continental and many marine species have typically been touched by genetic drift over longer spans of time due to random drift over the generations, with more effect likely in smaller populations/species. Large but temporary reductions in population size due to disease, weather, or other factors also create bottleneck effects. With a few good examples, exercises, and analogies, this concept can be taught effectively.
- Symbiosis: While essentially all species are involved in some form of symbiosis, many groups have been established and transformed by the establishment of intimate symbioses. *Free-living* bacteria have arguably been less affected by this factor than say the hermatypic corals (those housing commensal photosynthetic zooxanthellae). Being animals, corals are also members of the eukaryote clade which was "born" through endosymbiosis whereby prokaryotes were incorporated into a larger cell, and these prokaryotes evolved to become mitochondria in this line of cells. Photosynthetic eukaryotes later originated when cyanobacteria incorporated mutualistically into an existing eukaryote line. Other photosynthetic lines like the brown algae resulted later from secondary endosymbiotic events that have been elucidated only recently through studies of ultrastructure and comparative genomics. Though most speciation events did not involve significant symbiosis factors, some significant evolutionary events most certainly did.
- Neutral Evolution: At least some degree of neutral evolution has occurred in every species. This is due in part to the redundancy of the genetic code and to the possibility of slightly different proteins being equally effective in carrying out their tasks. However, those species (mainly eukaryotes) having vast amounts of non-coding DNA in their genomes have undoubtedly experienced significantly more neutral evolution due to the vastly greater arena open to its occurrence. Genomic studies continue to increase our knowledge of and appreciation for the role of neutral evolution in genomic evolution.
- Polyploidy: Though we are still deciphering how pervasive this maximal chromosomal mutation event has been, the consensus is that polyploidy has affected eukaryotes significantly over their long history, with plants having been more significantly affected than animals.
- Transposible Elements: Since these fundamentally parasitic DNA units are far more common and numerous in eukaryotes than prokaryotes, they have had a far greater influence and effect in the genomic evolution of eukaryotes as compared to the prokaryotes. With more than 50 % of the human genome deriving from various forms of parasitic elements, this is surely an evolutionary force that should be mentioned in evolution courses if time allows.
- Opportunity: Opportunity is a factor only appreciated in the last few decades as a major player in the evolutionary process. It is unfortunately hard to comprehend or recognize the relative role of this factor on various groups and lines of descent. We do categorize some species as "opportunistic species" because they have what it takes to disperse, gain a foothold, perhaps outcompete other species, evolve quickly, etc. Only some chemosynthetic prokaryotes have the opportunity to live in fine cracks in rock layers half a mile below the ground. Only some bacteria can go through two or more generations in a morning dewdrop before it evaporates. Only small ectotherms can evolve and adapt to sustained full-time cave living. Among insects, only those already having attained wings could then adapt wing color for camouflage, or evolve the ability to create sounds with their wings for use in courtship, or any of the other secondary uses insect wings have adapted to. When opportunity exists, it does not exist for all—only for those possessing the properties to gain the respective foothold and adapt quickly to the unique opening that is available. The inclusion of opportunity and contingency into our understanding of the evolutionary process has effectively displaced the older and now rejected notions of innate progression and orthogenesis in evolution. Jettisoning these latter unscientific notions alone was a major step forward in the cumulative change in evolutionary thinking.

All these factors and more are now recognized as important components of a full understanding of the evolutionary process. It is obviously becoming harder and harder to keep up and to formulate a synthetic comprehension of evolution, both for ourselves and for our students, yet what a great example of the cumulative nature of science—that we now understand something of how all these various factors have contributed to the evolutionary process. One might do well in the face of this daunting challenge to recall the oft-used phrase: "When the going gets tough, the tough get going." Teachers have their work cut out for them in terms of any major field of science because the knowledge just keeps evolving and expanding. This has especially been the case in evolutionary biology. Keeping up is both the challenge and the excitement of being a devoted science teacher. And again, this progress in our understanding so clearly illustrates the cumulative nature of the scientific enterprise. Let's make sure our students see that progress. One method we older profs (at least this one) use involves telling our classes that much of what is now covered in class was unknown, wrongly interpreted, or not fully appreciated back when we were undergraduate biology students. This should illustrate for them that knowledge has grown recently and significantly through new discoveries and analyses.

Though we continue to hold that all scientific findings are provisional, most scientists understand that DNA *is* the genetic material, that the Earth *is* the third planet from our sun, that evolution *did* take place. There are few if any rational people who could understand the evidence behind these facts and still question that they do indeed qualify as facts. Scientists are of course open to hear new explanations and look at new data, but the completeness of many findings like the three above seems by all practical measures to be complete and final. Accepting that we can have this kind of confidence in scientific progress is another aspect of the cumulative nature of science. It says that we can learn, we can make real progress in understanding, and we can at least approach that goal of a complete understanding of the physical universe. We can therefore consider that our quest is worthwhile and not just another viewpoint of no more validity than creationism, astrology, numerology, and tens (hundreds?) of other philosophies that make their claims on truth. It would seem appropriate to end with this quote from Bertrand Russell: "I cannot admit any method of arriving at truth except that of science" (Russel 1997). When it comes to non-personal and non-subjective conclusions, I find myself in full agreement with Mr. Russell.

References

Brusca RC, Brusca GJ. Invertebrates. 2nd ed. Sunderland: Sinauer Associates, Inc.; 2003.

Flanagan D. Flanagan's Version. NY: Vintage Books; 1989.

Russell B. Religion and Science. Oxford: Oxford University Press; 1997.

Wilson EO. Consilience. NY: Vintage Books; 1999.