About 10 years ago, my university instituted a new core curriculum. Among the courses created for it was “Scientific Inquiry.” It’s the only required science course in the core, and, much to my chagrin, it is not required of science majors, the assumption being that these students learn all about how science is done in their major courses. I personally think this is a dicey assumption, having been a science major myself and having learned about how science is done only after I graduated and began to teach. However, I have no power, so this is the way things stand, and this is really my only serious problem with the course, which I have come to enjoy, love, savor (if only my students would).

As the title implies, this course emphasizes what scientists do rather than a particular body of knowledge. But scientists always work on a specific problem, so the course needs to focus on some disciplinary area, and that area varies depending on whether the course is taught by a biologist, chemist, physicist, or geologist. Each discipline focuses on a major theory, and for biologists this is obviously evolution. Needless to say, I had taught about evolution long before this course was developed, but not in as much detail, and not with the emphasis on how evolutionary biology can explicate the processes of science.

The development of the Scientific Inquiry course was a major undertaking and one that continues. Since it’s taught by faculty in several sciences, there were four departments involved in working out the syllabus. Each individual on the committee came in with a different view of what the course should look like, and none of us left with all of what we wanted. However, I think we were all satisfied with the product. After the course had been taught for a few years, the syllabus was reevaluated as part of a US Department of Education Title III grant to the university. While the original syllabus carefully outlined each of the themes that could be used – for example, evolution, atomic theory, plate tectonics – the revision was much more general and just stated that the chosen theme had to deal with a major scientific theory. This turned out to be a little too broad, so last year we overhauled the syllabus yet again, coming up with what we think is a workable compromise (http://stjohns.campusguides.com/data/files3/89769/SciInq%20syllabus09.pdf). But as with any course taught by many individuals and in an area as dynamic as science, this syllabus will never be finished. We just had a very spirited faculty meeting this spring about whether or not evolution should be the only biological theme used or whether genetics and infectious disease are also possible topics. Though I was at the meeting, I’m still not quite clear on the outcome.

At this point, I think that I do a decent job of covering the course’s objectives. If you would like to get some idea of what I do, you are more than welcome to visit the course Web site at http://stjohns.campusguides.com/honorsspublic. At the moment, I’m teaching an honors class, but the basic outline is the same no matter what group of students I have. I see the course as divided into three sections: the first on the history of evolutionary thought, the second on evidence for evolution, and the third on the implications of evolution in the world today. Along with fulfilling the basic objectives these three themes imply, the course also aims to improve students’ critical-thinking skills. In addition, I have two objectives of my own: to develop students’ visual literacy and to have students leave the course with a more positive attitude toward science. The former I’ve discussed often in ABT, the latter has been one of my goals since my early years of teaching, and I am not sure how well I’ve accomplished it. This is obviously a difficult thing to assess. However, I have hints, at least, that I am sometimes successful. For example, yesterday we were discussing orchids and when I asked questions, Angela repeatedly raised her hand. She knew the answers because her final project is on the vanilla orchid (Vanilla planifolia). Now Angela frequently raises her hand and frequently knows the answer, but she usually doesn’t have quite the passion she had yesterday. The vanilla orchid apparently has gotten hold of her, and I see this as a sign that someone who will never be a science major at least has some inkling of why another person might get excited about science and pursue such a major.

Dealing with Inquiry

Having introduced the course design, I want to get down to what it means to teach about scientific inquiry. Because the emphasis is on the processes of science, it is quite different from most introductory science courses. In other words, it’s not like what students had in high school – not a survey of a discipline – and they are not really prepared for this approach. I don’t have to tell you that many students equate learning science with learning facts, and when they aren’t given a list of definitions, they start to get uneasy. Some even think this emphasis on method means that this isn’t a “real” science course; because they don’t have to memorize a lot of unpronounceable terms, which they would hate, they aren’t getting their money’s worth. In part, the problem is that they aren’t sure what they’ll be tested on. The fact that a large part of their grade doesn’t come from tests, but from papers and a portfolio, makes them even more queasy.

On the other hand, I like this different emphasis. For years, I’ve wanted to spend more time on how science is done rather than just on the products of inquiry, because I think it’s important for people who are not going to spend their lives in science to appreciate what science is really about. In this article, I’m not going into everything that I cover in delving into the methods of science. I’ve decided instead to focus on one aspect that seems to me to be central to the way biology is done, and that’s comparison. This appears to be a very simple idea, one that’s easy to understand and easily taught. After all, it’s one of the exercises done on Sesame Street: ‘Which one of these things is not like the others?’ But as with many thought processes, what starts out simply can lead in many different and interesting directions.

I was first led to think more deeply about comparison when I read Ernst Mayr’s (1982) tome, The Growth of Biological Thought. In it, he argues that the philosophical analysis of science up to that time had been...
dominated by physics: “That there are important differences between biology and the physical sciences is often entirely ignored. Most physicists seem to take it for granted that physics is the paradigm of science and that once one understands physics, one can understand any other science, including biology” (p. 33). Mayr begs to differ; he sees the methods of biology, though equally legitimate, as different from those of physics. This is despite the fact that “when naturalists and other biologists as well as some philosophers stressed the importance of quality, uniqueness, and history in biology, their efforts were often ridiculed and simply brushed aside as ‘bad science’” (p. 36).

Mayr considers comparison one of the fundamental methods used to deal with this “quality, uniqueness, and history.” Sometimes experiments aren’t possible, but comparative methods are, and he traces their use in biology back to Aristotle. Mayr goes on to show that the dominant interest of those studying the living world in the 18th century was the description, comparison, and classification of species. However, he thinks that the comparative method wasn’t fully developed until the mid-18th century and that it came to its peak with the work of the French anatomist Georges Cuvier in the first half of the 19th century. Cuvier did not accept an evolutionary view as his colleague Jean-Baptiste Lamarck did; however, Cuvier championed the meticulous comparison of structures among species. From this work grew his conviction that many fossils were of species that no longer exist on earth, which convinced the biological community of the reality of extinction.

At another point, Mayr argues that comparative morphology did not consciously become evolutionary morphology until the 1950s, with the rise of the new evolutionary synthesis, of which Mayr was one of the chief architects. The synthesis brought morphology in contact with ecology and behavioral biology, leading to the asking of “why” questions. This querying obviously continues to this day, and that’s part of what I want to write about here, as well as about the comparative work that is at the heart of today’s genomics. The idea of comparison may begin with Sesame Street, but in biology it leads to some very complex work in informatics, and I think my students should at least be aware of how this very fundamental thought process plays out at the frontiers of biological science.

**History**

Over the years that I’ve been teaching Scientific Inquiry, as I’ve become more aware of how central comparison is to biological inquiry, I’ve tried to be more deliberate in developing this theme in my teaching. I begin early in the semester when we’re dealing with the history of the idea of evolution. For readings, I use the History of Evolutionary Thought section (http://evolution.berkeley.edu/evolibrary/article/0_0_0/history_01) of the Understanding Evolution Web site, which I find to be one of the best resources for teaching evolution. The history section begins with a timeline tracing the growth of four themes: earth’s history, life’s history, evolutionary mechanisms, and development and genetics. At the base of the timeline is comparative anatomy – a tradition, as I’ve already mentioned, that dates back to Aristotle.

Although comparative biology has waxed and waned, this thread has never been broken in the history of biology. Those who study the living world have always felt a need to organize its diversity, and organization requires comparison and demands decisions about what goes together and what doesn’t. The bases on which these decisions are made have changed. For example, Linnaeus’s classification system now seems quaint, and the basis of classification continues to be a point of contention. Read the latest taxonomic journal articles, and you’ll see that such arguments are still rife, one notable example being the controversy over the reorganization of *Drosophila* (Dalton, 2010). I think it’s important for students to appreciate that classifications are hardly written in stone. They are human constructs and therefore open to change. There are quite intense and sophisticated arguments about “natural kinds,” that is, about whether or not species, as such, even exist in nature (Webster & Goodwin, 1996) I don’t bring this level of analysis into the classroom, but I discuss how the criteria for classification change, the difference between artificial and natural classification systems, and why taxonomy is important in the first place: so that one biologist knows what organism another biologist is talking about.

Early in the semester, about the time that we’re investigating the History of Evolutionary Thought timeline, I give the students a list of about 25 organisms and ask them to place each on a line from the simplest to the most complex. I’m trying to get them to replicate the thinking behind the “Great Chain of Being” (Lovejoy, 1936). This was the idea, prominent during and after the Renaissance, that God had created a perfect chain of beings from the simplest to the most sublime (meaning angels). So the way to classify organisms was on the basis of where they fit in this chain, keeping in mind that since it was divinely made, it was perfect and therefore there were no missing links.

The Great Chain was an important concept in classification efforts for some time, and though the idea is no longer accepted, its remnants obviously remain in today’s vocabulary. I have students create a Great Chain (which I name only after they have completed theirs). It’s an impossible task, and there is usually a great variety of ordering among the students’ chains. Some put HIV and TB at the complex end of the spectrum because these microbes still aren’t well understood, so they must be very complicated. Others place them at the simple end because they are so small. Some students sort on the basis of lifestyle – putting fish, clams, and lobsters together because these creatures live in the sea, whereas flies and birds inhabit the air. Interestingly, there are old depictions of the Great Chain with just this division. As I ask students why they came up with the order they did, they become more aware that they in fact had criteria for their decisions, just as biologists have criteria for theirs.

**Darwin**

A few weeks later, after we’ve discussed Darwin’s theory, I give students the same list of organisms and ask them to create a tree of relationships. Here again, I get a variety of constructions, but they are a bit more sophisticated because students know more and have a better appreciation for the thought involved. They are more aware of the different ways to compare two organisms, on the basis of lifestyle vs. anatomy, internal vs. external structure, size vs. complexity, and so on. Also, by this time we’ve discussed another way in which comparison was used in the development of evolutionary theory, namely how Darwin (1859) begins *On the Origin of Species* with a comparison of artificial and natural selection.

Darwin is introducing a new concept to his reader: that species change over time as a result of differential reproductive success – some individuals produce more viable offspring than others. Here the environment is, in a sense, doing the selecting, as opposed to artificial selection, where a breeder picks the offspring with the desired traits and mates them to produce the next generation, when the same process is repeated. Darwin used this example because he was addressing his argument to educated laymen (and I am using “laymen” advisedly) who were landowners with a knowledge of animal husbandry and were also frequently amateur breeders of fancy pigeons, the example he used to begin his book.

By employing this strategy, Darwin was being an effective teacher: using what his audience already knew to explain a new concept to them. As Lakslov and Johnson (1980) illustrated years ago, thinking in metaphors, making comparisons, is an integral part of how the mind works. It’s impossible for humans not to do this, so it’s hardly surprising that the method comes up so frequently in biological work. It is so important in this science because there are just so many organisms to compare, and each has so many characteristics that can serve for comparison. Look at any new study on human evolution and you will find comparisons made among fossils – Ardipithecus ramidus is compared with Lucy (*Australopithecus afarensis*) (Gibbons, 2009), the recently discovered species...
Australopithecus sediba with Homo habilis (Balter, 2010). Microbiologists are learning about infectious disease genes by comparing Escherichia coli and Bacillus subtilis with Mycoplasma pneumoniae, which has a much smaller genome (Ochman & Raghavan, 2009). Conservation biologists use comparison of extinction rates among species to try to predict which species are most endangered (Fisher & Owens, 2004), though such analysis—like many comparisons—are tricky. The issue of which criteria are key arises: population size versus rate of reproduction, for example.

Genetics

The biological specialty in which comparative methods have bloomed most copiously in the second half of the 20th century is genetics: in the analyses of gene sequences and the obviously related RNA and protein sequences. Not only has an entirely new field of biology grown up around such comparative work, but an area of computer science as well. While you may be able to compare the characteristics of two duck or shrimp or even bacterial species with your eyes and a microscope as tools, you can’t even get past the simplest sequence analyses without a computer. The human mind simply can’t deal with the amount of data and the number of comparisons involved, to say nothing of the computerization of the sequencing process itself. If you go to the National Center for Biotechnology Information Web site (http://www.ncbi.nlm.nih.gov/), you’ll get an appreciation for how much sequence information is available and for the many ways it can be analyzed.

I have been looking back over materials I wrote about evolution over 10 years ago, and they are terribly dated. Obviously, there has been much experimental work done in that time and many significant fossil finds reported, but it’s the burgeoning of sequence analyses that seems to me to be the most striking change. It’s almost to the point that if you are going to make an argument about the relationship between species, you need sequence data to back up your viewpoint. Anatomical, behavioral, and physiological evidence aren’t enough—though, of course, sequence data aren’t enough either. So there is what might be called the metacomparative issue as to which types of comparisons are most important. I am definitely not getting into that debate, but since this ABT issue is devoted to biological inquiry, these issues are all germane—this is what such inquiry involves today.

At one end of a spectrum of sequence analysis issues is the whole barcode debate: is the way to catalogue species to tag them with “barcodes,” relatively short genetic sequences that are unique for each species? There are biologists who see the barcoding effort as central to preserving biodiversity: it’s difficult to save species if we don’t even know what species we have; therefore, we need a fast and relatively easy way to identify as many species as possible (Marshall, 2005). Other biologists cringe at what they see as the ultimate in reductionism: taking the complexity and richness of organisms and reducing them to computerized sequences. Barcodes would indeed be very dull if not viewed in terms of the richness of each species represented. However, for a quick way to identify species and census them, barcodes could become vital.

This brings up another issue in inquiry: research style. Different people are attracted to different kinds of inquiry. There are those who like field work and those who never want to leave the lab. The latter are more likely to embrace barcodes than the former. Arthur Kornberg (1989) wrote that he found working with enzymes just right for him. He saw the chemistry of simpler molecules as less interesting and cell biology as justtoo complex and messy. Well, there is, to put it trivially, no accounting for taste. And just as a variety of tastes makes human society interesting and dynamic, so does a variety of scientific tastes. Matters of taste play a subtle but significant role in many scientific controversies, and this is one of the many aspects of biological inquiry that I touch upon in my course.

At the other end of the spectrum of approaches to sequencing from barcoding are those dealing with not only entire genomes, but many genomes at once. The Human Variome Project aims to collect information on all genetic variations that affect human health—a very tall order (Cotton et al., 2008). Then there’s the 1000 Genomes Project, with its goal of studying human diversity by sequencing DNA from a variety of racial and ethnic groups around the world (Hayden, 2009). This goes to the heart of the comparative process: the more points of comparison, the better able biologists will be to evaluate just how rich the human genome is in individual differences. There’s also a project to sequence the genomes of 10,000 vertebrate species—called Genome 10K (Pennisi, 2009b). The invertebrate zoologists aren’t too happy with this focus, particularly because they represent the interests of 95% of the animal species on earth. As David Maddison, who studies beetle evolution, notes, only one beetle genome has been sequenced, even though there are six times more beetle species than vertebrates. He has a point. Obviously, since humans are doing the sequencing and we tend to be a self-absorbed species, the beetles aren’t going to catch up genomics any time soon, but Maddison’s comment is a reminder that we aren’t going to run out of genomes to sequence any time soon either.

Still another approach is called metagenomics, defined as “sampling the genome sequences of a community of organisms inhabiting a common environment” or more broadly as “any type of analysis of DNA obtained directly from the environment” (Hugenholz & Tyson, 2008). This tactic has been used with microbial communities, and a massive amount of genetic diversity has been discovered in ocean water, the human gut, and farm soil. Comparative work on the human gut has shown that the microbial diversity varies with diet and ethnicity; a study on Japanese who eat sushi regularly is particularly revealing (Sonneburg, 2010). There just seems to be no end to the riches that comparative studies can unearth.

For just one more example of the genomic approach, there is the ecological, with biologists investigating the role of environmental differences on genetic makeup. An article on this theme cites the work of the entomologist May Berenbaum, who has compared the sequences for the P450 genes in a variety of insects (Pennisi, 2009a). Cytochrome P450 is a protein that breaks down toxins, allowing insects to deal with many plant products; thus, it is a measure of insects’ abilities to deal with plant defenses. In her comparative work, Berenbaum was surprised to find that honey bees had 48 different P450 genes, whereas fruit flies had 87 and beetles 144. Berenbaum had trouble figuring out why bees seemed to have such a deficient defense system until she reflected on the fact that bees take pollen and nectar from flowers and chemically change them into honey and bee “bread” when they return to the hive. In these processes the toxins are broken down, and the bees are thus exposed to fewer toxins in their diet. This is a great example of the interplay of research on behavior, ecology, and genomics—all from a comparative viewpoint. It seems a fitting way to end this article about a subject that is about as much a part of our biological thinking that we take it for granted—something dangerous for any teacher of biological inquiry to do.

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References


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