Here is Systematics

My department is looking to hire an evolutionary biologist to teach (along with courses on evolution) courses that fulfill the systematics requirement. I feel the need to explain. The word systematics is largely unknown to the non-biologist, yet it deserves to be known in the same way ecology or physiology is generally recognizable as a major province within biology. Systematists do things like describe new species and figure out how species are related to one another on the tree of life, but they do much, much more, and what they do deserves to be understood by biology majors and by the educated public. The systematics requirement is a good one, and I want to explain why.

Before trying to appreciate the work of the systematist, however, it is helpful to consider the possibility that evolutionary biology is not a province of biology in the same way as are ecology, physiology, embryology, cellular-molecular biology, and genetics. Those sub-disciplines along with a few others can be thought of as analogous to states, like Alabama and Wyoming, that divide up the nation of biology. The borders are somewhat arbitrary, and there are many squabbles between the provinces, but the subdivision is necessary because the nation is so vast. Each of the sub-disciplines has a body of techniques and a jurisdiction of phenomena, but evolutionary biology is a little different. It is more like the rivers that flow through the provinces. Evolutionary biology is the biology related to a theme, and the theme is the exploration of the processes that are responsible for the way organisms have come to be the way they are through the innumerable generations that led up to them.

When I teach Evolutionary Biology, I feel like a reporter in a canoe starting at the headwaters of the Yellowstone River and paddling to the Gulf of Mexico. No state belongs to the river, but the river provides a watershed to all the provinces that it passes through. Other than its way of thinking, evolutionary biology doesn't have any subjects that aren't part of some other sub-discipline's jurisdiction.

Just consider what evolutionary biologists actually do. They relate the characteristics of babies to the characteristics of their mamas and their papas (genetics). They measure how organisms are influenced by their environment (ecology). They watch individuals behave (ethology). Sometimes they figure out how the different systems in the organism function (physiology). They are mesmerized by how an egg plus a sperm turns into a complex organism (embryology). They might work on how enzymes differ from one another (biochemistry). Perhaps, the province where evolutionary biologists spend the plurality of their time is in tabulating the similarities and dissimilarities of organisms (systematics). No evolutionary biologist does any empirical research without relying on the laboratory and field methods of the provinces within biology, and all the factual results could just as well belong to the provinces. What belongs to evolutionary biology is the relevance of the results to evolutionary processes. Evolutionary thinking provides one way of interpreting the results. Evolutionary biology has 150 years of trying to explain the relevance of this and that to understanding the origins of the way organisms are. For 150 years, evolutionary biologists have been correcting each other's logic, and it is this set of logical constructs that evolutionary biology can call its own.

The provinces of biology, to a greater or lesser extent, orient themselves around the watershed of evolutionary thought. A great deal of ecological research, for example, is motivated by evolutionary theories - how some individuals have characteristics that allow them to better survive harsh environmental episodes compared to other individuals, how organisms have adapted to one another through their interactions within a community, how a plot of forest in the tropics can have hundreds of species of trees compared to a plot of forest in the temperate zone with a few dozen species of trees. Yet, there are some projects in ecology that are not evolutionary - what nutrient limits productivity in a stand of Black Spruce over feather mosses, how to save an endangered species of sunflower, what rotation of crops will result in the best yield over decades.

Physiologists are often quite successful without any evolutionary thinking. How does a mammal mother regulate itself during gestation? This and that hormone carries this and that signal to one or another kind of cell, that responds in a particular way, etc. etc. Just as evolution is a theme in biology, so also is there a second theme in biology, which evolutionary biologists call "proximate causation" (and non-evolutionary biologists call "biology"). Using proximate explanation, ecologists tell us how ecosystem function is effected by organisms doing specific things, such as fixing nitrogen or holding moisture in the soil or photosynthesizing more than they are respiring under certain conditions. Using proximate explanations, physiologists tell us how individual organisms work, and physiological function is explained in terms of anatomical, cellular and molecular function, which is sometimes dependent on dialogues between genes and the internal or external environment. If you keep on going, sooner or later, the machinery of life can be sketched out as phenomena that emerge from chemical interactions.

Evolutionary biologists have often suggested that research on proximate causation can be moved forward with a little guidance from evolutionary thinking. For example, evolutionary biologists have a theory about how there is a conflict of interest between mammal mothers and their fetuses. This is due to the fetus having genes not only from the mother but also from the father. Fetuses can be expected to signal to their placenta (via hormones) that they should be treated better than is really in the mother's best interests. If times get rough, it is in the best interests of the mother's genes to (unconsciously) abort a fetus. It is in the best interests of fetus genes to be more reluctant at signaling that abortion is warranted. Thinking such thoughts regarding "ultimate causation" suggests a series of hypotheses that could lead to better proximate explanations. Since more often than not, the ultimate explanations get on the right track, they also end up shedding light on the proximate mechanisms that are responsible. In the case of mothers and their fetuses, the hormone concentrations by which the two communicate are orders of magnitude higher than hormone concentrations for other types of signaling not related to pregnancy. Evidently, there has been an evolutionary escalation in signaling and ignoring signals. Fetuses and mothers are, in effect, screaming at each other, which to an evolutionary biologist is only natural, and to a physiologist explains a number of common pregnancy complications.

Now, turn your attention to systematics. Systematics is defined as the study of patterns of diversity in the characteristics of organisms. A great deal of evolutionary biology is supported by the subjects, the methods, and the results of systematics. You need systematics to do a good job at studying tradeoffs between litter size and birth weight among a bunch of related species. You would be studying correlated evolutionary change. Those correlations would be results within the jurisdiction of systematics. They would occur on an evolutionary tree, called a phylogeny, and figuring out the branching pattern of that phylogeny would be a systematics project. At an even more fundamental level, the recognition of how many species are in the group and the circumscriptions of those species would have to have been worked out by systematists.

Anyone who does research on evolutionary biology – except perhaps a pure theorist – must also be a practitioner in one or more of the provinces of biology. A few are evolutionary physiologists. More are evolutionary ecologists. Many are evolutionary systematists, though I admit many systematists will feel there is no other type of systematist. I agree that in a department such as ours in which a premium is placed on intellectual rifting around the conceptual unification of biology we very much want to hire a systematist who uses systematics to address evolutionary questions.

It is worth recognizing, however, that it would be possible for a systematist to work long hours producing large contributions to the field of study while rarely testing hypotheses about evolutionary process. Many research projects in systematics require little more of evolutionary biology than a basic recognition that descent with modification has produced biological diversity that is usually fairly hierarchical and has resulted in lineages that are more or less distinct from one another and contain more or less geographical variation. Systematics is not a discipline contained entirely within evolutionary biology any more than ecology is a discipline contained entirely within evolutionary biology. None who has mastered systematics as a field would be ignorant of evolutionary biology, nor would anyone who has mastered the breadth of ecology. But systematics does have its own subjects and occupations that need not be focused on revealing abstract evolutionary processes.

Let me take you by the hand and lead you through some of the topics that could be taught in a systematics course.

It would be possible to have a methods course in systematics, which might teach about methods for getting molecular data and analyzing it or might teach more thoroughly about all kinds of systematic data and analyses. However, many systematists have a favorite group of organisms and delight in appreciating the diversity found in that group. We have a course on insects, and an insect systematist would take a substantial portion of the semester to pace out the orders and families of insects, how this or that groups has its own distinctive characters and way of life. My favorite group of organisms is the mosses, and I like to show the students both the common local genera of mosses and some wacky ones from around the world.

Taxonomy (in this context) is the formal classification of biological diversity into taxa, most notably species, genera, families, orders, classes, phyla and kingdoms. Taxonomy is not all there is to systematics, though it is the oldest contributor to systematics. Much of it pre-dates Darwin, and in certain groups such as mosses, I doubt the taxonomic treatments refined in the hundred years after *The Origin of Species* would have been very different had the taxonomists involved never read *The Origin* or learned any other such thing about evolutionary processes.

There is a movement afoot to come up with a new taxonomy of life that attempts to reflect the historical order of branching points in the evolutionary tree following a very strict rule: the rule would be that every taxon must be a whole branch of the evolutionary tree and not exclude any of the descendants of the common ancestor of the lineages included in the group. There are various schools on how this should be done. With some regrets and after much soul-searching, I am in the school that says we should more or less start from scratch with a new system that does not have ranks, a rank-free system of classification. A group wouldn't be ranked at the family level or the genus level. There are pros and cons, and I hope that our new professor will be able to lead a discussion of a lively hour or two on the subject without running of things to say about it.

Whether one presents diversity using a traditional or new-fangled classification, the students need some way of organizing diversity. It helps them systematize the information they receive about how some mosses have one structure and others another structure that reflects or doesn't reflect their relatedness to one another. Biologists do all sorts of studies with all sorts of organisms. There has to be at least an arbitrary but hopefully a natural system for filing that information away. If you study the physiology of a moss that you keep in culture from an accession that you got out of the cracks in the sidewalk, you need to report that you studied plants in the species *Bryum argentium*. Other studies of similar physiological topics will be done with other organisms, and all of that information then becomes available for comparing and contrasting. This is the most basic form of comparative biology, which is systematics that has a certain flare.

But for tradition, comparative biology would have been just as good a sub-discipline name as systematics. Traditionally comparative biology has had a special fascination with extreme morphologies and convergent evolution. Classical comparative anatomy takes note of the oddities of gradualism. For example, consider the vagus nerve of a giraffe. It runs from the brain all the way down the neck, loops around the artery that comes out of the heart, and then runs all the way back up the neck to the larynx. The giraffe's larynx makes me think of a dog on a rope that runs from the doghouse around a distant flagpole and back almost to the doghouse. Because fishes don't have much of a neck, the vagus had a reasonably straight connection in our distant ancestors. Now it wanders in us and is ludicrous in a giraffe, but every gradual step from our fishy ancestors to the giraffe was functional and none of it involved redesigning the way vertebrates are wired.

These days comparative biologists are excited about new methods for studying of how distantly related organisms with dissimilar ancestors have arrived at similar ways of doing business. The past couple of decades have seen huge strides in statistical analyses for carrying out comparative methods.

New statistics have been invented for studying adaptive correlations. Say one is studying a group of plants with 15 species that have radiated in a region that has experienced increasing desertification over the last million years. Eight of the species live in the desert, and 7 of the species live in various nearby mountains in much moister spots. Let's say that the 8 desert species are mostly annuals, and the 7 montane species are mostly perennials. If one has a well-resolved phylogeny, then one can ask if the evolutionary changes between annual-versus-perennial are correlated with the evolutionary changes between montane-versus-desert. One might well infer a history of character evolution in which the common ancestor of the whole group lived in a mesic environment such as is still found in the mountains and was a perennial, then lineage after lineage of plants in the desert evolved into having the annual life history. If so, you tell an account of convergent evolution.

Or, one might find that all the montane species form one group, which is perennial, and all the desert species form another group, which is annual. In that case, there are other new statistics. Attributing causation is a bit dicey. But one can at least quantify the amount of phylogenetic niche conservatism. If the two groups consistently differ in both their life histories and habitat preferences, then they have been following the appropriate habitat around despite the fact that they've each turned into numerous species. Revealing either convergence or conservatism, the new statistics are very useful at allowing one to see if data are consistent with one evolutionary characterization or another. These methods for studying patterns of character evolution are an important part of contemporary systematics.

My next exhibit of what is included in systematics is more removed from addressing evolutionary questions, namely, the practical task of describing new species. Yes, systematists are aware of Darwin's point of view that various species are in varying degrees distinct, that they contain variable amounts of intraspecific variation, that they are of varying ages, and that they vary from being widespread to occurring in only a tiny spot upon the Earth. But as a practical matter, we need to put every individual into a nominal species, be it monotonous and distinct or otherwise. Alpha taxonomists working near the species level will correlate characters against one another and look for gaps between groups indicated by multiple characters, then they will do the best they can. Generally, they do remarkably well most of the time.

The usual method of recognizing species does not assure that the resulting nominal species each contain all the descendants of the species' common ancestor. It is quite common for one nominal species, the parent species, to have given rise to another species, the offspring species, and the two to not be sister species in a genealogical sense. This is not a totally cut-and-dry topic. Different genes within the organisms can have different genealogical branching patterns, but at any rate, the groups and gaps of the nominal species need not correspond to other ways of looking at the relationships of the individuals in the populations.

Those other relationships, which are almost always best studied using genetic markers, are another topic within systematics. "Phylogeography" is an upstart subsub-discipline. The approach is related to amongpopulation "population genetics." One studies how much geographically distant populations have become genetically distinct, and with phylogeography there's the added twist that one maps the phylogeny of the genes. A similar field is called "molecular ecology," the reference to ecology being often a misnomer. Since geographic isolation is a major factor in the evolution of new kinds of organisms, this area of systematics coupled with some old-fashioned species-level taxonomy sheds light on the origin of what are commonly called species.

A good systematist will have plenty to say about various species concepts. The nominal species of alpha taxonomists are not particularly evolutionary, but of course the patterns reflect evolution. There are various phylogentic and genealogical species concepts that attempt to reflect evolutionary history. I'm rather fond of some ecological species concepts. And you probably remember from some past biology class, the biological species concept as a group of actually or potentially interbreeding organisms separated from other such biological species by reproductive isolating barriers. Because of the sway once given the biological species concept, the word "speciation" now means the origin of reproductive isolating barriers. The word claimed rather more ground for the concept than has turned out to be merited, but the study of patterns of reproductive isolating barriers is nevertheless one that sparks valid excitement.

Studies of reproductive isolating mechanisms among species are still done and published with some fanfare. Before phylogenetics became all the rage, the last big thing was biosystematics, which meant that one studied not just the dead specimens but how the putative species and geographic races reproduce or not with one another, how they differ in the environments where they do well, in their chromosomal compatibles, in their special defenses against parasites, in their rates of development and maturation, etc., etc. All of that would now be best done in a phylogenetic context. It would shed light on the ways in which the species have diversified and the ways in which they've stayed the same.

I have mentioned phylogenies and phylogenetics many times now, and should perhaps feel ashamed at not putting it first in the list of things that systematists do. Inferring the phylogeny with its sequence of branching points, is to the contemporary systematist like growing rice is to the peasant who lives on the flood plains of the Far East. It takes great skill to do well. There are many little things that one ought to pay attention to year round. Phylogenies are the staple of the diet. At the same time, I recognize, it would be pretty boring to only eat rice with nothing to go along with it. Some people can be happy as a clam cranking out evolutionary trees as a career. You probably wouldn't want to have a clam teaching a systematics course however.

Systematists are constantly improving on statistical methods for inferring phylogenies, and they are constantly adding new sources of data. The cottage industry for new data is derived in various ways from DNA. Molecular tools are allowing for a growth industry with no end in sight. However, systematists generally recognize that other forms of data are also very useful in inferring the trees, especially when it comes to figuring out short internodes from long ago. Such data might come from almost any aspect of the organism involved in function. They could come from enzymes, ultrastructure, or defensive chemistry, but they could come from the gross morphology that systematists have been tabulating for 300 years. If at least some of the data are from non-expressed stretches of DNA, then one added benefit is that the systematist might have a crack at using a molecular clock to crudely date evolutionary events. For example, it is sweet deal when one can say whether a species that occurs in both Spain and California has a common ancestor of only upto a few tens of thousands of years versus millions of years. It tells us something about the dispersal of species versus the conservatism of species.

Turning next to a skill that is less evolutionary, a systematics class usually involves practice using identification keys and often writing identification keys. These are meticulously precise outlines that allow one to take an unknown specimen and determine its identity (species, or genus, or at least family). Writing keys that work well is a fine craft of exactitude. Using them also takes mental powers and an ability to work backwards and forwards to eliminate all implausible possibilities. These days, computers promise to provide more versatile methods of keying, allowing the user to be more visually discerning without having to know as much specialized vocabulary and allowing random access rather than pre-structuring the series of questions. Using keys and other identification guides with accuracy is a skill necessary for many jobs, for example dealing with agricultural pests, parasites of people and other organisms, conservation of sensitive species, searching for new drugs, and so on. Many of these professions have an aging workforce, and there are few universities with programs as good as ours at training systematists.

An obscure area in systematics these days is phenetics above the species level. Phenetics got started when computers first became available. In its current version, it is a statistical approach at summarizing similarities versus differences in a large number of features of representative specimens in one's study group. In class, I have students score all the characters they see varying from 26 species in my favorite group of ferns. We get out tidy diagrams that show which species are most similar to which other species and which clusters of species are different from one another. The analysis is not meant to infer anything about the evolution of these ferns. I use it in the same spirit as if I were doing a gradient analysis of vegetation plots as they change on a landscape. In fact, a compelling use of phenetics is when one is doing ecological systematics, and the characters are not how hairy the fern is or how many times the leaf is divided but instead the amount of sun it prefers, the type of substrate it grows on, its degree of desiccation tolerance, etc. Phenetics is still commonly used by systematists who revise species boundaries, but for exactly the same reasons I think it retains validity above

the species level as well. Not everything in systematics is about inferring phylogenies.

From the standpoint of motivations, an undertaking that is akin to phylogenetics is the inference of hybrid origins. In both textbook phylogenetics and the inference of hybridity, the systematist is trying to figure out the historical pathways that led to the current species. Hybrid inference is usually done using multiple lines of evidence, and since there are several different types of entities that are derived from hybridization, different lines of evidence are used depending on the hypothesis under consideration. Many species of ferns have arisen through hybridization followed by chromosome doubling. For this kind of hybrid, one checks to see that character after character is intermediate, that the chromosome numbers are distributed as predicted, and that the parents' enzymes are both present in the putative hybrids.

Another pattern that derives from the hybridization of divergent species is the phenomenon of a hybrid cline. For example, Timberline Beardstongue lives on the high peaks of California's Sierra Nevada, while on the slopes of the mountains lives Mountain Pride, and in between there's a swarm of hybrids. Such hybrid clines have drawn the attention of systematists for decades. Sometimes the parents are not each other's closest relatives, are very different from one another, and it would be just plane wrong to put them in the same species. So hybrid clines bring out a sense of irony for systematists. How can the species be maintained if they are interbreeding so much? In the case of Timberline Bearstongue and Mountain Pride, it seems to be that there is such strong environmentdependent selection that the habitat difference keeps the two species from merging.

Systematists also entertain the possibility that geographic clines have arisen in place and without hybridization. A familiar primary cline in humans is the way skin pigmentation decreases with latitude. Widespread species often display clines in one or a few characters like this, and it keeps systematists busy mapping out the details and trying to figure out the reasons. As regards skin pigmentation, the likely reason is that people of the far north have been wearing lots of clothes for tens of thousands of years, and this has kept their skin from receiving enough sunlight to generate healthy quantities of vitamin E, so in northern climates there was selection to be less pigmented because individuals with less skin pigment made more vitamin E on the rare occasions when they were outside naked. Plotting out clinal patterns in less familiar organisms is a job for a systematist.

Systematists delight in diversity, and they like to find generalizations that apply to groups of species, taking note of whether or not those groups are close relatives and if so how. Systematists have been the custodians of such information as how pollination mechanisms vary among flowers. For one thing, it spices up a lecture if when introducing the orchid family one talks about orchid pollination, and when introducing the subfamily of peas one talks about how their distinctive flowers work. Systematists have also come up with a classification of pollination syndromes, and usually the species in the syndromes arrived at their flowers through convergent evolution. The systematics of each group of organisms is customized for the phenomena that the group presents.

Ecologists like species too, and that's good. A community ecologist might study all the vertebrates in a park, how they manage to get food in different ways and the threats to them from various enemies. These many animals will not be particularly related, and most ecological research will include species in the study based on their co-occurrence, whereas systematists are much more concerned with comparing the various species in a group unlimited by where they occur geographically. A population ecologist might hone in on the local representative of just one focal species, figuring out the factors that affect rates of survival and reproduction, toiling to learn about that population. Ecologists add miscellaneous information about this and that species all the time. Systematists compare closely related species. Sometimes systematists tabulate ecological data on a series of closely related species.

Ecologists in fact need the research done by systematists. Systematics is a service science to the other provinces, and it is far from done. Systematists circumscribe species and higher taxa, then tell us how to identify those taxa. Ecologists who work with organisms other than the most familiar ones or who work in parts of the world very unlike London, New York and Tokyo often stumble upon seemingly undescribed species. They don't know what to do other than call them Species-A, Species-B, etc. They send specimens to systematists if they can find a systematist who specializes on that group. But there are fewer and fewer professional systematists available. For many groups of organisms, none of the experts on the group are alive any longer. Now, I'm not trying to hire a professor to take on an orphaned group of beetles, but I do think that biology majors should be told about the situation with graphic drama.

Expert systematics is important in many practical ways, but actually my emotion is that the most important role of systematics is to give us perspective in environmental ethics. If you've never taken a class on the systematics of any group of organisms, then all plants are green blurs, all insects are just lizard food, and who would have guessed there is variety in the lives of the warblers. I'm not sure that readers who have not taken a systematics course will follow what I'm saying. Consider a species of sunflower or cricket or lizard that is endangered. Against odds, its case has wound its way through the bureaucracy of the U.S. Fish and Wildlife Service. There's even a bit of money available if a grad student wants to do a thesis on how to manage it out of extinction. Yes, most of that thesis will be ecology, but how are you going to find a student who can tell that's species story if she hasn't had class on flowering plants in the case of the sunflower, or insects in the case of the cricket, or in herpetology in the case of the lizard. She'll think it looks just like other sunflowers or crickets or lizards. Okay, but say that some old guy who once upon a time took systematics courses gets her to do the project purely on abstract grounds. Well, again she ends up being the one who has to tell the story of this endangered species. A crucial part of telling that story is telling what unique features her species has that separates it from its closest relatives, and then there is the question of how those relatives are doing, whether they too are rare, what it is that varies within the group and what is similar among the species in the group. The people who gathered this information or will gather this information will be doing the work of systematics.

It is only proper to disclose that when I was in college, I took eight systematics course on various groups of organisms. Learning species diversity came naturally to me. I used to say that young primates were born to learn the species that surrounded them, which ones were good to eat and which ones were good to show to special-friend primates. Once language evolved in humans, the names of organisms I am sure were a standard subject for someone in any society to study, at least the apprentice shaman. And so it was for me. I learned my myriad mosses. From time to time I return to them, and trace a hundred twigs or so on the tree of life, way out on one of its branches. I do this to test evolutionary hypotheses, yes it is all very logical, but it also makes me aware of something. It gives me respect for the vastness of the tree of life, and a sense of humble kinship as a member of a species, the tip of just one twig, way far out on just one branch of just one limb of just one trunk. The tree in its entirety with what twigs it has sprouted at this moment in geological time, well now, that is an object of worship.*

Paul Wilson/April 2009