Systematics as a Hypothesis-Based Science and its Fundamental Role in Understanding Oceans

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Abstract – **Far from its static "stamp collecting" image, systematics is a dynamic, hypothesis-driven pursuit to perceive, describe, and explain organismal diversity in an organized and useful manner. The activities of the systematist (identification, the provision of names, description, classification, and phylogenetics) provide data that are at the core of many other fields of biology, ranging from environmental science and ecology to evolutionary biology. In terms of education, systematics has qualities that make it an ideal subject around which K-12 lessons in biology can be designed. Unfortunately, in terms of ocean education, the substantial potential for systematics is unfulfilled. New curriculum that uses real world systematic research for classroom lessons could provide meaningful educational experiences, particularly those that improve ocean literacy. This assertion is illustrated using the example of research that involves the genetic identification of whale meat sold in Japanese and Korean markets. New lessons drawn from systematic research should reflect up-to-date educational philosophy, explicitly address science methodology and the nature of science, and address socioscientific issues. Greater support for the development of such lessons, in terms of funding, making research data available, and collaboration between educators and scientists, should be encouraged.**

INTRODUCTION

For the ocean science and education communities, it is a critical and exciting time. Newly released documents -- such as the *U. S. Commission on Ocean Policy* [1] and the *PEW Oceans Commission Report* [2] -- spell out the degraded and threatened state of our "One Ocean" and emphasize the need for change at international, federal, and local levels. Those of us working in ocean research and education have an unprecedented opportunity and a responsibility to put ocean issues in the forefront of public attention. Ensuring survival of our ocean resources is dependent upon future stewards appreciating how healthy marine ecosystems play an integral role in every person's life, and how ocean resources can be sustained. Such an appreciation can best be achieved by promoting ocean literacy, which we characterize as an understanding of fundamental ocean-related concepts. (For more on ocean literacy, see [3].)

Achieving ocean literacy is no doubt a great challenge, considering our nation's low rate of scientific literacy [4]. Rising to this challenge is imperative, however, because scientific comprehension is a critical factor in determining the public's willingness to support scientific endeavors [5] and people's ability to make educated decisions at the polls [6,7]. Thus, if we wish to understand and protect the ocean and its attendant resources, we must make great strides to improve both scientific and ocean literacy. A small but vital step toward such literacy is understanding systematics.

Systematics is often dryly presented in K-12 educational materials as that branch of biology dealing with the naming and classifying of organisms. Instead, systematics is the study of life's organismal diversity. Systematics therefore plays a central role in addressing biodiversity problems [8]. Systematic study proceeds through a dynamic, hypothesis-driven process that generates an ever growing understanding of which organisms live where and how these distributions have changed through time. There already exists a mandate to integrate systematics into classroom instruction because it adheres to guidelines from the National Science Education Standards and AAAS Benchmarks. However, we contend that systematics has much greater potential in education than is currently achieved.

First, systematic research, particularly in the marine realm, deals with bizarre, beautiful, and creepy critters that can potentially be used to excite and interest students. Furthermore, because it is integrative and hypothesis driven, systematic research aligns well with contemporary educational recommendations that emphasize the need for inquiry-based lessons that actively engage students in the process of science. Topics in marine systematics also provide numerous avenues for illustrating the very practical concept that the health and wellbeing of both people and the ocean are interrelated. Through reference to an example involving whale meat (see below), we encourage researchers and educators to collaborate in the development of new curricular material that is based on real research, and which explicitly illustrates science methodology and the nature of science. Such lessons have the potential to not only teach important content, but also to foster both an understanding of how science works and the development of high-order cognitive skills. As a consequence, students will become decision makers who are better informed about ocean issues that affect society.

WHAT IS SYSTEMATICS?

Before discussing systematics in the context of education, we present a brief description of what systematics entails. Systematics is the study of life's organismal, as opposed to genetic or ecological, diversity. Put another way, the job of the systematist is to perceive, describe, and explain organismal diversity in a sensible manner. There are five essential tasks involved in systematic inquiry: 1) identification (placing names on specimens or photo observations that refer to previously named groups); 2) naming (following a code of nomenclature to provide formal names to species or groups of species that have not previously been named in the scientific literature); 3) description (publishing formal accounts/definitions for species or groups of species that have not previously been recognized); 4) classification (grouping sets of organisms according to some organized and logical method); and 5) phylogenetics (forming and testing hypotheses on the evolutionary relationships among organisms). Taxonomy is often equated with systematics, but taxonomy does not explicitly involve phylogenetic analysis [9].

When the process of systematics is broken down into its component tasks, it becomes obvious that elements of systematics are practiced by a wide variety of individuals, not all of whom are systematists. For instance, the task of identification is practiced by a range of people from amateur nature enthusiasts to countless biologists who encounter diverse species in the course of their work. It should go without saying that accuracy in the basic step of identification is often imperative for people pursuing various interests, such as environmental science, physiology, behavior, embryology, molecular evolution, biogeography, ecology, and more [10]. Just imagine the marine ecologist investigating community structure on tropical reefs who mistakenly identifies three similar species of coral as one, or the fisheries biologist who applies developmental data gathered from one fish species in managing a second because it is wrongly assumed that the two species are one (for examples, see [11]). Phylogenetics, because of its widely recognized utility for making predictions [12] and inferences about biological history, is also pursued by a large number of diverse biologists who are not systematists per se. Finally, even taxonomic naming and description is carried out by researchers whose main interests lie outside of systematics. For instance, ecologists often perform these basic tasks in the course of their work because the need for systematic expertise far outweighs the supply of systematists. This is especially true for the marine realm, where gaps in our basic knowledge of biodiversity are enormous.

What is perhaps less readily apparent from reading through the list of systematic tasks above is the underlying nature of systematic inquiry. Systematics is a process that is essentially comparative, integrative, and hypothesis driven. The comparative quality of systematics becomes clear when one recognizes that assessments of variation are involved when systematists make conclusions such as, "this specimen should be given the name A, as opposed to B", or "A groups with B to the exclusion of C". While systematics involves a great deal of pattern recognition, it also seeks to uncover the processes underlying these patterns. Thus, systematics is necessarily integrative - broadly intersecting most other fields in biology, from paleontology and evolutionary biology to ecology and conservation biology. Systematics also interfaces, and even intercalates, with population genetics (which emphasizes more short-term evolutionary processes) because the systematist seeks to delimit species and therefore must often assess population structures within species.

Finally, a point we wish to emphasize is that each of the basic tasks of systematics involves the formation and evaluation of hypotheses. When a specimen is identified, it is most properly viewed as a hypothesis. The determination has been weighed against alternatives, and is subject to change when new information comes to light. Similarly, whereas applications of the rules of nomenclature are not scientific procedures, the acts of providing a name and description for a new species are scientific endeavors. Later work, may in fact, find that two or more species have been recognized as one, or that what was previously given a name and description was simply a variant form within a previously recognized species.

Determining whether or not the activity of classifying is a hypothesis driven endeavor is somewhat problematic. A thorough discussion would be much too long for this paper. Suffice it to say that at present, it is widely accepted among the systematic community that classification schemes must in some way reflect hypothesized evolutionary history, whereas the determination of ranks (as in phylum, order, etc.) is largely arbitrary. The task of classification has become intertwined with the more broad aim of identifying the best corroborated hypothesis of phylogenetic relationships.

As we illustrate below, many introductory classroom lessons that explain activities related to systematics fail to communicate that systematics is a process driven by the creation and assessment of hypotheses. While this failure leads to a misrepresentation of systematics, we are more concerned with the lost opportunity for providing meaningful educational experiences, particularly those that incorporate content and skills to improve ocean literacy.

EXISTING LESSONS IN SYSTEMATICS

A. *Our search techniques*

To gain an appreciation of the nature and quality of existing lessons related to systematics we conducted searches for online teaching resources in several noteworthy education Web sites, including Digital Library for Earth System Education (DLESE) [13], Bridge [14], Understanding Evolution (UE) [15], Access Excellence [16] and Evolution and Nature of Science Institute (ENSI) [17]. We chose these resources because of our familiarity with them and because they are recognized among educators as housing a number of quality lessons. Additionally, there is some degree of monitoring and/or reviewing of the linked lessons for quality. We limited our searches to online resources because of their accessibility to a wide range of teachers. Keyword searches in each database were done using the following terms; "systematics", "classification", "taxonomy," "phylogenetics," "identification". We were unable to review every reference that came up in our search because many of the "hits" led to additional lists of still more references. Rather, we wanted to simulate the probable search efforts of a teacher with limited time trying to find lessons on different aspects of systematics. It is not possible in this paper to fully address the variety of online lessons we encountered and it is quite likely that we missed some that are relevant due to the search limitations. However, we highlight lessons that illustrate both positive and negative attributes and that appear to represent a spectrum of systematics related educational resources presently available to the K-12 teacher.

B. Generalizations of lessons revealed

Using the search term "systematics," we uncovered only one relevant lesson, *What, If Anything Is a Zebra* [18] an essay by Stephen Jay Gould with accompanying questions. When refining the search to include specific aspects of systematics, a reasonably large number of lessons came up. In many of these lessons, students learn how to create and/or use dichotomous keys for the purposes of identification. For example, in *Classifying and Sequencing* [19], students are presented with fictional organisms from which they identify similarities and differences, then use these observations to develop a key. Others, such as *Potato Chip Classification* [20] use non-living items to have students do the same. Alternatively, several lessons present students with an already designed dichotomous key that they can use to key out unknown specimens. For example, *Key to Major Clades of Echinoidea* [21] and *What is the Key to Classification?* [22] provide students with introductory experiences using online keys to identify a handful of marine organisms. These basic lessons in identification give students a sense of how organisms can be identified, and help students focus on features that certain groups of organisms possess.

We had difficulty finding lessons that give students opportunities to apply their identification skills in a larger, real-world context. However, we did find *The Stream Study* [23] that used *Save Our Streams Monitoring Guide Aquatic Microinvertebrate Key* [24]. This lesson challenges students to use the key to identify invertebrates found in stream water. Once species are identified, students use the presence of indicator species to determine likely pollutant levels in the water to infer the health of the stream.

Classification activities form another set of relatively common lessons dealing with the tasks of the systematist. In such lessons students are typically presented with a group of objects or organisms - ranging from shoes to fish - in which they must look for morphological similarities and differences that help divide the items into separate groups. When real organisms are used in classification lessons, students become familiar with larger taxonomic groups such as phyla, classes, or orders, which should serve to increase their appreciation of the vastness of biological diversity. Moreover, these activities assist students in developing observational skills as they examine morphological similarities and differences in organisms or objects. These lessons often show that grouping objects is inherent to humans (e.g., cultures classify important and influential elements in their environment, such as snow types to those native to the far north). The history of biological classification, going back to Linneaus, and before him to other great thinkers such as Aristotle, is also touched upon in different materials we found.

Phylogenetics, the search for and application of the best corroborated hypothesis of evolutionary relationships among a group of organisms, has great but unrealized potential for education. Available activities that present phylogenetics are much more limited in number then those that address identification and classification. There are some lessons on cladistics, a particular technique that relies on the principle of parsimony for deriving a phylogenetic hypothesis. These often involve having students complete or use a matrix of characters, which is subsequently used as the basis for constructing a tree topology called a cladogram. A cladogram is most parsimonious in the sense that it represents the set of relationships that requires the smallest number of assumed character changes during evolution. In our search, it was difficult to find cladistics and phylogenetics lessons focused on marine organisms and the ocean.

Aside from lessons on the cladistic method, just a handful of phylogenetic lessons exist. For example, *What Did T. rex Taste Like* [25] teaches students the basics of phylogenetic trees, then challenges students to use their understanding of evolutionary relationships to address questions (in this case, the relatively silly but engaging query about the likely flavor of *T. rex*). Other lessons such as *Anolis Lizards in the Greater Antilles Using Phylogeny to Test Hypotheses* [26] and *Island Biogeography and Evolution: Solving a Phylogenetic Puzzle with Molecular Genetics* [27] go even further by using real research questions and data. These latter lessons provide opportunities for students to apply their understanding of phylogenetics and emphasize the usefulness of phylogenetic inquiry. So far as we know, no such lessons have been designed based on examples and data taken from marine organisms.

C. Limitations of the lessons found

When seeking lessons related to systematics, teachers are likely to come across a large number of lessons that fall short of actively involving students in the skills applied by systematists. Existing lessons are often designed as stand-alone experiences in which the objectives are to simply learn how to use or make a key, how to classify a set of objects, or how to create or read a cladogram. Some may additionally provide opportunities for students to learn about specific groups of organisms. Though these skills and content knowledge are important, they do not provide students with an authentic understanding of how scientists pursue systematics in their quests to address real world questions.

Specifically, many lessons imply a perfect, or at least static, knowledge of diversity, which is far from what biologists encounter. In reality, many marine invertebrate species have never been incorporated into any identification key because their existence is not known. Marine scientists certainly rely on dichotomous keys as aids for identification, but for poorly documented groups, researchers are (or should be) mindful of the enormous number of marine species that have yet to be named and described. For example, a not particularly uncommon jellyfish that boasts a bell one meter (m) in diameter and tentacles stretching to 30 m was not given a name or description until 1997 [28], when it became the largest invertebrate described during the 20th century. Given the depth of our ignorance about biodiversity, the outcomes of applying dichotomous keys should more properly be viewed as hypotheses subject to further revision. Rudimentary lessons in identification overlook this important source of uncertainty and its vital impact on subsequent biological inquiry.

Classification exercises are often not particularly challenging as it is not very difficult for students to develop their own schemes for a given set of objects or organisms. These lessons typically emphasize the value of morphological similarity and differences among a group of items or organisms. However, students should also understand the importance of having a classification based on a systematic scheme that is meaningful in a broader context, i.e., one that aids in understanding some biological pattern or phenomenon. In biology, classification is based on hypothesized evolutionary relationships, a scheme that is more subtle, complex, and definitively useful for addressing biological questions than are those based on morphological characteristics or overall similarity. We found one model lesson that aids students in understanding these differences, *Nuts and bolts: Is Classification Arbitrary or Not?* [29]. In this lesson students compare the nature of classifying non-living items, such as furniture, with that of classifying organisms. Students learn that biological groupings differ because organisms are put into groups meant to reflect nested hierarchies of ancestral relationships. Like exercises on classification, the cladistics lessons we found have educational value but too often are not set in a larger scientific framework.

In general, there is still much room for curriculum developers to take advantage of the unusual and exciting marine organisms that could grasp students and get them eager to learn. After all, many professional biologists can trace their start to an interest in some animal or group of animals that fascinated them. The marine realm is replete with examples of organisms that are odd, frightening, beautiful, and of practical importance. Even the fact that so much is still unknown about marine diversity should connect with many students. Just among jellyfish (a group for which we have a particular fondness), there are species that can kill humans, see with complex eyes, have courtship rituals prior to mating, and bloom in numbers large enough to devastate fisheries. In all of these cases, there is relevant systematic research underlying what we do and do not yet know about these species. As a community of scientists and educators, we need to take advantage of topics that offer intrigue and personal relevance, rather than rely on simplified lessons without an engaging hook.

CREATING SYSTEMATICS LESSONS INVOLVING MARINE DIVERSITY

With few exceptions, there is a disconnect between the focus of the lessons we have found and how systematics really works. This is important to recognize because we are missing an opportunity to use systematics (aspects of which are mentioned by various educational standards) in a way that can improve ocean literacy. The K-12 community needs new and better lessons that provide students with opportunities to apply basic systematic inquiry in much the same way practicing marine biologists do, thereby serving to sharpen students' skills that are critical to making informed decisions about the ocean. Future lessons need to reflect up-to-date educational reforms that actively engage students in the process of science, explicitly illustrate the nature of science, and bring up socioscientific issues. In addition to lessons being scientifically and educationally sound, they should build upon the inherent interest in weird and beautiful things, the unknown, and practical implications that real examples from nature provide. In order to support the development of these lessons, funding agencies should be lobbied to allocate funds for curriculum development, scientific researchers should be encouraged to make marine biodiversity data available, and perhaps most importantly collaboration between educators and scientists should be promoted.

A. Whale Meat Example

In order to better illustrate some of our ideas about designing systematics-related lessons, we will make reference to a lesson that we are currently developing. This lesson is based on ongoing research, begun in the mid 1990s [30,31], that uses molecular techniques to identify meat sold as kujira (or whale meat) in Japan and Korea. This research has been able to determine that a variety of whales including endangered minke whales, dolphins, porpoises, sperm whale, and horse has been sold as kujira. The beauty of this example as the foundation for a lesson on systematics is that in addition to it being real science, it should be interesting to students. We presume that many (and hope that most) students have some sort of emotional connection to whales. In addition to making the association between particular species of these seemingly gentle giants and hunks of meat, this lesson will exploit the fact that the identifications are used to make conclusions about illegal hunting of protected species and the misrepresentation of products. Thus, students are provided with the opportunity to deal with real-world questions that have socioscientific relevance.

Here is a brief outline of the basic steps that we imagine being involved in our planned lesson adapted from the whale meat research.

1) Engage the students (e.g. discuss whales and endangered species, brainstorm resources that come from the ocean used by different cultures, and/or potentially take a virtual trip to a foreign market);
2) Collect and sequence samples of meat obtained in a foreign market (e.g., provide students with sequence data);
3) Identify the species by comparing sequences to those that are publicly available (e.g. exploiting the tools, especially BLAST, available at GenBank [32]);
4) Determine the legal status of the species identified (e.g. use online resources to compare their

identifications to a list of protected species);

5) Learn about the practical implications of such findings (e.g. research the legal debates surrounding illegal whaling and protecting species);
6) Present their findings (e.g. write a research paper, create a poster, or give a talk);
7) Discuss how the nature of science is demonstrated in the lesson.
8) Apply their results in a practical way (e.g. write a mock recommendation to the *Scientific Committee of the International Whaling Commission,* simulate public debate among biologists, policy makers, whalers, and fishermen, or create a public awareness campaign); and
9) Seek out other applications of how molecular data can be used to identify unknown organisms of importance, (e.g., bird strikes on airplanes, jellyfish stings based on skin swipes, pathogens, or parasites).

By following these steps, students replicate the process that researchers undertook. They also have the opportunity to see how science is applied to real-world issues that have big impacts on a variety of human interests. This approach aligns well with education standards, and also incorporates effective instructional approaches, as we discuss next.

B. *Incorporating Standards*

The whale example aligns well with science standards and benchmarks [33,34]. Content standards for teaching specific tasks related to systematics can be found for various grade levels [33]. For example, 5th-8th graders are required to learn "Although different species might look dissimilar, the unity among organisms becomes apparent from an analysis of internal structures, the similarity of their chemical processes, and the evidence of common ancestry." Older students are expected to learn "Biological classifications are based on how organisms are related. Organisms are classified into a hierarchy of groups and subgroups based on similarities which reflect their evolutionary relationships. Species is the most fundamental unit of classification," and "The millions of different species of plants, animals, and microorganisms that live on earth today are related by descent from common ancestors."

Additionally, the *National Science Education Standards* place a strong emphasis on inquiry-learning at each of the grade levels [33]. Inquiry, which goes beyond "science as a process" requires that students combine content knowledge with a variety of process skills, including observation, forming inferences, and carrying out experimentation. The *National Science Education Standards* also incorporate "Science in Personal and Social Perspectives Standards" for each grade level [33]. These emphasize the importance of training students to develop skills that allow them to make decisions that involve personal and social issues.

C. *Reflecting Current Educational Reform Efforts*

Current educational reform is making it easier to justify spending time on activities designed to have students follow real research and is changing the roles of students, teachers, assessment methods, and social characteristics of the classroom [35]. This provides teachers an opportunity to engage their students in active in-depth learning. Instead of students being expected to absorb or memorize isolated facts and skills handed down by teachers or dictated by other resources and then to regurgitate that "knowledge" on paper and pencil tests, reform approaches encourage teachers to guide students in inquiry so that students create personal knowledge and appropriately apply skills and content to real world problems and situations. Inquiry-based approaches also provide opportunities for students to evaluate, analyze, synthesize, and generate ideas and products [36], thereby strengthening higher-order cognitive skills essential for effective decision making.

Reform efforts support a constructivist approach, which is based on the premise that learning is contextual and influenced by individuals' beliefs, attitudes, and experiences. According to constructivists, learning occurs when students come into contact with new information that conflicts with their existing frameworks. This challenges students to figure out how the new information applies to the old. How students construct new meaning in this manner is highly impacted by their personal experiences [37].

More specifically, the whale lesson as we envision it engenders a constructivist approach because it begins by giving students opportunities to express their personal perspectives on various aspects of the topic. The students also must explore the questions before them from multiple perspectives (i.e., as researcher, policy maker) thereby helping them form connections between their discoveries (identifications) and the larger context of the legalities of whale hunting. Moreover, students will be given time to process their learning. By having students present their findings to others, they come to better understand what they have learned and how they have learned it.

Systematic studies are diverse and provide a number of intriguing opportunities for implementing these educational approaches, the whale example being just one. For those interested in developing new lessons, a great place to start is the primary scientific literature. A number of Journals, including *American Naturalist*, *Biological Journal of the Linnaean Society*, *Cladistics, Evolution*, *Journal of Evolutionary Biology*, *Marine Biology*, *Molecular Ecology*, *Nature*, *Royal Society Proceedings B*, *Science*, and *Systematic Biology* routinely publish research that in some way uses aspects of systematics. Finding the right study to form the premise of an activity is obviously dependent upon student learning level, desired objectives, and alignment to standards. However, equally important is to find studies that are likely to be interesting and relevant.

D. *Science Methodology and the Nature of Science*

Science lessons that have students serve as "cognitive apprentices" are particularly effective [35]. The idea behind such lessons is relatively straight forward; students are guided through the same steps -- making observations, forming multiple hypotheses, collecting and analyzing data to falsify hypotheses, presenting data, drawing and defending conclusions, etc. -- that scientists made in order to investigate a question. The challenge is to make the experience authentic given the practical constraints facing the teacher. For example, students cannot easily go to the store and purchase whale meat. Therefore, the lesson developers need to get creative and design engaging lessons that teachers can use with relative ease in their classrooms.

Lessons based on real research also provide opportunities to reinforce students' understanding of the nature of science (NOS). Though there does not appear to be perfect agreement among scientists as to which tenets apply to all science disciplines [38] some of the most universally agreed upon include;

"1. Scientific knowledge while durable has a tentative character.
2. Scientific knowledge relies heavily but not entirely, on observation, experimental evidence, rational arguments, and skepticism.
3. There is no one way to do science (therefore, there is no universal step-by-step scientific method).
4. Science is an attempt to explain natural phenomena.
5. Laws and theories serve different roles in science; therefore students should note that theories do not become laws even with additional evidence.
6. People from all cultures contribute to science.
7. New knowledge must be reported clearly and openly.
8. Scientists require accurate record keeping, peer review, and replicability.
9. Observations are theory-laden.
10. Scientists are creative.
11. The history of science reveals both an evolutionary and revolutionary character.
12. Science is part of social and cultural traditions.
13. Science and technology impact each other.
14. Scientific ideas are affected by their social and historical milieu." [39]

Versions of these tenets can be found in both state and *National Science Education Standards.* It is important to include instruction on the NOS because by understanding the nuances of science, students can learn how science is different, in terms of strengths and limitations, from other disciplines. This in turn should contribute to students better appreciating the value of scientific work. But to improve students' understanding of science, it is likely they need explicit, activity-based, reflective and repeated exposure to the tenets [40]. There are some outstanding introductory lessons that deal directly with various NOS tenets (though most do not directly relate to the ocean) [17] . In our whale meat lesson, students will identify and discuss when a tenet is being used in order to reinforce their understanding of the NOS.

E. Incorporating Socioscientific Issues

Because of the widespread practical application of systematics, teaching systematics opens up the opportunity to prepare our students to use scientific data to make decisions about controversial or sociosicentific issues related to ocean health. Controversial issues are those about which a large number of people argue without reaching a conclusion [41], whereas socioscientific issues are controversies that specifically involve scientific findings [Kolstø, et al.]. While somewhat less controversial than other topics, e.g., the Endangered Species Act or fishing practices, the whale study is a good example of how scientific research plays a role in questions that are political, personal and ethical.

Teaching socioscientific and controversial issues is not easy. Ocean educators should be aware that even if students are presented with and understand scientific data that support a particular argument, students may not react to the data in an expected manner. People are often more influenced by their personal perspectives than by new data which is presented to them [43,44]. Rather than looking at data objectively, people appear to be more apt to seek specific evidence that supports their own personal views and ignore contradictory evidence [43.]. A person's common sense, circumstantial evidence, personal experience, personal values, economy, and moral values tend to have more weight when making decisions about an issue. Thus, even students well versed in scientific knowledge may be unable to use it to express a well-reasoned position on a controversial topic.

We contend that a good strategy for combating this phenomenon is to allow students to explore how their own personal perspectives play a role in their evaluation of socioscientific issues. The constructionist approach outlined above serves this purpose. Thus, educators who wish to help students view data more objectively and see how it is appropriately used to support or refute claims, should strive to have their students evaluate new information in the light of existing data. This will also help students to: 1) have a more positive and realistic view of science and how it is involved in controversial issues; 2) develop critical thinking and reflection skills; 3) challenge views rather then just accept them; 4) recognize that scientific knowledge is tentative and subject to change; 5) search for additional information; and 6) improve their ability to argue their position on an issue, including the incorporation of philosophical and ethical aspects [41]. These are important in terms of making decisions that impact our ocean and our ability to sustain its resources.

SUPPORTING THE DEVELOPMENT OF NEW CURRICULUM

Creating lessons that are scientifically accurate, educationally sound, interesting, and appropriately geared for the target audience is not simple. It requires science expertise, educational expertise, classroom experience, and time. Therefore we strongly advocate a collaborative approach to developing the new curriculum that is necessary to support ocean education. Ideally, both educators and researchers should be brought together to carry out the design process. Scientists who pursue systematics-related questions are likely to know of numerous examples of systematics in action and have a grasp of the nuances of the topic. The education experts are best suited to identify the example that can be translated into a useful and engaging lesson for the intended audience. Newly developed resources such as *Explorations Through Time* [45] and *Understanding Evolution* [15] stand as excellent examples of the fruits of this type of collaboration.

It will take more than encouraging words to bring about such valuable collaborations. In order to combat the continued operation of educators and scientific researchers in separate spheres, real support for these efforts needs to be forthcoming. Scientists who are interested in education need to have professional expectations for public outreach that go beyond giving a lecture with lots of pretty pictures, or authoring a Web page. Similarly, educators with an interest in curriculum development need to be occasionally set free from their classrooms and students. Therefore, both communities should be creative about developing prospects for working together. The Research Experience for Teachers supplemental award program of the US National Science Foundation is a nice model that brings educators and scientists together, though it does not specifically support the development of curriculum. Scientists and educators should also attempt to exploit collaborative opportunities in funding programs, many of which require an education outreach component.

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