Teaching the questions: An approach to undergraduate biology

If doing science is fun, why should teaching and learning science be drudgery?

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Abstract: Could science be taught better if we emphasized open questions and uncertain generalizations? Perhaps we should be teaching the UNKNOWN. What are the primary open questions, the burning controversies? What are the internal contradictions? What generalizations underlie the wealth of available information?

Science is learned by experimenters who were attracted to their field because of the fun of problem solving and detective work. By experimentation they can eliminate some ideas and come closer to the truth, without ever achieving absolute fact. Thus the process of science and perhaps it's greatest allure lies in its uncertainty and in attempts to narrow the gap by experimentation. Despite this inherent lack of certainty, science is traditionally taught by requiring students to memorize facts. This approach repels scientists from teaching and loads students with material that is hard to memorize, easy to forget and subject to change without notice. Why not emphasize the questions and show students that real science is a continuous series of puzzles that they can help solve. The framework of open questions is a basis for organizing new information.

The unique quality of scientists is not the body of fact that they know. It is widely assumed that scientists are remarkable because they know lots of facts. In hope of producing new scientists, we give our students facts to memorize. This is a joyless boring process that repels the best students and drives scientists away from teaching. The strongest (or least creative) survive.

Scientists are unique in their ability to visualize open questions and find experimental ways to test new ideas. The more secure the information becomes, the less interesting it is. Scientists do retain a lot of factual information and have a remarkable ability to remember details, but they don't attain that information by rote memorization. They acquire and maintain the information by using it continuously.

Scientists remember information by using a "framework or tree of questions" Scientists are not unique because the have better brains -- student brains are fine. Rather scientists differ by having a distinct way of thinking. They maintain an internal world-view which they use to make sense of their surroundings. I characterize this world-view as a "framework of questions" or a "tree of ideas", which records known things and experimental evidence and supplies homemade theory to fill in the gaps. Each new information bit is measured against this framework. Does it fit? Are there reasons to doubt it? Does it contradict the structure? Does it require that the internal framework be remodeled? The size, breadth and quality of these frameworks vary from one scientist to the next. Some are very broad, extending to physics, biology, history, music. Some are more narrowly focused and deal with a single discipline. This framework or tree allows scientists (or intellectuals of any kind) to think continuously about the problems they study. (It's why we get reputations as "absent-minded professors" who walk in front of buses.)

Scientists did not learn their facts by memorization. Scientists do retain vast amounts of factual information that they accumulated slowly and added to this framework over the course of their life. This information is remembered because it occupies key positions in their world-view. Even arcane minutiae are subject to instant recall if they are key support for some fondly held theory or nascent principle. Information is retained because it is useful today ---- it helps us answer open questions and fill in gaps in our world-view. These vast repositories were not accumulated by rote memorization in the hope that the info might become useful at some later time. However we expect students to memorize and remember facts without the structures that help others acquire and retain information. We hope they'll remember and have the information on tap as background for their next course, but often they don't.

Some students with lovely brains have never met anyone with a framework of questions, but they might develop a framework of their own if they saw one in action. It is our contention that the habits of mind that characterize an intellectual can be taught. Doing this requires a teacher that is in possession of a "framework of questions". If a student receives information arrayed according the instructor's general worldview or framework --- perhaps they can see that emulate that structure and establish a tree of their own that takes root, grows and evolves. The point is not that they should accept a less-than-certain view of the world, but that they initiate a framework of their own that can expand during their own education and later life. By seeing a teacher who tries to fit everything together (however imperfectly) they can at least have a role model for how important it is to integrate their own learning. The special role of a research university is to bring students together with practicing researchers who can serve as these role models. The point is to NOT to feed students a set of facts (they can get this from the text or Google), but rather to show students a set of instructors whose minds have become adept at framing, examining and answering questions. We are confident that an intellectual mindset can be taught.

Some examples - Undergraduates that start a laboratory project of their own early in the course of their academic careers are given (in the form of their project) a sort of intellectual framework to use in testing new ideas obtained in their course work. Every math, chemistry, evolution course they take throws up ideas that they can consider in the light of their own project. Might this mathematical technique be used to model their work? Does this chemistry suggest a new approach to their problem? How might selection have contributed to evolution of the mechanism they're analyzing? If entry-level lecture courses provided questions and puzzles worthy of pondering, perhaps they could serve as frameworks for acquiring information.

The problems with teaching questions: This approach puts demands on the instructor. Teaching the questions requires a developed framework that works. It also requires that that the teacher be brave enough to reveal aspects of their world-view that are uncertain. The uncertainties can be clearly labeled as such, but the framework provides a way for student to see how a body of irregular facts can be fit together.

It is much easier for an instructor to take a textbook and recite its contents to a captive student audience. Teaching the questions requires instructors who know their disciple so thoroughly that they can identify the logical beams and timbers that hold the edifice together and can present those (and the uncertain aspects of the inherent structure) in a logical way with the essential underlying evidence. It's easier to sink in a morass of secondary memorizable detail much of which is not essential, especially when the details are new. Teaching the questions requires knowing the weaknesses of the structure, what controversies that are raging, what principles are subject to revision. What evidence supports one view, what evidence supports the opposite view. This is a difficult task for instructors that are not engaged in the practice of science. Textbooks are constrained by market forces to be conservative and avoid controversies – they don't like speculation. The practical problem of this approach is finding scientists that are willing to give it a try. They have to be pretty arrogant (no problem there) and simultaneously be willing to expose their possible weaknesses (a rarer commodity).

The benefits of this approach: For students this can give a more accurate view of what fun science is. It can explain the problems and open areas of research. Teaching the facts gives the impression that everything is known and constitutes a daunting body of knowledge. In fact, even in the most mundane area of science, two or three "why" questions get you into uncharted territory. The simplest text-book fact – if discussed by the world experts – is likely to generate a lively argument. From a teacher's point of view, the effort expended in teaching the questions is rewarding. It's not just a do-good effort of pulling the university wagon. The process of teaching the unknown, makes you examine your own discipline and stimulates your own scientific thinking. It serves as a conduit to colleagues in related disciplines, who can help you sort out the key questions and essential principles. It's more interesting and exciting to teach material that you've just organized and is pushing you beyond your comfort zone. The intellectual challenges of teaching this way might help us coax our more distinguished researchers into teaching "elementary" courses. By doing this, they are being called upon to define their subject and present their personal view of it. To teach in this way, we need the most experienced heads with the most elaborate "mental trees".

How this is being tried in biology at UC Davis In introducing entering biology students to the chemical, genetic, cellular aspects of life, we've developed a course (Bis2A) that is organized around the "mother of all biological questions" ---- How did life arise on earth? This is a question with few secure established facts. Despite the uncertainties, it is serious science -- theories can be advanced and can be tested (falsified) experimentally in the lab. Our views of life's origin have changed considerably. This discipline developed initially from geochemistry, but is increasingly including experimental chemistry, current metabolism and genetic sequence analysis. There is a growing area of biology directed at creating life in the laboratory, based on our current understanding of biological cell functions. It seems likely that within the lifetime of our current students, we will hear credible claims that life has been created de novo in the lab.

While the course is organized around origins of life, it actually presents the basic properties of living things and how each individual property might have arisen. What is the essence of metabolism and how did it arise? Why are catalysts so critical? How could inheritance have started? Was there metabolism before inheritance? Was there genetic recombination before there was life? Why is cellularity critical? Why isn't everything multi-cellular? Why is anything multi-cellular? What was the situation just <u>before</u> life arose? Could selection have operated before life? These questions seem imponderable, but they focus attention on the basics, which is the material we're hoping to convey. If such questions can be conveyed and instilled with the information, perhaps that framework will persist and help students organize more detailed material in their own ways.