Inquiry Textbooks for the Sciences

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Introduction

Not long ago I encountered an undergraduate who was finding his study of science to be deeply unsatisfying. He was continually oppressed by the feeling that his only role was to "shut up and learn." He felt there was nothing he could say to his instructors that they would find interesting. Nor did he feel that there was anything he could tell his fellow-students that they would find interesting. As he sat in the science lecture hall, he was utterly silent. That's not a good state to be in when you're 19 years old.

Doubly galling was the fact that at the same time his roommate was taking a far more student-active history course. One day the roommate had come back to their dorm room filled with excitement over a class discussion on whether we were right to have dropped the Bomb on Hiroshima. Another friend at the time was taking a literature course, and had recently made a point the instructor herself had found striking.

Meanwhile, my student was busy with Ampere's Law. He never had any fascinating class discussions about this law. No one, teacher or student, ever asked him what he thought about it. More than that: he never asked himself what he thought about it.

Will this student keep on in science? Many do not. In a ground-breaking study sociologists interviewed a number of students who, after beginning their undergraduate careers with a science major, eventually switched into other fields. The study was seeking to determine what had lead these students to abandon their first love. What it found[1] makes for disturbing reading:

> "My literature professor's fantastic. They should ask her to teach the science professors how to teach. For the first time, I had a professor who asks your ideas – not just what you've read. And she respects your ideas and your thought processes."
>
> "I liked science, I really did. But in the liberal arts, you would bring more of yourself into the class. . . . My parents didn't go to college and it was the first time I had really had an intellectual discussion about

> issues with someone. And it opened this entirely new world to me that I just fell in love with.”
>
> “If you’re one of 30 in a history seminar, and you’re exchanging ideas and people are asking each other about their thoughts and opinions, it’s a warm exchange of ideas. That’s one thing. But if you’re one of two women in a thirty-person math lecture, where you sit there listening to what the professor has to say, hardly ask any questions, go home, open the book and do the problem sets on your own, it’s very different.”

The distinguished physicist and educator Carl Wieman has written[2]:

> “A study by Rena Subotnik and colleagues that tracked high-school Westinghouse (now Intel) talent search winners, an extraordinarily elite group already deeply immersed in science, found that a substantial fraction, including nearly half of the women, had switched out of science within a few years, largely because of their experiences in the formal education system. It is not that such enrichment experiences are bad, just that they are inherently limited in their effectiveness. Programs that introduce these motivational elements as an integral part of every aspect of the STEM learning process, particularly in formal schooling, would probably be more effective.”

Wieman additionally emphasizes:

> “Another shortcoming of teaching at all levels is the strong tendency to teach ‘anti-creativity.’ Students are taught and tested on solving well-defined artificial problems posed by the teacher, where the goal is to use the specific procedure the teacher intended to produce the intended answer. This requires essentially the opposite cognitive process from STEM creativity, which is primarily recognizing the relevance of previously unappreciated relationships or information to solve a problem in a novel way.
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> “At the undergraduate level, STEM teachers generally have a high degree of subject expertise. Unfortunately, this is not reflected in the cognitive activities of the students in the classroom, which again consist largely of listening, with very little cognitive processing needed or possible. Students do homework and exam problems that primarily involve practicing solution procedures, albeit complex and/or mathematically sophisticated ones. However, the assigned problems almost never explicitly require the sorts of cognitive tasks that are the critical components of expertise…”

We are all familiar with the sort of assignments we give our students in the sciences. As an alternative, consider the following assignment from a textbook of philosophy:

> "These are strange times, what with *The National Enquirer* regularly featuring stories about people who say they have been kidnapped by aliens, and actress Shirley MacLaine reporting that in a previous life she was stomped to death by a white elephant. On the other hand, in recent decades we have also seen live television transmissions from the moon and electron microscope photographs of individual atoms. *How* can people tell the difference between truth and fiction? Are the people crazy who refused to believe their own eyes and said that the pictures of men on the moon were faked?[3]"

This is not the sort of assignment we traditionally offer! But why not?

I am concerned that, in focusing exclusively on our traditional view of science education we are doing our students a disservice. More than that: we are driving many young people out of the field.

I am not arguing that we should abandon our traditional assignments. Discursive information in textbook and lectures, combined with regular problem sets, are how we most efficiently present material and force our students to pay attention to it. But in concentrating exclusively on such a pedagogical strategy, we are constricting our students' educational experiences. I would argue that both our science majors and our non-science majors would benefit greatly from textbooks explicitly designed with an inquiry approach in mind.

Of course these texts cannot present material which would seriously challenge our students at a highly technical level. But does this mean that we must never ask them to think for themselves? Even our least prepared non-science majors are not stupid: they're just not very good at math and science. The student stumped by what strikes us as an easy problem is perfectly capable of analyzing with brilliance a difficult passage from Shakespeare. Isn't it possible to find material which our students, majors and non-majors alike, will find challenging and interesting, and worthy of mature attention?

Examples of Inquiry Instruction

Perhaps it will be helpful to look at non-scientific disciplines to see how they succeed in challenging their students. In what follows, focus attention not on the subject matter under discussion, but in the manner in which it is being discussed – on the pedagogical techniques the instructional materials employ. They might point to an improvement in the way we write our science textbooks.

A textbook in political science[4] explains in its preface that the book is --

> "designed to force students to join issue and take sides on some of the most profound controversies of our times… [Students] should come to understand history as more than a story to be appreciated for its own sake. They should see it as a weapon of analysis and persuasion that can be used, and is now being used, for both good and evil ends. So armed, students might even come in time to improve the intellectual and moral quality of American political debate."

The book is enlisting the student in a difficult but all-important task – and, in so doing, treating the student as a mature adult capable of participating in the life of the nation.

From a textbook of philosophy[5] --

> "Is there such a thing as an *African-American philosophy*? What would such a philosophy be? . . . . . I should like, rather tentatively, to suggest that a true African-American philosophy must be a literature devoted to an exploration of the philosophical implications of the African-American experience. That exploration, I believe, must focus on . . . . ."

Note well here the words "tentatively" and "believe." The student is being treated to the rare sight of a textbook writer grappling with a question he himself finds difficult, and to which he has only a partial answer.

Students are asked not just to read about, but actively participate in, daunting and difficult debates:

From an undergraduate course in Legal Studies[6] --

> "In <u>Korematsu v. U.S.</u>, the Supreme Court found constitutional, over vigorous dissents, the exclusion orders issued by the U.S. military against Japanese-American citizens and all persons of Japanese extraction living on the West Coast of the U.S. immediately after the Japanese attack on Pearl Harbor in 1941. By implication, this court decision found the entire internment program (curfew, exclusion, and relocation) constitutionally valid, even though the internment orders used the criterion of race to deprive Japanese-Americans of their property and liberty without granting them due process hearings about their individual loyalty. It was not until 1983 that a U.S. Congressional Commission found that the Internment had not been a military necessity, and it was not until 1988 that a law was passed providing an apology and the payment of reparations to the survivors.

> The Korematsu case dealt with the proper power of government in protecting national security and with the importance of individual freedoms in time of crisis.
>
> 1) **Explain** carefully the Court's strongest reasons (the main elements of the Court's *majority opinion*) for reaching its decision. **Also analyze** one strength and one weakness in one of the *dissenting* opinions.
>
> 2) **Using** course materials concerning the Internment, **briefly discuss** one general lesson about law and society that could be drawn from the case. **Explain how** that lesson **might be applied** to the conflict between national security and individual rights in the U. S. today, as referred to by the claims made by some that since 9/11 the U.S. has been engaged in illegal domestic spying, torture, and undermining due process and the rule of law for those labeled "enemy combatants." … Please do not spend time discussing anything else about how the "war on terrorism" should be conducted or about your opinion of that war or of loyalty and patriotism *in general*."

From an undergraduate course in history[7] --

> "Why did the US go to war in Vietnam and why did it lose?
>
> **"N. B.** Your answers to these questions will probably not be categorical or conclusive. You should come to a position on each, but this is not a "debate" in the stylized sense of a debate tournament. The point is not to win but to *clarify* an argument."

Each of these assignments is very open-ended. There can be nothing cut-and-dried about the student's response: it must be detailed, and it must involve a good deal of independent thought. Each assignment asks the student to back away from his personal opinions and emotional response, and approach the issues dispassionately and analytically. And finally, each question asks the student to do all this using tools she has gleaned from the course.

Such questions provide the instructor with evidence that the student has or has not learned the course material. But they also do a lot more. They treat the student as an independent thinker, capable of grappling responsibly with complex and difficult issues. They engage the student's full intelligence. They give the student a sense of self-worth.

The Inquiry Science Textbook: Examples

Such an approach has also been employed in the sciences, albeit rarely. Following are two examples.

(1) From an introductory genetics textbook:[8]

> "The basic problem of cellular self-reproduction can now be restated…….How is that particular sequence of the twenty protein amino acids assembled that makes up the primary structure of any given one of the one to two thousand different enzyme molecules? …… When we try to imagine how, at each step of the assembly process of a particular polypeptide chain, one and only one kind of amino acid is to be selected from the twenty kinds available for insertion into the chain, we encounter a difficulty.
>
> "THE ENZYME-CANNOT-MAKE-ENZYME PARADOX
>
> "If we were to imagine that the ordered amino acid assembly is the work of yet another 'ordering enzyme,' then we are obliged to postulate that to each particular protein of given primary structure there corresponds a specific 'ordering enzyme' that 'knows' how to assemble that particular protein. But if that 'ordering enzyme' also turns out to be a protein of specific amino acid sequence, it becomes apparent that, instead of providing an answer, we have merely generated a paradox. Obviously the postulated 'ordering enzyme' would require postulation of yet another 'ordering enzyme' for its own formation, which, in turn, would require postulation of a third 'ordering enzyme,' and so on *ad infinitum*……
>
> "The enzyme-cannot-make-enzyme paradox thus leads to the insight that cells owe their character to the possession of self-reproducing informational elements that govern enzyme synthesis…."

This can be regarded as a historical narrative – but more significantly, it is also a logical argument. The reader is asked to follow a chain of reasoning that begins with a hypothesis, but then points out a paradox which renders the hypothesis untenable, and ultimately leads to a new conclusion. Such an approach is far preferable to simply presenting the reader with a conclusion unaccompanied by the argument that points the way to it.

(2) Consider the question of tides in the ocean. A traditional textbook might begin by reminding the student of the existence of tides, and then moving on to an explanation of their cause. Imagine, however, a different approach.

After pointing out the phenomenon of tides, do not immediately present the correct theory. Instead, present a wrong theory – two of them in fact. Each is explicitly advanced not as The Answer, but as a hypothesis to be considered:

1. One hypothesis is that the Moon gravitationally attracts the oceans towards it. Oceans are "sucked upwards" as the Moon passes overhead.

2. The other hypothesis is Galileo's -- that the Earth's spin, combined with its orbital motion about the Sun, causes the velocity of a point on its surface to vary over the course of a day[9]. Oceans "slosh" as the Earth rotates.

Emphasize that skepticism is a vital component of scientific practice. It is never enough to propose a theory. The theory must be tested by comparing its predictions with observation. Move, then, to an analysis of the proposed theories. Point out that both predict one tide a day, in conflict with the observations.

Now what? There are in fact not one but two interesting objects in the sky: the Moon and the Sun. Could gravitation from these two bodies combine to yield the observed tides? Here is an opportunity to repeat, and therefore reinforce, our insistence on comparing prediction with observation as we test our hypotheses. Once again the hypotheses are found insufficient, refined, and yet again compared with observation. Ultimately we arrive at a theory to which we can find no objection.

Comments on the Inquiry Textbook

We need to present our students with such nuanced treatments of the process of science – not just occasionally, but as part and parcel of our textbooks. They should regularly exhibit instances in which a hypothesis is suggested by incomplete data, analyzed and modified; how better data is obtained and wrong hypotheses are rejected; how blind alleys are abandoned and how ultimately a final understanding is reached.

I can think of no finer education for a future scientist. With regard to textbooks aimed at non-science majors, such a strategy can serve as a useful corrective to the public misunderstanding of the field. Far too many people regard science as being nothing more than The Ultimate Big List of Facts. We need our textbooks to exhibit a more generous view. The above examples make clear that the inquiry method of instruction significantly widens the range of topics addressed. The standard textbook treatment of an issue treats of just one topic – the issue. But in our examples a number of broader subjects have emerged:

- Science involves skepticism. Hypotheses must be tested.

- A theory must make specific predictions. If it doesn't it isn't a theory, it is a "theory."

- In science, data are paramount. If a hypothesis disagrees with observation, we must reject the hypothesis no matter how much we may like it.

- Science involves creativity, and there are no rules for creativity. There is no algorithm for coming up with a good theory. The process is never cut-and-dried. It involves a good deal of trying this and trying that.

- We never know whether our hypothesis is correct. We only know that we have found no evidence that it is wrong.

And perhaps the most important point of all:

- Science involves habits of mind which you, the student, can master, and which will serve you well in whatever career you choose. And it will serve society well that its citizens have a truer grasp of the nature of scientific evidence, as debates on global warming and evolution roil.

Looking over our examples, we see that <u>the inquiry method is slow</u>. It takes a long discussion to treat a topic normally covered far more rapidly. There is only so much room in a textbook, and there is only so much time in a semester. We cannot cover everything: if we spend a lot of time on one issue, many other issues will be left out.

With regard to texts aimed at science majors this is a significant issue, and the needs of traditional instruction must temper the space requirements posed by the inquiry method. But with regard to books aimed at non-science majors is this so terrible? Why worry that our teaching is inefficient? Why do we care whether non-science students learn a few or many of the facts of our field?

At first blush, such questions sound like madness. Is it not a disservice to our students to offer them an astronomy course which never mentions, say, the Hertzsprung-Russell diagram, or a chemistry course which omits redox reactions? But it is worth asking why such a possibility makes us nervous. Are we really required to give our students a full survey of our field's most important discoveries? If that is our goal, it is worth asking why it is our goal.

Students in our courses for non-scientists are not going to become scientists themselves. So we are not training them for a future career. Nor will more than a few take a second course in the field, so we are not even preparing them for further study. Indeed, many of our introductory non-science students will never take another science course in their lives.

One reaction is to decide that this one semester is the only opportunity we have to expose our students to the beauty of our field -- and so to jam as much science as possible into those few hundred pages of the textbook, and those few short months of lectures. Another reaction is to decide that a well-rounded adult simply ought to know a certain basic body of material. For both reasons, the urge is great to steadfastly resist anything that would shorten the list of topics covered.

I myself am not immune from the urge to cover everything. But whenever I seek to define just what this "everything" should be, I find myself faced with a surfeit of riches. How could I, an Astronomer, discuss Mars but not asteroids –and, now that I mention it, planetary nebulae and the mechanism of supernovae and the nature of dark matter? What right does a physics course have to cover the conservation of energy but not the conservation of angular momentum? If a biology course has delved deeply into the genetic code, why has it not delved equally deeply into the structure of RNA – or the evolution of Homo Sapiens, or the distinction between cell walls and cell membranes, or . . . . ?

The more we go down such a road the more we find ourselves facing what feels suspiciously like an infinite regress, and the more we realize that we are dashing through each topic with a minimum of attention. Perhaps we have been trying to cover the material, when we should have been discovering it.

Perhaps there is simply no need to present all of a pre-selected body of material in our introductory courses for non-science majors. Maybe we should feel free to take as much time as we like on as small a list of topics as we like. There's no denying that it is a hard trade-off, and if we employ the inquiry method much science will have to be left unexplored. To my mind, though, it is more important that future citizens have a broader, more nuanced view of the field. A larger objective is to encourage "future citizens" to think as true future citizens – to enlarge their capacity for critical thinking, and to not take things on authority.

Inquiry Exercises

Students must be asked to do their own inquiry work. If our textbooks are inquiry-based, but their assignments are solely of the more traditional nature, students will quickly decide that we are not serious about inquiry thinking and they will behave accordingly.

Wieman writes[2] above

> "We are learning that complex expertise is a matter not of filling up an existing brain with knowledge, but of brain development. This development comes about as the result of intensive practice of the cognitive processes that define the specific expertise…"

To learn to play baseball, reading about baseball is not enough: one must play the game. We must ask our students not just to observe us as we practice inquiry thinking, but to do it themselves.

One obvious approach is to ask students to identify the predictions made by hypotheses presented but not analyzed in the text. Following are some more extensive examples:

(1) From a biology text:

> "In colorectal cancer, tumor suppressor genes are not active. This is an important factor resulting in uncontrolled cell division. Two possible explanations for the inactive genes are: a mutation in the coding region, resulting in an inactive protein, or epigenetic silencing at the promoter of the gene, resulting in reduced transcription. How would you investigate these two possibilities[10]?"

(2) From an astronomy text for non-science majors, in a discussion of the evolution of stars:

> "Visit a spot where trees are growing. List the different things you find there and the evidence you can put together about their relative place in the life cycle of trees[11]."

(3) An astronomy textbook for non-science majors[12] presents the student with a problem to which there is no "right answer:"

> "Consider two possible ways to support planetary research
>
> - "Fund a low-cost robotic mission to Mars
> - "Use the same amount of money to support the development of ground-based active-optics telescopes
>
> "You are an officer in the National Science Foundation. You have sufficient funds to cover one but not both of these proposals. Write a memo in which you present
>
> - "The arguments for and against each option
> - "Your decision of which to fund
> - "The reasons for your choice
>
> "Be prepared to defend your decision before a hostile congressional subcommittee."

L'Envoi

All our students, future scientists and non-scientists alike, would benefit immeasurably from a broader view of science. Efficient though they may be at conveying information, our textbooks present a far too limited view. They should explicitly model the process of discovery that is so important a part of our field. Soren Kierkegaard once said "It is not at all true that the scientist goes after truth. It goes after him.[13]" The urge to solve problems appears to be universal: witness the pleasure so many of us take in solving puzzles, or in following along in a mystery as the detective cracks the case. Enlisting this love can be a marvelous instructional technique, and one which should inform the way we write our textbooks.

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[1] E. Seymour, N. M. Hewitt, *Talking About Leaving: Why Undergraduates Leave the Sciences*, Westview Press, Boulder CO, 1997.

[2] C. Wieman, *Issues In Science and Technology*, pgs 1-7 (Fall 2001).

[3] R. P. Wolff, *About Philosophy (8th edition)*, Prentice Hall, Upper Saddle River, NJ 2000 pg 85.

[4] C. H. Pyle, R. M. Pious, *The President, Congress and the Constitution,* The Free Press, New York NY, 1984.

[5] R. P. Wolff, *About Philosophy (8th edition)*, Prentice Hall, Upper Saddle River, NJ 2000 pg 36.

[6] Legal Studies 250, taught by Professor Steve Arons at the University of Massachusetts in the Fall of 2009.

[7] History 155, taught by Professor Frank Couvares at Amherst College in the Spring of 2012.

[8] G. S. Stent, R. Calendar, *Molecular Genetics, an Introductory Narrative (2nd ed*), W. H. Freeman, San Francisco, CA, 1978 pg 129-130.

[9] The Earth spins in the same sense that it orbits the Sun. Consider a point on the Earth's surface from which the Sun is directly overhead – i.e. at which it is noon. At this point the rotational velocity subtracts from the orbital velocity. Twelve hours later, however, the two velocities add.

[10] D. Sadava, D. M. Hillis, H. C. Heller, M. R. Berenbaum, *Life: the Science of Biology, (9th ed)*, Sinauer Associates, Sunderland, MA, 2011.

[11] S. Schneider, T. T. Arny, *Pathways to Astronomy*, McGraw Hill, New York NY 2007, Pg 488.

[12] G. Greenstein, *Understanding the Universe: An Inquiry Approach to Astronomy and the Nature of Scientific Research*, Cambridge University Press, Cambridge UK 2013.

[13] Attributed to Soren Kierkegaard by Francis Wilkins. I have been unable to find the source of this quote.

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