The Attributes of a General Education in the Sciences

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Thank you for the kind introductory remarks and especially for the honor of being able to speak to you tonight. Before I begin the substance of my talk, I want to preface my remarks by pointing out that I actually have some prior history with Union College, having applied for admittance in my senior year of high school. Of all the schools I applied to, Union was the only one that didn't accept me. But I do know exactly where my application went wrong. As part of the process, I had to participate in an interview with an alumnus of the college who lived in my area. After exchanging pleasantries and taking care of background types of questions, he proceeded to ask me:

"So how would you solve the problems of the world?"

My first response was a question: "Do you mean all the problems of the world?"

To which he replied "Yes."

My next response, and remember I was a 17-year old at the time, was that I thought it was a stupid question. My answer didn't seem to sit too well with him and things deteriorated from there. Needless to say, when the rejection letter arrived, I was not surprised.

It was undoubtably flippant and disrespectful of me to be so blunt in my response to this well-meaning individual. Tonight I will try to avoid flippancy and disrespect, but I think I will still be pointed with some of my comments. And tonight, rather than solving all of the problems of the world, I've been asked to provide some comments on what I think it means to provide a general education in the sciences.

Let me start by identifying one thing that I hear lots of scientists say that often makes me feel uncomfortable. It's the statement that we need general education science requirements because we would like all of our students to be "scientifically literate". Now don't get me wrong, because I think "scientific literacy" is a worthwhile goal. But when you pursue this topic further, and ask why our students need to be "scientifically literate", I hear scientists often say things like "we live in an increasingly technological world and people need to understand aspects of how this technology works" or "that people will face issues in their community, jobs, etc., that involve science, and they need to know enough to ask the right questions, evaluate the answers, and provide input into making informed decisions."

Picking up on this latter point, as a concerned citizen I've participated in lots of public forums related to issues that involve science. What I see that usually happens, if for example someone wants to site a shopping mall and fill in a wetland area, is that scientific “experts” are brought in, and these individuals are usually dismissive of the comments and questions of the public because, after all, the public really isn’t as expert as the scientific expert. So I think we need to insure that future scientists are educated about being more receptive to input from the public.

And regarding the former point, is it really important that we know how all this technology works? For example, I’m curious how many of you actually know the underlying mechanism that accounts for the ability of a microwave oven to heat things.

I like to do the crossword puzzle in my local paper. Since the same person always creates these crosswords, over time you notice some of the same clues coming up. One that appears about every couple of months is: “cook food in microwave.” The answer is four letters long. Does anybody here know the answer? Well, it’s N-U-K-E, NUKE. So is this correct? Is a microwave oven a little nuclear reactor, or perhaps a little bitty nuclear bomb that is heating our food? Well, it actually turns out that there is no nuclear process related in any way to nuclear reactivity that occurs with the heating of food in a microwave oven.

At this point I’d like to do a little activity. Since you all just ate and are probably feeling a bit sleepy, and because my talk is likely to contribute toward your sleepiness, I’d like you all to stand up for me. Now that you’re up, you will need to extend your arms slightly out from and away from the sides of your body, but rather than fully extending them out, still have them pointing down toward the floor like me. Also, clench each of your hands into a fist.

One important molecule is water, and I suspect that all of you probably know that water is H_2O. It also turns out that the three atoms of the water molecule are not in a straight line, but are in a bent alignment. If we then imagine that your head is the oxygen atom of water, and your two fists represent the two hydrogen atoms of water, you now represent a model for what turns out to be the bent structure of the water molecule.

Now, I want each of you to move your fists in and out at the same time by bending your arms at the elbow. This movement of your fists in and out relative to the oxygen atom of water is called a vibration. This particular vibration, since both hydrogen atoms move in and out at the same time, is called a symmetrical vibration. Water molecules can also undergo an asymmetric vibration, which involves one hydrogen atom moving in toward the oxygen atom while the other moves out away from the oxygen atom. Let’s try the asymmetric vibration. Finally, there is a bending vibration for water that involves moving the two hydrogen atoms symmetrically in closer to the sides of your body and then further away. At any time, different water molecules are undergoing these different vibrations.

But guess what, these three vibrational processes have nothing to do with how a microwave oven works. These vibrations are important if we were to try to understand the molecular basis of global warming, but that’s not what we’re talking about tonight, we’re talking about how a microwave oven works.

Well there's something else the water molecule can do. It turns out that it can rotate about an axis through the oxygen atom. So would you all join me by spinning around in a circle, making sure not to strike your neighbors with your fists. Water molecules naturally undergo this rotation. And microwave radiation is of just the right energy to cause the water molecules to rotate faster. But the water molecules don't really want to rotate faster because that means they have extra energy. So they crash into neighboring molecules in the food like proteins, fats, and carbohydrates and give off this extra rotational energy to these other molecules in a form of energy known as heat. But once they slow down, more microwaves come in so the water molecule gets excited again to a faster rotational state, the process continues, and the food heats.

Okay, you can all sit down now that you've had some exercise and are hopefully more awake for the rest of my talk.

Now, are you better off knowing how a microwave oven works? Perhaps, but I'm not sure that I've made you all that much more "scientifically literate." Now this is not to say that I don't think microwave ovens are interesting. This is not to say that I don't tell my students in general chemistry how a microwave oven works. But it is to say that general education in science has to be more than just learning scientific "facts" about how the world works.

What I've really given you with a description of how a microwave oven works is something I like to call an RBCT. An RBCT is a Random Bit of Chemical Trivia. And I suspect that anyone here who has taken an introductory level chemistry course but is not a chemist feels quite familiar with the concept of RBCTs. And if you've taken organic chemistry, well …

Of course, the problem with this approach to scientific literacy is that learning how a microwave oven works, or learning the accepted "facts" within certain areas of science, is an attempt to define some fundamental science content that we think all people ought to know. And what we will inevitably find is that there will never be a way to get all scientists to agree on what that essential content ought to be.

But I do not refute the idea that there is such a thing as "scientific literacy", and that one facet of a college education ought to have every student come away more "scientifically literate". What I do think is that many scientists focus their efforts in the wrong direction as they try to define what it means to be a "scientifically literate" individual.

For me, after spending about ten years designing courses based on what it was I wanted to cover, I had this epiphany when I realized what really mattered was what the students learned. Now maybe it was obvious to everyone but me that teaching is actually about student learning. But if so, how come so many of us talk about what topics we want to COVER in our courses? If anything, it seems to me that we ought to at least talk about the topics we want to UNCOVER in our courses. We design syllabi based on content, listing the topics and the order we intend to cover them in. When it finally hit me that what really mattered was student learning, it led to some profound questions.

The first was: What did I really want my students to learn through their education?

This is a question I will return to, because it's at the heart of my talk tonight, but at this point it is probably helpful to mention a remark that really resonated with me when I first heard it. I don't know the originator of this remark, since a brief search of internet sites attributed different versions of it to Ben Franklin, Albert Einstein, and Oscar Wilde, so I will attribute it to Anonymous. But it goes something to the effect that:

"Education is what's left over after you've forgotten everything that you learned."

To me this quote implies that we learn lots of content in our studies, but education involves the development of a set of skills that go beyond content. And so I began to ponder whether my courses should have learning goals much broader than what I was trying to accomplish.

Another question I had was: How could my students better learn the things I wanted them to learn? And I began to ponder whether there were teaching methods more effective than what I was using at the time?

And still another was: What is the essence of science? What are the important experiences that a student needs to have after either a general introduction to or a major in a scientific discipline?

So what do I see as the essence of science? As I thought about this, I came up with two things.

The first is that science involves the process of investigation of an original question, with the hope of discovering new knowledge. Now perhaps it is reasonable to argue that all disciplines involve a search for new insights. If so, then maybe a lot of my comments tonight apply to all disciplines and to all facets of an undergraduate education. In fact, the thought that our disciplines involve a process of discovering new insights IS why I have spent many years working with the Council on Undergraduate Research to promote the idea that all undergraduate students ought to participate in an original scholarly project.

Just recently I came across the following quote from James Conant Bryant in his work *On Understanding Science* published in 1946. In it he asks the question: "When does a scientist become a scientist? His answer:

"It is not when a person knows many facts and even understands in depth some aspect of the natural world. I would suggest the transition occurs when curiosity about a phenomenon leads to an inquiry for new knowledge. This can occur in a person with little or lots of knowledge about a subject. It is an attitude of inquiry."

The second essential element of science is that scientific conclusions are always accompanied by some level of uncertainty, and that the degree of uncertainty varies depending on the question that is being investigated. For example, consider studies into the phenomenon of global warming and its potential climactic impacts. Predictions of future temperature and climate have to be done using models that rely on available, known data. These models and predictions are inherently characterized by uncertainty. What interests me is that all of the existing models predict warming with accompanying events like sea level rise and climate change. What differs among the models is the extent of warming and the exact nature of the changes that will occur. Scientists involved in this work are not arguing about whether warming and climate change will occur, but instead about how much and how severe. Waiting for universal agreement among scientists on how much and how severe before taking actions will be a wait into eternity, because these predictions will always have associated uncertainties.

I would hope that everyone, and especially the scientists, here tonight would agree that investigation and uncertainty are fundamental to the nature of science. And it’s my position that only those science courses that include a rich component of investigation and uncertainty ought to count toward a general education science requirement. Although, I will welcome in the comments afterward additional suggestions for other items to add to my list of two, since one thing I am CERTAIN about is that I don’t have all the answers on this topic.

What I find interesting, or perhaps disturbing, or perhaps confusing then, is the way in which we scientists have chosen to structure most of our courses. If anything, it seems to me, and this is especially so at the introductory level, that we teach our courses as if everything is known. The textbook presents to the students a body of material as if it were all factual and unequivocally true. Our exams tend to test factual material. The textbook that accompanies a general chemistry course rarely if ever includes any component of investigation. Our laboratory assignments tend to augment the content of the class, so students often undertake laboratory experiments in which the answer is known ahead of time and we expect them to reproduce that answer.

Besides investigation and uncertainty, I believe that scientists also need to consider whether there are other goals of a general education that can be better incorporated into our courses. In considering what these goals might be, I would like to examine a series of learning outcomes described in a 2001 publication on assessment by Peter Ewell. These outcomes resonate with me because I think they speak broadly to the idea of what it means to be “generally educated”. He groups these into four categories, and as I read through them, I want you to think about whether these outcomes are or are not incorporated into what we might consider a “traditional” science course.

The first are “knowledge outcomes”. These are “particular areas of disciplinary or professional content that students can recall, relate, and appropriately deploy.” I think we would agree that most “traditional” science courses include “knowledge outcomes”.

The second are “skills outcomes”. These involve “the learned capacity to do something – for example, think critically, communicate effectively, productively collaborate, or perform particular technical procedures – as either an end in itself or as a prerequisite for further development.” Other then “performing particular technical procedures”, I would argue that traditional science courses do not really teach students to think critically, communicate effectively, or productively collaborate.

The third are “affective outcomes”. These “usually involve changes in beliefs or in the development of particular values, for example, empathy, ethical behavior, self-respect, or respect for others.” I do not think traditional science courses address these.

And the fourth are “learned abilities.” These “typically involve the integration of knowledge, skills, and attitudes in complex ways that require multiple elements of learning. Examples embrace leadership, teamwork, effective problem-solving, and reflective practice.” Again, I don’t think traditional science courses address these learning outcomes.

Yet, I think science courses have the potential to include all of these learning outcomes. What I have tried, then, is to broaden the learning goals for my courses, not only by incorporating elements of investigation and uncertainty into them, but by incorporating these other learning outcomes as well. I first started this process in my upper-level courses.

My area of specialty is analytical chemistry. I examine the processes and techniques that are used to identify and quantify the chemicals in samples from the environment, living systems, water, food, etc. Now my guess is that every one of you can think of some particular analysis that interests you. This may involve the level of cholesterol in your blood; the quality of your drinking water; the fat content of the meal we ate tonight; whether or not a beverage has caffeine; did Barry Bonds really take steroids? The list goes on and on. At some level, everyone is intrigued with analytical chemistry. When it comes to designing an analytical chemistry course, it would seem that the possibilities are endless. But in many analytical labs, it turns out that students seldom analyze interesting things, seldom conduct investigations, and seldom solve real problems. Instead many instructors give them “canned” unknowns in which the amount of the constituents are known to the instructor. The students individually undertake a rigorously prescribed, step-by-step analysis procedure provided in a lab manual, and are graded on how close their answer comes to the known value. The learning outcomes realized through this approach only represent a modest few from those I described earlier. So many potential learning outcomes are sacrificed or ignored. So much of the real nature of analytical chemistry is omitted.

I used such a traditional approach for about ten years until I finally thought about what was really important for students to learn, and decided instead to give my students ambitious, semester-long, small-group projects. Examples include the analysis of benzene and toluene in air from car exhaust; trihalomethanes in drinking water; the amino acid content of foods such as popcorn and beer (two staples of a college student’s diet); caffeine, theophylline, and theobromine in chocolate; nitrate and nitrite in hot dogs; cancer-causing polycyclic aromatic hydrocarbons in hamburgers, oysters, diesel exhaust and wood smoke; and toxic metals in sludges from the local wastewater treatment plant. I believe these projects develop a much broader skill set and provide students with a much better understanding of the true nature of science. In executing these projects, students encounter problems with answers that are either not obvious or not known. They gain experience working as part of a team, have the chance to develop self-respect and respect for others, and they develop oral and written communication skills. They have opportunities to exhibit leadership. Many of these same skills are further developed through the collaborative group learning I use in the classroom, although I don’t have time tonight to describe the details of my use of cooperative learning.

But I realized that this learning opportunity at the advanced level only affected a relatively small number of students. What I really needed to do, if I wanted to reach the most important audience, was to incorporate similar methods at the introductory level. Of course, one problem involved the size of the different courses. Now admittedly, I don’t face the issue that confronts people at the larger research universities, where introductory courses may have hundreds of students, but adopting the methods that worked for me in a 15-person advanced-level course to a 60-person introductory-level course seemed daunting. But I was determined to do so and have found a way to make it work. I do incorporate a substantial amount of cooperative learning in the classroom portion of the course (I’d say about 50% of the time) and the students undertake a semester-long project in the lab.

What I also did was broaden the goals for my introductory course. In my introductory chemistry course I now develop fundamental concepts of chemistry around a theme. For me, the theme relates to the study of the environment – which works for me because I have a lot of experience and interest with environmental topics. But I think there are many possible themes about which one could design an introductory course with goals similar to mine. I want to emphasize that this course is a thematic version of our majors’ general chemistry sequence, since we do not offer a non-majors sequence. The course fulfills the general chemistry prerequisite requirement for all upper-level chemistry courses. Yet, the course is also designed to be quite suitable for students who are not majoring in the sciences, and many of them take it and do well in it.

The theme is useful for several purposes. One is to provide some obvious relevance to the material so that the chemical concepts are developed in context. The other is that it allows me to more readily develop additional skills and realizations about the nature of chemistry and science. I have five major goals that I specify in the syllabus.

The first goal is to learn fundamental concepts of chemistry. It is a basic chemistry course and must prepare students for upper-level offerings. And besides, I don’t know how you would teach a chemistry course that at some level is not rooted in content. You cannot carry out an investigation without developing some level of background content. Sure, most of the content will likely be forgotten somewhere down the road, but I think the broader skills will better stand the test of time. So if there is a particular set of material that you think absolutely belongs in a general chemistry course, it is possible to include it through the investigations and examples you have the students look into.

The second goal is to learn that science does not know all the answers. I think most introductory courses create the impression that science knows all the answers because they focus on accepted "facts." Demonstrating that science doesn't know all the answers is rather straight forward through discussions of environmental topics, but I also try to show the uncertainty in some of the chemical concepts we discuss as well, even though the text may present them as facts. For example, the concept of electrons residing in discreet orbitals is something that we cannot see, that we must accept on a bit of faith, and, who knows, some day someone may prove it wrong.

The third goal is to participate in and learn about the process through which scientists undertake investigations and create knowledge. This is mostly accomplished through the lab, but we also look at the historical development of some of the topics as well to see how one person's insights fueled later discoveries by others. For example, we explore the historical development of our current understanding of the structure of the atom, and examine how unsettling the notion of quantum mechanics and discreet energy states was in explaining what we believe to be the structure of atoms. We also look at the historical events that led to the discovery of depletion of the ozone layer by chlorofluorocarbons, a story replete with opportunity, serendipity, disagreement, uncertainty, great science, and bad science. And we read material about women in nuclear chemistry as a way of examining the experience of women in chemistry in the first half of the 20th century.

The fourth goal is to learn in interaction with, rather than isolation from, other students. Both the class and lab are done as cooperative, group activities. In fact, I actively encourage and create ways for my students to cooperate with each other both in and out of class. After all, the goal is student learning and student cooperation increases the amount of instructional resources available to them, and the breadth of learning outcomes that can be achieved in the course.

The fifth goal is to appreciate that science occurs in a social context. This is easy to show by connecting the course to environmental topics. We can examine how the questions we ask, the priorities we set, the research we fund, depends on what some segment of society defines as important. In addition to trying to promote "scientific literacy" among all my students, I also want students who will go into a science field to appreciate the importance of being involved in policy-making decisions.

But the lab really constitutes the most important part of my introductory course. In the lab, I present the students with two questions to explore.

The first is whether plants grown in soil contaminated with lead take up more lead than plants grown in uncontaminated soil. The students start with the expectation that plants grown in contaminated soil will probably have higher levels of lead.

The second is whether the lead uptake by plants varies with the acidity of the rain water. In other words, does acid rain influence lead uptake? Laboratory studies show that lead salts become more soluble in more acidic solutions. So long as the increased acidity doesn't affect the plant's mechanism for taking up lead, having more lead dissolved in the water might be expected to increase the level of lead in the plants.

Given these two questions, the students need to decide how to conduct the investigation. Among other things they need to decide what plants to grow, what soil to grow them in, how to mimic acid rain, how much lead to add to contaminate the soil, what watering schedule to follow, and what to use as a control.

As far as what plants to grow, I provide them with the two pages of seeds that can be purchased from a supply firm known as Connecticut Biological. After each group of four has made their choice (and these range from beans to tomatoes to marigolds to lettuce), I ask them to consider what they might be likely to grow if we lived in a Southeast Asian country. Invariably, they answer "rice", but see that rice isn't an option with Connecticut Biological. At a small level, the sense that our social context can influence a scientific study becomes apparent.

In carrying out the project, they need to make up everything themselves. Once the plants are up and growing (which is done in the greenhouse on top of the other science building at Bates), we integrate in several other experiments that augment aspects of the project (for example, we collect rainwater over the semester and analyze it for nitric and sulfuric acid, the two principal components of acid rain). With about three weeks to go in the term the students harvest their plants, analyze them for the lead content, interpret the results, present their group's results orally to the rest of their lab section, and each individual student writes a lab report in the form of a journal article describing their group's results and putting them into the context of their overall lab section's findings.

I am convinced that this laboratory experience promotes many of the learning outcomes I described earlier. The students conduct a real scientific investigation where they have to ask and answer questions and design experiments. Groups routinely encounter unanticipated problems that need to be addressed. The group work provides opportunities to work as a team, fosters communication, and provides a chance for students to exhibit leadership. The need to water plants at off hours shows that science does not happen in three hour blocks. Watering becomes a special issue over the five-day break we have in October, because the students realize that the warmth of the greenhouse means that the plants will die if they aren't watered. I've actually encountered comments like "our group is so lucky because we have a football player." It turns out that the fall athletes are in high demand as most of them need to stay around for the break and they get enlisted to water all the group's plants. The project has created a degree of independence and empowerment that I never observed with the prior format. Access to the greenhouse, which is highly restricted, and the use of sophisticated equipment for the lead analysis is part of this. But I also think putting the onus on the students to actually develop and conduct the investigation is more important in promoting independence and empowerment.

The project also provides the opportunity to discuss aspects of uncertainty in scientific data and investigations. As a typical example, one year, the data for the entire class consisted of 29 sets of plants and controls, 26 of which had higher levels of lead for the plants grown in the contaminated soil. The students had a real dilemma deciding what to do with the three samples that showed the opposite result. Some of them wanted to omit these three figuring, without any evidence to the contrary, that they had either mixed up or mislabeled the samples. Others just wanted to ignore them on the grounds that they did not show the expected trend and therefore must be wrong. This enabled us to have a discussion about the ethical implications of arbitrarily omitting or ignoring data without a justified reason for doing so. Suppose those were three people out of 29 who showed symptoms of heart disease in response to a new medication? We also discussed how the overwhelming amount of evidence did support our initial hypothesis.

The data for the trend in lead uptake as a function of the acidity of the water is more baffling. For every group that finds one trend, we tend to have just as many showing the opposite. Still others with three different acidity values often find no consistent trend among the three. This enables us to examine the complexity of the system and the limitations of our experiment. We discuss how tighter adjustment of variables and controls may have been needed, and how an examination of the buffering capacity of the soil may be important. We consider the very limited data set we have on a relatively small number of samples collected over about 40 hours of work during the semester, and realize that the effect of acid rain would require a far more thorough set of measurements and considerations.

The difference in levels of uncertainty between the contaminated/uncontaminated question compared to the trend with acidity is obvious to the students, as is their realization about the degree to which they can feel certain or uncertain about conclusions they can draw from the study. I do think this experience, coupled with the other components of the course, is an example of one that provides students at the introductory level with a far better understanding of how science works, and does prepare them to be far more "scientifically literate" than the way I used to teach my introductory course.

I'd like to close my talk tonight with a quote from *Walden; or, Life in the Woods* by Henry David Thoreau. This is a book my students and I just completed in a first-year seminar in which we examine the human relationship to land. Thoreau rails against lots of things in *Walden,* one of which is the way we educate college students. As Thoreau writes:

"If I wished a boy to know something about the arts and sciences, for instance, I would not pursue the common course, which is merely to send him into the neighborhood of some professor, where any thing is professed and practiced but the art of life."

Thoreau goes on to say:

“Which would have advanced the most at the end of a month – the boy who had made his own jackknife from the ore which he had dug and smelted, reading as much as would be necessary for this, - or the boy who had attended the lectures on metallurgy at the Institute in the mean while, and had received a penknife from his father?”

I think that Thoreau provides an excellent example of what type of experience provides a more “general education” in the sciences, and what better instills in students the goal of “scientific literacy”. I think it is incumbent on those of us who teach in the sciences to provide similar experiences for our students, and to begin these in our introductory level courses.

I thank you for your attention tonight and welcome any comments or questions about my talk.

Learning Outcomes Reference:
Ewell, PT, *Accreditation and Student Learning Outcomes: A proposed Point of Departure*, Council for Higher Education Accreditation (CHEA) Occasional Paper, Washington, DC, September 2001.