How I teach chemistry – Dr. Philip G. Hultin

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Where I am coming from

While at one time I considered a career as an industrial researcher, I found that I could not imagine myself in a role that did not involve sharing my knowledge with young people. As a university researcher I saw my role primarily as mentoring and guiding the students in my lab, and I carried this belief into my undergraduate classrooms as well. Scientific research and teaching have always been intimately linked for me.

My teaching is about challenging students to exceed their own expectations. Every person has a certain innate intellectual capability, but this can always be developed and expanded by conscious acquisition of "techniques". Great athletes begin with certain physical and mental attributes, but only through skilful coaching can these be developed into outstanding abilities. The same is true for intellectual development. Every student can gain greater abilities by training his/her mind to think in an orderly and structured way, by learning how to organize factual information in a way that facilitates its application in problem solving, and by consciously developing strategies for evaluating complex situations and understanding them. The teacher, like the athletic coach, must consistently set challenges that push the student (or athlete) to grow and develop.

In this I am guided by my own experience. When I was in high school I found it easy to excel with a minimum of effort and I came to believe that I was "gifted". My first year of university did little to alter that belief, apart from increasing the effort I expended to remain near the top of my classes. But second year shattered my complacency. For the first time in my life I failed an exam, producing a truly existential crisis. My whole self-image rested on the arrogant notion that I was just one of those people who got good marks: that this defined me. Suddenly I didn't know who I was. Fortunately my professor was very supportive and he set me on the path to re-building my entire approach to learning. This was a slow process that was still incomplete by the time I graduated. It continued during graduate school, again assisted by the patient mentorship of my PhD supervisor, who believed strongly in teaching his graduate students through challenges. During my postdoctoral studies I began consciously to think about the fact that I now viewed chemistry differently than most of my fellow postdocs did, in a broader context and with a strong sense of questioning. This was the point at which I knew I needed to become a teacher.

Themes

Connections

Connections: an alternative view of change was a TV documentary series from 1979, followed up by sequel series in 1994 and 1997. Historian James Burke took the view that events and ideas in the modern world are not the inevitable results of a linear sequence of prior events or ideas, but that in hindsight a web of connections reaching into the past can be identified, revealing the antecedents of any part of the modern world.

This started me thinking about how ideas are linked to one another, and crystallized some of my thoughts on learning. If one actively sought out connections among the various concepts one was learning, the very inter-connectedness of the resulting web would make each concept easier to remember, and easier to use correctly. The other ideas that would be linked to it could provide a context in which it would make much more sense, and knowing that ideas were connected (or potentially were *not* connected) would facilitate making logical leaps that could help in problem solving.

As a teacher, I have striven to highlight such connections for my students, reminding them of fundamental ideas that relate to or contrast with new concepts. I have also suggested as exercises that students take a given concept and see how long a chain of related ideas they can create, and how far away the end of such a chain can be from the starting point.

Human context

Chemistry is often perceived by lay people as a remote, abstract science but chemists become fascinated by the subject for very human reasons, and they are driven by the basic human urges. Chemistry has played a crucial role in human history, reflecting the concerns of the times, solving the challenges of the moment, creating challenges for the future, addressing the problems of the past. In my teaching I always take the time to link the chemistry to the time and place in which it was created or discovered. Some of my favourite moments in teaching introductory organic chemistry are my "Synthetic dyes and the beginning of the modern chemical industry", "Agent Orange" and "Birth of The Pill" lectures. Each is built around a specific chemical process that I want students to understand, which is linked to a historical and social change. Students usually have a vague knowledge of the historical event, but not of the underlying science that drove it. Each year I have had students come up to me and express their enjoyment of these tales, and how it makes the chemistry come alive for them.

Interactive reading, active learning

A theme that I emphasize in all my classes is that learning requires engagement. I talk to students about how they must read their textbooks and other materials *interactively*. By this I mean that they have to challenge every assertion of fact in the material and seek justification and verification for it. They need to analyze every example presented to identify what it actually exemplifies; the example is usually not of great significance but what it is illustrating is the real take-home message. Instead of just high-lighting "important information" or copying it verbatim into notes, I urge students to create notes in their own words and to incorporate the process of justifying and verifying into these notes.

I also discourage studying by the reading and re-reading of notes and texts. I present students with numerous practice questions, and I tell them that doing the practice questions in a thoughtful manner is active learning through problem-solving. Over the years I have discovered that most students know what to do when they get a practice question wrong, but they are mystified when I ask "what do you do when you get the question right?" Usually they just immediately go on to the next question but I advise them to go through the correct answer to identify exactly what they did to get that correct answer. The learning occurs when they consciously recognize the useful facts and productive strategies that lead to the desired outcome, and consider how they fit in with the rest of the course material.

Information is not knowledge

One of the biggest challenges in teaching science is getting students away from the idea that memorizing lists of facts is all that is needed for success. Too much of their previous exposure to science has been purely descriptive, and they have been tested on their ability to recall the names of things or under what category compounds are filed. They have not usually had a lot of experience in *using* the concepts in open-ended problem-solving.

The way that I express this to my students is to distinguish *information* from *knowledge*. As I see it, information is not particularly useful on its own, unless one is competing on “Jeopardy”. Knowledge is distinguished from information by the application of *thought*. As part of the “interactive reading” described above, I push students to consider what each piece of new information actually means, how it relates to prior knowledge, whether it is consistent or inconsistent, and what might be implied by consistency or inconsistency. A new fact or concept should be examined, taken apart, criticized and analyzed before it is accepted and stored. This process naturally leads to forming *connections*! *Knowledge comes from thought applied to information.*

Logic!

1. All men are mortal.
2. Socrates is a man.
3. Therefore, Socrates is mortal.

Classical logic is rarely explicitly taught at high schools any longer, which is a pity. It provides a framework for the construction of an argument that simplifies learning and problem solving. Unfortunately it is not possible in an organic chemistry class to outline the structure of a syllogism or discuss the difference between biconditional and conditional statements. However, working one-on-one with students in office hours provides me with the chance to present these kinds of formal structures as tools. And, in presenting new material in a lecture scenario I always try to make my axioms explicit, to highlight the deductions drawn from them and to recap the overall argument when citing the final conclusion.

What, How, Why?

I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.

Rudyard Kipling, Just So Stories (1902)

The use of a set of rhetorical questions as a guide to understanding a situation dates back to the ancient world. It is still taught in journalism and law schools, and has been popular in business schools as well.

In my chemistry teaching I recognized that a subset of the “five Ws and one H” were coming up over and over again as I helped students during office hours. It struck me that often when students were stumped by a question they had begun with the question “why did that happen?”, but when I asked them “what” situation the question described they could only respond in generalities. Likewise, I discovered that they had not considered “how” this situation might have come about, or “how” it worked, even when in essence the question demanded the answer to “how”.

Starting with “why” effectively immobilized students’ thinking, because without a clear idea of “what” was going on, or “how” it worked, it was impossible to determine “why” the outcome arose. Students needed to defer asking “why” and concentrate *first* on determining “what” and “how”. This strategy became the basis for an essay that I posted on the website for my CHEM 2220 course outlining a strategy for problem solving in organic chemistry:
http://home.cc.umanitoba.ca/~hultin/chem2220/Support/WhatHowWhy.pdf

Dis-assembling problems: peeling back the layers.

Organic chemistry in particular is characterized by *complexity* which I distinguish from *conceptual difficulty*. Once the admittedly rather abstract notions of atoms and molecules are grasped, the concepts of organic chemistry can be expressed in very tangible terms, at least in an introductory course. What makes organic chemistry hard is that it is rare for a problem to be solvable by inspection. Organic chemistry problems are *multi-layered* and the layers must be peeled back to reveal what is going on. Once this is done, often an explanation for an outcome becomes obvious even though it was hidden to simple inspection.

Preparing a student to peel back the layers of a problem starts with the presentation of the basic material. Fundamental concepts must be learned in a way that fits them into a network of “connections” in the students’ minds. The instructor has to present concept and application together but without implying that the application is unique, or limiting on the concept. The student has to be encouraged to speculate on what other applications of the concept might be, and these ideas should be taken up in class for assessment in a critical but positive way. The important thing is to develop the students’ ability to imagine hypothetical outcomes within bounds established by the fundamental laws of chemistry and physics. With this ability, they will be able to imagine solutions to unsolved problems in the future.

Students must learn to identify the roles played by each component in a chemical reaction system. While there are millions of possible reactants, solvents, reagents and catalysts that can appear in specific reactions, the number of roles available to them is actually quite small. Thinking about the roles is a much more manageable prospect than memorizing every specific instance. In class, I present organic reactions in a reduced symbolic form that focuses on the relevant parts of the reacting molecules. I discuss specific reagents as exemplars of broader classes of similar reagents, and point out what it is that the specific reagent has that makes it behave as it does. I often use flamboyant physical analogies to make atomic-scale behaviours visible on a human scale, and to help the students remember the concepts better by remembering the funny or picturesque analogy.

Problem solving as an experiment

I have observed that students approach problems with the idea that one either knows the answer or one does not. I try to convince them that problem solving is a process of hypothesis testing, an application of the scientific method. In class, I often ask students simply to point out something interesting about a system we are about to discuss. In this, I am not looking for “the answer”. I encourage them to simply make specific observations about the system. With some of these suggestions in hand, we can hypothesize relationships that might help us to understand the system. These hypotheses must then be tested against the rest of our general chemical knowledge to see if they are consistent. The hypothesis that emerges from this testing can form the basis for an explanation of the phenomenon.

The key here is to encourage students to experiment, to explore, while seeking an answer to a problem. Students should learn to speculate, but also to critically examine their speculations before accepting them as fact.