"Decisions, Decisions…"

A paper contributed to the Fall 1999 electronic chemistry conference.
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I. INTRODUCTION

(1) Foreword

The question driving this electronic conference seems simple enough: "What should students know when they leave a General Chemistry course?" It is not simple. This topic is just one chamber sitting at an intersection of an n-dimensional labyrinth. To make matters worse, the various pathways in this maze shift unreasonably with the perceptions and experiences of both the maze-makers and the maze-walkers. How can any single decision or recommendation guide anyone? Nearly any recommendation is reasonable, and the criteria by which value judgments can be made are conspicuously absent. The perplexing choices of the labyrinth invite many instructors to the same answer: just sit down and make a list of scientific topics, comfortably characterized, neatly separated, and conveniently tested and graded. Instructors can convincingly justify including any given topic as important, so a compelling answer cannot rest solely on good rhetoric. The criteria on which value judgments can be based are needed.

Many students in the labyrinth visit this introductory chemistry chamber we have made and they spend a short while. We certify their visit (and sometimes their visits), then they exit. What our students learn varies wildly, so I am only confident about one generalization about what students learn when they leave General Chemistry courses. Namely, I am sure that 'A' and 'B' students have learned how to perform well on general chemistry examinations. Is this the same as learning chemistry? We assume so. Does this achievement permit students to make informed decisions about anything…even about becoming a better learner? We want to think so. Are we designing and supporting learning environments that invite and then educate students to achieve a plurality of goals? We hope so.

A labyrinth, *n'est-ce pas*?

In the first part of this paper, including this foreword, I will reflect on the variety of voices I have heard in conversations about introductory chemistry instruction over the last decade or so. The last voice will be mine. In the second part, I will offer a set of underlying assumptions (or, I might argue, myths) that shape the different voices in the first part. Finally, in the third part, I will reply directly to the question (maybe you just want to skip ahead) in two ways. First, I will provide the information we already give to students and faculty in direct reply to the question about our expectations, and second, I will give a broader answer that underlies the first reply.

My overall goal is to raise ideas that might inform student and faculty practice about the decisions they make regarding introductory chemistry education. These suggestions include possible criteria with which value judgments could be made.

(2) Some voices who answer the question

Stakeholders in two main categories are impacted by the General Chemistry question. The first category includes those who have decided that this course is prerequisite to something else.

(a) A voice from sophomore organic chemistry. Organic chemistry instructors certainly presume prior chemical knowledge. Students who have not encountered certain fundamental ideas (particulate nature of matter, atomic and molecular models, periodic properties, pH and pK) would not usually have the background they need to succeed in the organic course. A more provocative idea is whether students with an adequate high school experience gain any added value from taking a year of college chemistry before taking organic chemistry. Surely, this depends on the expectations of the organic chemistry program. In general, though, the discussion goes something like this: a general chemistry instructor will ask "How can an organic student possibly understand esterification without the understanding of equilibrium provided by the introductory course?" This raises a recurring theme (call it an ideological battle) relating to the interplay between mathematical and molecular representations for chemical phenomena. The reply I give to this question reveals my prejudice, namely, "How can a student possibly understand equilibrium without a concrete context like esterification?" After completing the first drafts of this manuscript, I happened to review a series of three instructional videotapes for organic chemistry students ("The Deep-Fried World of Organic Chemistry," Parts 1, 2, and 3. Cerebellum Corporation, 1997, www.cerebellum.com) Interestingly enough, this group devoted 1 hour of the first 2-hour tape to reviewing explicitly "What you should remember from General Chemistry." The topics they selected were atomic structure, Lewis structures, VSEPR, covalent and ionic bonding, intermolecular forces, and acids and bases.

(b) A voice from pre-professional health science. Sometimes I think that medical, dental, and veterinary schools should remove basic science requirements from the undergraduate program, just to demonstrate how dramatically faculty beliefs have been impacted by the tyranny of the standardized examination. Having contributed questions to these examinations in the past, I find it humorously ironic that it is always the impersonal "they" who are blamed for confining the topics on these examinations. "They" are "we," and we are caught in a closed loop. We have created a national standard without a national conversation, so conservatism rules: the general set of topics that these students review in 1999 looks remarkably like the list from 1969 except for the addition of, say, buckminsterfullerene. My colleagues in the medical school certainly believe that an education in the physical sciences is necessary for success in medical bio-science courses. In contrast, my former students (now in medical school) report that molecular thinking is more of a surreptitious advantage than a prerequisite since their courses do not particularly depend on molecular understanding. While I do not actually wish for a dramatic, wholesale change in pre-health science requirements, I do think there should be better and more public articulation between members of the American Chemical Society and the medical, dental, and veterinary societies on this topic.

(c) A voice from pre-professional chemical sciences. We know this group has a minority voice in all of introductory chemistry, and includes future chemists, chemistry and science teachers, and chemical engineers. We believe deeply in the structured ordering of courses and in the foundational nature of an introductory course. This voice also asks us to make undergraduate education more relevant to teamwork and topics that more closely resemble the chemistry professions that chemistry majors pursue. In many ways, this minority voice has the most influence on curriculum design.

The second category of voices includes those who own the General Chemistry course. While no individual needs to represent a single characteristic, the intrinsic orientations of instructors naturally impacts their instructional goals. Loud, vocal answers to what students should know after leaving General Chemistry are often heard from extremists, so understanding these characters is the first step to a strategy for turning monologues into conversations.

(a) The traditionalist is known for aphorisms. "If it was good enough for me, it is good enough for you." Or, "If it ain't broke, don't fix it." As in other introductory courses, there is a body of knowledge that represents the topic, and this knowledge needs to be transmitted to students.
(b) The experimentalist focuses on instructional methodology but suffers from a kind of "magic bullet" mentality. Uninformed by ideas of pedagogical content knowledge (PCK, or the strategic match between content and the methodology used to design instruction), the experimentalist deconstructs the (evil) lecture classroom, or begins classroom voting on every topic, or tends to assign collaborative projects that do not require more than parsing the workload and using a stapler to join it together. The experimentalist can sometimes become the evangelist.
(c) The sociologist subordinates the centrality of chemistry (in a chemistry course) for issues under the heading of relevance. Environmentalism, biological application, nutrition, and so forth, are important and interesting topics, but there is a significant difference between learning chemistry and learning how it has been applied in aligned areas of study.
(d) The reductionist maintains that chemistry is a derivation of physics. Indeed, until recently, philosophers of science saw no need to identify a separate philosophy of chemistry because it was believed to reduce to physics. According to this premise, chemistry simply follows the provision of the theoretical, quantum mechanical model for atoms.
(e) The cynic can be jaded for many reasons. "Students today…" are never quite as bright or motivated as they were in the old days. The course is invariably being "dumbed down." I have visited departments where the faculty was so outrightly suspicious and communally hostile towards students who wanted to ask questions and meet in office hours because "everyone knows they are just trying to improve their grades and get letters of recommendation."
(f) Like the cynic, the mechanical instructor is more or less serving time in a course and does not typically advance the teaching in the course. This could be either a highly research-active person or an all-but-retired person who are joined in their disinterest in the curriculum. Followers rather than leaders, these folks will often not get in the way of new ideas, either, and can work in team situations as long as they do not have to be decision-makers.

(3) Personal reflection

As many know, The University of Michigan faculty implemented a new undergraduate chemistry program in 1989 that we revised in 1996 (link to a quick refresher course on our program if you're interested). From 1982-86 I taught sophomore organic chemistry in a small department in the University of Wisconsin system and then from 1986-89 in Ann Arbor. Since Fall 1989 I have helped to lead the first-year, organic chemistry based course sequence we call *Structure and Reactivity*. For 10 years, a steady-state population of 50-55% of first-term, first-year students have enrolled each Fall term, the remainder being students who waited until their sophomore year (including but not exclusively those who have taken our one-term general principles course).

We know the following as facts.

(a) Students who enroll in *Structure and Reactivity* directly from high school do slightly better, but not significantly so, compared with students who have already taken a college chemistry course.
(b) Advanced Placement students (35-40% of the class) on average, perform the same as non-AP students (the trend within the AP group, however, follows the AP score: AP3 below class average, AP4 at the average, AP5 above the average).
(c) Students with poor chemistry backgrounds, as indicated by a placement test that recommends their enrollment in the principles course, can achieve at the same level as Honors students if they take the *Structure and Reactivity* course along with a Supplemental Instruction option (instead of taking the principles course).

As I stated earlier, it is not clear whether students with an adequate high school experience gain any added value from taking a year of college chemistry before taking organic chemistry.

As an organic chemistry instructor who had taught sophomores for 6 years, I was curious (and a little cautious) about working with first-year students when we began *Structure and Reactivity*. Except for a kind of naiveté about university life, students without prior college chemistry have been consistently more flexible in learning and in accepting a quite different way of looking at chemistry compared with a class of sophomores. Although the nature of the organic chemistry subject matter is usually blamed for "sophomore shock" in chemistry, it is more likely the change in expectation from one kind of subject to another. Consequently, we have still seen a "sophomore shock" when the students from the *Structure and Reactivity* course move into more mathematically-oriented introductory physical and analytical courses during the second year of our program. This observation is important because it attenuates the idea that problems with the General Chemistry to Organic Chemistry transition are due to the subject matter. In our experience, it is more a question of students becoming accustomed to a style and then having difficulty with change.

II. Underlying assumptions (or are they myths?)

At the end of the last section, I have demonstrated that an underlying assumption about the relationship between courses can impact the question about what students should know when they leave General Chemistry. If the "sophomore organic shock" is due to inadequate preparation in the subject matter, then there are certain strategies that might be followed that relate to the subject matter. If the shock is more due to the fact that any change is traumatic because it goes against the expectations that have been built up the year before, then there are different strategies that do not relate to the subject matter at all. In this section, I will propose that a number of assumptions like this one need to be acknowledged, and their validity reconciled, before a productive answer can be generated. The myths that underlie chemistry instruction impact greatly on the answer to the question about what needs to be learned.

Assumption/Myth 1: the chemistry curriculum is a highly articulated hierarchy of courses and course content. I have picked this one first because it follows directly from the previous paragraph. While students with no prior chemistry knowledge would have a difficult time in organic chemistry, in our experience there is a smaller need for General Chemistry than its place as a prerequisite implies. If anything, it is easy to believe the organic wags who claim, as do some medical school faculty, that filtering ("weeding out") students in the introductory course based on their general learning skills contributes more significantly to the performance of students than any mastery of particular subject matter. Most faculty members I know, it seems, find it impossible to assume prerequisite knowledge when they teach and take the time to present (re-present, or is that represent?) key ideas from the vantage of the new course. I think this is okay, and faculty should just accept the reality of this and move on. Because articulation between courses is so difficult unless someone has taught both of them, it is difficult for a faculty member to know in what way the students learned and understand ideas. I think the organic course pair is one of the few left where the prerequisite of the first term course for the second term course is real. If course sequences were actually highly articulated, then this kind of linkage would exist through the entire curriculum (i.e., the older idea of a "course of study"). It does not. Many programs are too large and too diverse, and the demands on faculty too great (including in small departments), to achieve this kind of cross-course communication.

Assumption/Myth 2: consumer-oriented curriculum design is inevitable. Consumerism has infected many parts of higher education, and it is most obvious is in recruitment and advising. As far as I am concerned, the worst thing to happen in higher education has been the consumer-client model for relating to students. Paying tuition does not buy any particular outcome, job offer, or post-graduate position. Paying tuition provides access to courses and an opportunity. This does not let faculty members (or the institution) off the hook and allow them to do whatever they feel like, because there are still responsibilities and obligations of the highest order. In addition, and this is a downfall, designing effective instructional environments is not something faculty are trained to do, even though it is part of the job. Consumerism affects course and learning expectations by adding an external dictatorial voice. It turns instructional goals and learning outcomes from skills and knowledge into products, and students into receivers of market goods. In a consumer-based education, the only viable student outcome is for them to learn how to perform well on chemistry examinations regardless of whether they learn chemistry or not. Faculty members are (still) wholly responsible for design and supervision of courses, and I think that a faculty better educated in ways of design and supervision is needed to counterbalance consumer rhetoric. (A footnote on design. There are all sorts of designs, both effective and ineffective. A cultural evolution has taken place that rejects the quaint 19th century "spare the rod…" methodology with both education and child-rearing. Given the number of classrooms and research groups that appear to operate with a "what does not kill you makes you stronger" mentality, it seems that education still needs to do a little catching up. Again, I have seen departments where the first reaction to consumerism has been to tighten the thumbscrews, and that is troublesome.)

Assumption/Myth 3: the good of the few outweighs the good of the many. All future chemical scientists are in the introductory chemistry program, and chemistry faculty members feel a justifiable obligation to their progeny. But these students will be with us for a long while, so I think an introductory program dominated by serving numerous imagined needs for this minority group has distorted introductory instruction. In cases where all students take a single course sequence, this means that every student is a member of the farm team of future chemistry majors and the program takes on a aura of delayed gratification. Its mantra is "Trust me, you need to know this for the future." In other cases, the so-called non-majors course avoids this problem but can introduces another, depending on the sense and sensitivity of the faculty. The non-majors course is easy to marginalize, and the resulting marginalized populations are notoriously good at living down to their stereotypically lowered expectations. Classrooms of students can easily understand if they are deemed to be of lower value, so this is also a case where the good of the many non-majors can be subordinated to the few majors. In fact, the entire future of chemical science is the introductory course, from chemists to chemistry teachers, to anyone who will reflect on their experience in chemistry and help formulate the public perception of chemistry. If we do well for the majority of students, won't we also be doing well for the future chemists?

Assumption/Myth 4: if students only knew mathematics better, they would know the chemistry better. My chemical education research colleagues have demonstrated beyond any doubt that students are able to solve mathematical chemistry word problems without needing to understand the underlying chemical ideas. Students who know mathematics better simply know mathematics better. Certainly they are better equipped to not be hindered in their learning of chemistry because of lack of mathematical skills, but that is not the same as learning chemistry any more than good punctuation skills are the same as good writing. I am not opposed to mathematical representations for phenomena and relationships, but I sincerely question the way introductory chemistry is presented if students can so easily avoid learning the subject. With respect to the driving question about what students will know after the introductory course, this paragraph is a reminder that student learning is a central issue. Like a syllabus, a list of topics does not imply anything about the way in which those topics are understood. Let me emphasize that I am referring to the surface assumption that actual mathematics skills are the critical issue. It is not the only one. Students who score well of mathematics are generally better learners, regardless of the mathematical demand in the performance task. While the Math SAT score is a consistently strong predictor for general student achievement, cause and effect must be carefully considered. The ability to solve math problems taps into intrinsic analytical reasoning skills. For instance, the course performance of our Structure and Reactivity students correlates strongly with their Math SAT score as an independent variable, even though no formal mathematics appear in the course at all. It does not follow, however, that improving a student's math skills improves reasoning skills. The causal direction is just the opposite. Math performance is simply a sensitive measure of a learner's reasoning skills, but these skills do not necessarily follow from learning how to do math problems.

Assumption/Myth 5: we must cover the topics necessary for standardized examinations. One of the most powerful exchanges between a faculty member and a student that I have ever seen came a few years ago during a group exit interview between some of my colleagues and some of our majors. One of our physical chemists, who is also one of our best classroom instructors, raised the obligation for being sensitive to MCAT examination topics that he assumed would be a preeminent issue for the students going on to medical school. Not one student supported this idea. The overwhelming reply was that students would always prepare for these examinations on their own and what they needed was the kind of education that would allow them to prepare appropriately when the time came. My colleague pressed the issue a bit, I think partly because it was such a strongly held belief. One of the students heading to medical school, in a bit of a pique to counter this idea, turned and said "I did not pay tuition to attend Kaplan University!" That sentence still rings in my ears. The recommendation I made in the first section is worth reiterating. Whenever the "MCAT topics" were originally codified, it was a reflection of the chemistry contents of the time. If we want to be free from whatever tyranny is attributed to covering topics for standardized examinations, then the chemistry community needs to enter into a dialog about this (like this conference). We must find a way to promote better communication with the agencies that administer these examinations in conjunction with the health science professional societies.

Assumption/Myth 6: chemistry reduces to physics. Expecting to be shot at sunrise, I ask the question: to what degree is physical chemistry really chemistry, and to what degree is it applied physics? To one reading of history, the rise of the engineering disciplines in post-Industrial Age America contributed greatly to introductory chemistry instruction taking on its physical chemical looks. The remnants of this still persist in many engineering curricula, although the requirement-turned-recommendation for a semester of chemistry may not remain a fixture once the dust has settled on this latest round of ABET certification discussions. Once the century was underway, this momentum continued as a more physical inorganic chemistry emrged and the nature of the chemical bond became a significant focus. I am not going to try to summarize the ongoing debate in the philosophy of science community except to say that I agree with those who argue that a fundamental chemical identity exists in nature. Historically, there has been no substantial challenge to the implicit claim by philosophers of physics that everything in chemistry can be ultimately represented by physics and therefore "chemistry" does not exist independently and does not warrant philosophical consideration. The nature of quantum mechanics is the territory where this battle is being fought, in effect, to decide where the line should be drawn. It is an interesting question that impacts directly what we think students need to know after the introductory course in chemistry. When I think of chemistry, I think of the wonderful explanations that we have created for phenomena in the material world. I think of change and how we tell stories to describe these changes: changes in concentration, changes in state, changes in shape, changes in connectivity, and changes in aggregation. I understand and appreciate the quantitative relationships from which principles flow, but I think that chemistry is the story told about what that quantitative relationship implies about the world. My point here (before the sun rises) is that a core philosophical debate during the 20th century on the nature of chemistry and physics must be considered when we take up this question of what students need to know. If chemistry does not reduce to physics, and I do not think it does, then we owe introductory chemistry students the benefit of basic chemical ideas rather than physical ones.

Assumption/Myth 7: we must tell the truth, the whole truth and nothing but the truth. Does quantum mechanics, or any of its results, belong in the introductory chemistry course? From one perspective, and I consider it a distorted one, some argue that certain ideas must be implanted and repeated numerous times just so that chemistry students get accustomed to the terminology. That way, when they are ready to learn the material in an upper level course, it will not be a surprise. This triumph of "the good of the few…" results in first-year chemistry students seeing the Schrödinger equation. From another perspective, and I consider this an instructional corollary of Occam's Razor, students should be most responsible for a level of explanation that fulfills the needs of the data. The "most responsible" in this recommendation is critical. If my goal is to teach about the shape of the earth for the purpose of launching satellites, then the planetary scale is appropriate. Although the shape of the earth is fluxional and irregular, the degree to which these subtleties impact my need will dictate how much attention I give to those details. How much do my satellite students need to know in order to do what they need? If my students are architects who build private homes, it is certain that they learn the flat earth model for our planet: two plumb lines separated by a distance are parallel. I am convinced that if chemists where responsible for introductory architecture instruction they would spend an entire unit on correcting the squaring of walls for the curvature of the earth. Later on in their programs, many kinds of architecture students need to learn about accounting for the earth's curvature because certain structures are large enough to warrant its inclusion, but doing this for all students in their first year would be guaranteed to exclude other more generally useful information. This exclusion is a central issue we rarely deal with. I understand that all subject matter is important to someone, but I also know that an introductory course excludes topics on a scale that is orders of magnitude higher than it includes them. What could first-year students be learning about if they were not trying to understand why the Schrödinger equation was written on the board? Substantial parts of what we know today as truth, and probably all of it, is just the latest version of a "flat earth" model of nature and of the world, and it is not a problem. Science advances when conflicts arise between the data and our current explanations. Students need a better sense of what a scientific model means so that they do not get lost in relativism when they realize that scientific theories change and scientific facts are subject to reinterpretation. One way to organize instruction to reflect this is by using need-to-know as a decision-making tool.

III. Two replies

Here I will give two specific replies to the driving question. "Replies" rather than "a reply" because there are too many audiences, voices, and assumptions to permit a simple satisfactory answer.

(a) The answer we already give.

Given the course structure at The University of Michigan, it might not be surprising that we answer the prior knowledge question directly. At the beginning of the *Structure and Reactivity* course (Chem 210/211, lecture/lab), we provide our students with a one-page handout titled "Basic Chemical Knowledge for students starting out in Chemistry 210/211." It was tempting to present the one-page paper to this symposium and write "been there, done that." The handout looks like a list of topics written by a faculty member who sat down in the middle of that chamber in the labyrinth I described at the beginning, and I share this with you here (link to one-page handout). We also provide a more elaborate essay on our instructional philosophy and some detailed recommendations for student learning (link to teaching and learning essay). This essay begins to dig more deeply into what we would like students to be thinking and doing, and it is not limited to only what students should know as they leave a General Chemistry course. More accurately, these are the ideas and practices we hope were started in introductory instruction that we can add our own momentum to as the students move through our course.

(b) What sits beneath the surface.

We wrote the one-page handout with the comfort of our intended audience in mind. High school chemistry students should be familiar with a body of knowledge and ideas, and the conceptual relationships that hold them together. The essay on study skills is meant to open up a broader discourse on learning. There are more comprehensive ideas at work under the surface of the course, and these must be exposed along with the subject matter. Faculty should always think about instructional goals as student learning outcomes, and these goals come simultaneously on three distinct levels. These are (1) *professional technical goals*, or the learning outcomes that are tied directly to an understanding of the subject matter (e.g., organic chemistry), (2) *professional intellectual goals*, or the broader disciplinary contexts into which the professional technical goals fit (e.g., chemistry and science), and (3) *general intellectual goals*, or the way in which learning the specific content within the broader contexts helps students achieve an education in the broadest sense (e.g., a liberal arts education).

What should students know after the leave a General Chemistry course based on answering the question at all three levels?

• The professional technical level.

I would like to supplement the one page handout, perhaps even replace it, with a set of questions that point to the skills that I would like students to have when they leave a General Chemistry course. In the section for this level, as well as for the other two, I will not be providing an exhaustive list, but hopefully enough examples to make my point.

A. Given: $H_2O + H_2O \Leftarrow\Rightarrow H_3O^+ + OH^-$
   (A1) Derive the relationship between pH and pKa for H2O as an acid.
   (A2) Prove that the pKa of hydronium ion is equal to 1.7.
   (A3) Formic acid is a weaker acid than hydronium ion. Using equilibrium chemical equations and the pH/pKa relationship, prove that the pKa value for formic acid is higher than -1.7.
   (A4) Provide the balanced chemical equation, using complete Lewis structures, for the acid-base reaction between formic acid (HCO_2H) and sodium hydroxide. Label the conjugate acid-base pairs.
   (A4) Can a solution of a weak acid have a lower pH than the pH of a solution of a stronger acid? Why or why not?
   (A5) Sketch and label the titration curve expected from adding aqueous sodium hydroxide to an aqueous solution of formic acid (HCO_2H, pKa 3.75). What is the approximate ratio of formic acid to formate ion, its conjugate base, when 0.25 equivalent of NaOH has been added; when 0.5 equivalent has been added; when 0.75 equivalent has been added?
   (A6) Describe how acid-base indicators work. Add information to your titration curve in A5 to illustrate your explanation.

B. The water solubility at about room temperature for NaCl is 37 g/100 mL, for NaI is 184 g/100 mL, for CsCl is 180 g/100 mL, and for CsI is 55 g/100 mL.
   (B1) Create a 8-panel storyboard that depicts the dissolving process for NaCl in water.
   (B2) Using words and drawings, provide a rationalization for the differences in water solubility between NaCl and NaI.

(B3) Is the CsCl/CsI trend in water solubility consistent or inconsistent with your explanation to B2?
(B4) In general, increasing the temperature of a solution increases the solubility of a solute. Use words and pictures to explain this observation.

C. The pKa of acetic acid (CH_3CO_2H) is 4.75, the pKa of chloroacetic acid ($ClCH_2CO_2H$) is 2.89, the pKa of dichloroacetic acid (Cl_2CHCO_2H) is 1.30, and the pKa of trichloroacetic acid (Cl_3CCO_2H) is 0.66.
(C1) Provide an explanation for this trend. Use words and labeled drawings.
(C2) What parts of your explanation involve ideas about enthalpy and what parts involve entropy?
(C3) The standard enthalpies (dH, cal/mol) and entropies (TdS, cal/mol) for the ionization of these acids in water are acetic acid (dH = -137, TdS = -6570), chloroacetic acid (dH = -1120, TdS = -5040), dichloroacetic acid (dH = -100, TdS = -1790), trichloroacetic acid (dH = +1000, TdS = +595). Are these measured values consistent with your explanation or not? If so, explain fully the trends in the numerical values with words and drawings. If not, reconcile your answer with these values.
D. Water and methanol are completely miscible while water and oil are not. Provide an explanation for each of these observations, including labeled drawings.
E. Electrons were discovered around 1900, and they were accepted as the basis for chemical bonding around 1920.
(E1) Briefly describe a basis for chemical bonding prior to 1900.
(E2) What sort of observations led chemists to believe that atoms could be bonded in the first place?

• The professional intellectual level

A. There is a frequent public debate about natural versus synthetic chemical substances. Is a sample of natural vitamin C (ascorbic acid) extracted, isolated and purified from a fruit or plant source the same or different from a sample of vitamin C prepared from simpler substances in a laboratory setting?
B. Word origins often reveal scientific information and historical information about science. Briefly explain why the names "oxygen" and "hydrogen" were selected for these substances, and also the origin of the terms "electronegative" and "cation."
C. Chemists understand phenomena by explaining observable or detectable changes.
(C1) Provide an example where a change in molecular concentration is used to make an explanation.
(C1) Provide an example where a change in molecular aggregation is used to make an explanation.
(C1) Provide an example where a change in state is used to make an explanation.
(C1) Provide an example where a change in molecular connectivity is used to make an explanation.
(C1) Provide an example where a change in molecular shape is used to make an explanation.
D. You are an undergraduate research student engaged in the study of structural effects on the rates of reaction of a particular class of compounds... After performing a careful set of triplicate experiments, you go to your research director with a graph of rate constant vs. polarity. With the results of 10 different systems plotted, 8 of the 10 fall nicely on a straight

line, but 2 points are well above the line. Your research director is convinced that the two "deviant" points are in error and strongly recommends that you repeat those cases. What should you do? Who is affected by these choices?

• The general intellectual level

The lessons at this level are typically provided "by example" rather than "as examples." Short, direct questions to students are not the kind of assessment that can reveal these attributes. Instead, techniques involving surveys, interviews, and performance tasks are needed to answer educational and educational psychology research questions.

A. Do students take on more of a teaching and explanation role when they answer questions and work with their peers?
B. Have students developed their view about the epistemology of scientific knowledge?
C. Have students developed deeper learning skills or a greater sense of intrinsic motivation?
D. Can students provide critical feedback on their work and the work of others?
E. Are students capable of designing their own tasks and carrying them out?
F. Can students encounter counterintuitive information and reconcile it?

If the questions surrounding introductory chemistry could be answered easily, they would have been already. In this essay, I have pointed to the characters and ideas that make answering the question an interesting challenge. Whatever the content of the introductory course, however, I think that the more important issue is how we can make the ongoing examination of education a more informed and evolutionary process. My recommendations are:

(a) Broaden future faculty development to improve pedagogical decision-making skills.
(b) Improve or institute articulation between courses within chemistry departments.
(c) Improve or institute articulation between chemistry and the educational divisions of health science professions.
(d) Following from (a), (b), and (c), chemists could step back from preconceived and inherited ideas about introductory chemistry as a *corpus rigor mortis* (with accompanying "examinus abominus *ad nauseum*") and introduce chemistry, a molecular and supra-molecular science.

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Concept learning versus problem solving

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(q) Pickering, M. *J. Chem. Educ.*"Further Studies on Concept Learning versus Problem Solving" **1990**, *67*, 254-255.
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Stereotyping and intellectual identity

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Philosophy of chemistry

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2015 ADDENDUM

Many years have passed since this session was held. The University of Michigan program to start with organic chemistry is still in place and going strong.

With still share information with our entering students of our expectations about what they need to know from their introductory chemistry experiences, in this handout:

Chemistry 210
Typical questions that can be answered based on learning in General Chemistry courses.

I. Using precise language to represent atomic and molecular entities (also called atomic and molecular species).

Using accurate representational forms to distinguish between the following:
(a) bromide ion, molecular bromine, bromine atom
(b) ammonia, ammonium ion
(c) sodium ion, sodium atom
(d) molecular oxygen, oxygen atom
(e) hydrogen atom, molecular hydrogen, hydrogen cation (also called proton), hydrogen anion (also called hydride ion)

II. Electron configurations and the relative stability of the closed shell electron configuration.

Write electron configurations for the monoatomic species in Part I, and identify which have closed shell configurations.

III. Lewis structures. Representing covalent bonds with lines, using "dots" (i.e., ":") for non-bonding electrons and charge-separated ions for ionic bonds, draw Lewis structures for the following:

(a) ammonium bromide
(b) hydrogen
(c) hydrogen chloride
(d) nitrogen triiodide
(e) ammonium tetrafluroborate
(f) sodium fluoride
(g) potassium hydroxide
(h) lithium hydride
(i) lithium tetrachloroaluminate

IV. Phase changes and mixing.

Represent the following processes using a series of 3 or 4 drawings that involve a collection of atomic or molecular species.

(a) dissolving sodium chloride in water
(b) evaporation of liquid water
(c) melting sodium
(d) mixing oxygen and nitrogen gases
(e) evaporation of gold
(f) the solubility of cesium fluoride in water is 100 times greater than sodium fluoride (why?)

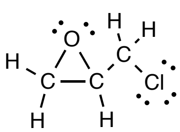
V. Inductive effects (electronegativity and electropositivity)

(a) Identify all dipolar and non-polar covalent bonds in the molecules named in Parts I-IV. Indicate the direction of the polarization in dipolar bonds according to the partial charges anticipated at each atom.
(b) Is iodide or fluoride a stronger reducing agent (why)?
(c) Can sodium or potassium be oxidized more easily (why)?

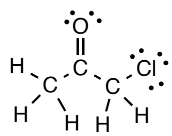
The following represents a sense of how we address what we think of as the three key principles from introductory chemistry that underlie one's study of organic chemistry.

A brief history Chemistry before 1700 - observable behaviors
taste (acid), smell (aromatics), color (chlorine) ⇦ "chloro" means green, like in chlorophyll
Chemistry ~ 1800 - elemental composition (e.g., C_3H_5ClO)
Chemistry since ~ 1850, esp 1950: From molecular structure, you can:
(1) explain observations and (2) predict behavior
These are the basic ideas of *Structure & Reactivity*

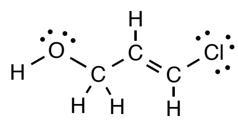
Cannot see molecules, so we use a variety of representational systems that much be learned, and the rules and conventions for writing and reading must be learned.
Elemental composition C_3H_5ClO (just a bag of atoms)
Structural drawing (CONNECTIVITY or DISCRETE MAP of atoms)



epichlorohydrin
use: synth rubber
contact carcinogen



chloroacetone
WWI chem weapon
lachyrmator



chloroallyl alcohol
fumigant by-product
pollutant

'gen' as in genesis: starter of, bringer of
"bringer of cancer"
halogen: bringer of salts; oxygen: bringer of acids

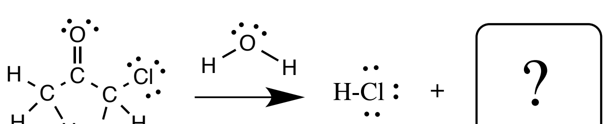
Humans love patterns!

As an experienced chemistry reader, I am ALWAYS assessing: is this a reasonable structure? Notice certain trends:
All these atoms are shown as "uncharged" (charge = 0), and:
H have 1 bond and 0 nbe pr
O have 2 bonds and 2 nbe
C have 4 bonds and 0 nbe

Note: pattern recognition can extend readily to reactivity.
Three key principles:

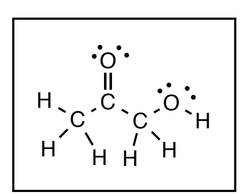
(1) atoms are conserved (SO LEARN TO COUNT)
(2) chemical rxns are rarely explosions (SO COMPLETE REORGANIZATION IS RARE)
(3) there are some simple bonding generalizations for the main group elements (SEE ABOVE)

GIVEN THIS INFORMATION (chloroacetone is a lachyrmator b/c it reacts with water to give HCl, which also scars your lungs and you drown in your own physiological response) AND THE THREE PRINCIPLES, APPLIED WITH BRUTE LOGIC:

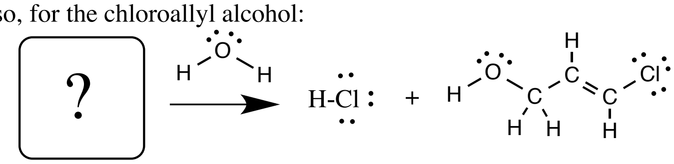


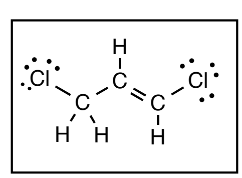
lachyrmator

this is why you cry



And, also, for the chloroallyl alcohol:





TRY THESE FOR NEXT TIME: WHAT ARE THE TWO "?" ?