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Chemistry, Life, the Universe, and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform

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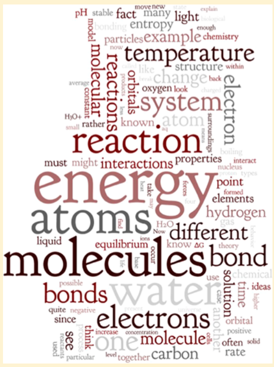
Ⓢ *Supporting Information*

ABSTRACT: The history of general chemistry is one of almost constant calls for reform, yet over the past 60 years little of substance has changed. Those reforms that have been implemented are almost entirely concerned with how the course is taught, rather than what is to be learned. Here we briefly discuss the history of the general chemistry curriculum and consider why meaningful change has been difficult. In this light we present a rationale for why curriculum reform is necessary, and how it can be accomplished, based on our current understanding of teaching and learning at the college level. We present a model for curriculum development based on five important questions: (i) What should students know? (ii) In what order should they learn it? (iii) What do students bring with them to the course? (iv) What materials are best suited for different purposes? and (v) How can student understanding be assessed? We use our new general chemistry course CLUE: Chemistry, Life, the Universe, and Everything as an example of materials developed in this way.



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■ INTRODUCTION

General chemistry is the first and, for many US college students, the last college chemistry course they will take. At most institutions the course's student population is not primarily chemistry majors, but rather students from a wide variety of other STEM disciplines, particularly engineering, biological sciences, and health-related majors. Over the years, there have been many calls to overhaul not only the general chemistry curriculum but also the way it is taught. As far back as 1929 Havighurst[1] railed against the "plan less expansion" of chemistry curricula, and since then a wide variety of authors have added their voices to the chorus calling for change. For example in 1994 Lloyd and Spencer[2] presented a report from the American Chemical Society's Division of Chemical Education that enumerated the problems with general chemistry.

Among the issues they discussed[2] are these concerns:

> The course covers too much material, sacrificing depth for breadth.
> It is taught as if students were chemistry majors, ignoring the fact that the majority is not.
> The course is generally ineffective at developing an understanding of basic concepts (whether or not the students are chemistry majors).
> It uses a course or curricular design that is inconsistent with the realities (and the research observations) of how students learn.
> General chemistry is not usually taught in a pedagogically sound (i.e., effective) manner.
> The course often fails to engage student interest.

Unfortunately, while the past 20 years have seen many initiatives aimed at improving chemistry education,[3] as the President's Council of Advisors on Science and Technology reported in 2012,[4] little of substance has changed in most introductory STEM courses.

What has changed is the emergence of discipline-based education research (DBER), as a viable and relevant field. DBER combines disciplinary knowledge with research on teaching and learning,[5] and together with ongoing research on K−12 level learning numerous research studies have led to improved understanding of the specific problems associated with teaching and learning in STEM disciplines at the college level. We believe that it is now time to systematically incorporate these insights into the development of more effective approaches to STEM teaching and student learning.

That said, a number of studies indicate that reform efforts are fragmented, evidence for meaningful change is weak, and faculty beliefs about teaching, learning, and content are among the barriers to change.[6,7] In this light we present a rationale for why we should change both our practices and content, and a model for curriculum reform, using the findings from research on teaching and learning. We use a new general chemistry curriculum, CLUE: Chemistry, Life, the Universe, and Everything,[8] as an example to help clarify some of the ideas.

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A SHORT HISTORY OF GENERAL CHEMISTRY—AND WHY IT IS TIME FOR A CHANGE

The earliest chemistry courses were designed for those planning to enter the job-force as technicians (for example to analyze fertilizers). Shortly thereafter, introductory chemistry joined the ranks of courses seen as an integral of part of a liberal arts education. These "primordial" courses (which continued to exist until the early 1960s) were largely descriptive in nature, and based on memorization and pattern recognition. Students learned how to prepare gases, and industrially important chemicals, but little of the underlying theory. Alex Johnstone notes that as a new teacher in the late 1950s he was startled to find that his notes were identical to those he found in the chemistry stockroom from 60 years earlier.[6]

The late 1950s and early 1960s saw new initiatives, including the Chem Study[9] and Chemical Bond Approaches[10] for high school, and a new textbook by Sienko and Plane[11] for the college level. The content was updated to reflect more current chemistry, and more theoretical foundational support was included in the hope that this would make chemistry courses more coherent, understandable, and intellectually stimulating. That is, the curricula changed from mostly descriptive chemistry, to an approach designed to provide appropriate background and theory. Current incarnations of general chemistry (as evidenced by most popular textbooks) are direct descendants of these changes. Unfortunately, their efficacy has yet to be supported by objective evidence for improved student understanding of core chemical concepts. While these (now more than 50-year-old) changes were often highly satisfying, self-consistent, and meaningful to experts in chemistry, they did not seem to impact learners in the same way. As Johnstone notes,[12] "they mistook their own enthusiasm for that of their students".

While the foundational ideas of chemistry have not changed significantly, the past 50 years have seen new materials (both content and supplementary) added to what was already a full curriculum. At the same time, there is no evidence that the rapid cycle of textbook development has been associated with improved outcomes. Although textbooks are commonly reviewed by disciplinary experts, there are rarely, if ever, independent data provided on learning outcomes associated with a particular text or text revision. While some findings from science education research have been incorporated into chemistry curriculum materials, for example, multiple levels of visualization are now routinely presented,[13] there is little evidence for the efficacy of most textbook designs as implemented. That is, there is no evidence that common textbook learning aids actually have positive effects on student mastery of core chemistry concepts and ways of thinking "in the wild". In fact it has been reported that students' grades are inversely correlated with the number of such aids they use.[14]

It should also be noted that the most successful of the numerous reform efforts aimed at general chemistry have been mainly focused on changing the pedagogical approaches, rather than the content and direction of the course. For example, both peer-led team learning (PLTL)[15] and process-oriented, guided-inquiry learning (POGIL)[16] have been implemented in general chemistry courses. Both of these approaches rely on the well-documented efficacy of socially mediated learning,[5] either in or out of the classroom setting. Neither of these approaches requires changes in course content, and each focuses primarily on a constructivist approach to knowledge development. However, the content structure of most general chemistry courses, even those taught with reformed pedagogies, remains very similar to those of 50 years ago. While there have been a number of projects aimed at changing the content,[17−20] these have not been widely adopted for different reasons, not the least being that change is difficult to accomplish.[6] While we are aware that change requires all stakeholders to work together to produce a shared vision, clearly the change conversation must start somewhere. In this paper we present our model for changing general chemistry—an approach that can be used in a variety of settings and courses.

RETHINKING GENERAL CHEMISTRY—AGAIN

We propose a model for reform based on answering the following questions:

1. What do we (really) want students to be able to know and do by the end of the course? That is, what knowledge and skills should be emphasized?
2. Is there an optimum order of topics that facilitates students' development of a deeper understanding?
3. What knowledge, assumptions, and skills do students bring with them, and how do we determine what students already know?
4. What materials and experiences are most appropriate for learning different types of knowledge and skills?
5. How will we assess the knowledge and skills we want students to develop?

We used these five questions to develop a new general chemistry curriculum, CLUE: Chemistry, Life, the Universe, and Everything[21] (NSF 0816692). This report describes the rationale behind how and why we made the choices that we made, using examples from CLUE as necessary. To answer these questions, we initially called upon the available research on learning and cognition, and subsequently on data generated in the process of teaching courses using CLUE. It is important to emphasize that answers to question 5 feed back on questions 1−4, as CLUE (or any other curriculum) undergoes iterative design.[22] That said, this is an evolving area with many gaps in the "actionable" research and newly uncovered questions that need to be addressed. We see CLUE, and other curricula generated in this way, as constantly evolving, in response to research findings, and student feedback.

Question 1: What Do We Want Students To Know and Do?

Our overarching goal for the CLUE curriculum was to develop a molecular-level understanding of core chemical principles, so that students can explain and understand at the molecular level the relationship between the molecular-level structure of a substance, how and why a chemical reaction may occur, and how energy changes resulting from interacting materials can be understood. The goal of the course is to help students develop a mechanistic understanding of chemistry. It is our contention that current approaches to general chemistry instruction often sacrifice depth for breadth, leaving students with no choice but to complete the course by pattern recognition and memorization, rather then applying core chemical principles to explain and predict how a system will behave. The content of the course should support student understanding of important concepts in chemistry, and the skills developed should be useful and ideally transferable. That a solid conceptual foundation is necessary is suggested by studies that reveal that multiple chemistry courses often fail to produce a clear understanding of key concepts.[23,24]

In CLUE we focus on three inter-related core concepts: (i) molecular level structure; (ii) macroscopic properties; and (iii) energetics (thermodynamics). We have attempted to avoid unnecessary digressions; instead, we return, reiterate, extend, and relate these ideas repeatedly as we progress through the text. The approach is similar, in some ways, to that taken by the Next Generation Science Standards[25] (from the National Research Council, or NRC, Framework for STEM Education),[26] the AP chemistry redesign,[27] the College Board Science Standard for College Readiness,[28] and those developed as part of the curriculum map by the ACS Examinations Institute.[29] These projects all focus on disciplinary core concepts or "big ideas" in an attempt to pare down the extraneous material that often clutters the curriculum. It should be noted that each of these reform efforts focuses on slightly different ideas of different grain size, (e.g., AP redesign has six "big ideas", while the College Board has three core concepts, and the NRC Framework has only four disciplinary core ideas for all of the physical sciences). We settled on our three core concepts—structure, properties, and energy—because we could use them to develop progressions of ideas that connected and interconnected throughout the curriculum (this idea is further developed in the next section). Using these core ideas and the principles of backward design,[30] we developed a set of knowledge statements for each chapter that delineate the knowledge that students will learn (see the Supporting Information for an example).

However, focusing solely on the content of any course without concomitant consideration of what students should be able to do with that knowledge almost guarantees that the result is a collection of facts or algorithms that can be searched on the Web (or solved using the Wolfram Alpha general chemistry app).[31] Understanding of science requires application of what are, by now, fairly well-defined science practices that involve activities such as developing and using models, formulating arguments from evidence, and developing scientific explanations; these are in addition to the ones more likely to be found in chemistry courses, such as planning and carrying out experiments, analyzing data, and using mathematical reasoning. These science practices are adapted from the NRC Framework for Science Education.[26]

We combined these knowledge statements and science practices to produce performance expectations, that is, explicit tasks we expect students to be able to perform, and that are assessable. Analysis of these statements enables us to determine whether the knowledge statements and science practices are relevant, adequate, and realistic. That is, they make explicit what will be assessed, and by merging knowledge and practices into one performance expectation, the emphasis is changed from memorization or rote numerical tasks to activities that require students to develop and use the practices. (It should be noted that this is something of a departure from the more traditional approach of developing learning objectives that have different "levels" according to Bloom's taxonomy.[32]) Examples of performance expectations are given in Box 1.

Box 1. Sample Performance Expectations Combining Science Practices and Disciplinary Knowledge

- Using evidence from experiments, explain how and why models of atomic structure changed over time.
- Construct diagrams, graphs, and mathematical expressions to show the relationship between frequency, wavelength, and velocity of a wave.
- Gather data on a range of elements in the periodic table, construct graphical representations of the data, and use them to predict periodic properties such as atomic radius, ionization energies, and relative electronegativities of other elements.
- Construct a representation (draw a molecular-level picture) of what happens when a discrete molecular substance freezes or is vaporized. Indicate the kinds of interactions/bonds that are broken or formed.

Question 2: Is There an Optimum Order of Topics—A Learning Progression?

While use of performance expectations and knowledge statements mirrors approaches taken by the NRC Framework for Science Education,[26] the NGSS,[25] and the AP reinvention project,[27] any curriculum development project must include a crucial next step, which is to consider in what order concepts and skills can, most effectively, be learned. That is: How can a curriculum be designed in which core knowledge is developed in an appropriate way over time? There is growing recognition that a curriculum sequence must take into account not only the cognitive factors that affect how people learn but also that difficult (often counterintuitive) concepts take time to develop; learning concepts involves synthesis, application, and reinforcement; and complex concepts need to be introduced and developed in an increasingly sophisticated way. There is also robust evidence from cognitive science that it is preferable for students to build up their knowledge over time, rather than (try) to learn it in one concentrated attempt.[33] These "learning progressions"[34−36] are evidence-based descriptions of conceptual and logical pathways that are more likely to lead to improved understanding of core ideas in science. Learning progressions have been proposed for a number of concepts,[36−38] including the structure−property learning progression we developed for CLUE, for which we have documented significant improvements in CLUE students' abilities to construct and use chemical structures when compared to an equivalent cohort of students.[39]

Learning progressions are based on theories of learning and cognition, and available evidence; they are our best way forward, and it is important to think about how complex concepts can be scaffolded and developed as curricula are revised. In CLUE we interweave the core ideas in the text, and reinforce and extend them through activities and assessments. Figure 1 shows how the three core ideas are interwoven as the curriculum progresses in the first semester. (A more detailed explanation of how the three core ideas are connected and developed throughout the curriculum, along with a diagram for the second semester, is provided in the Supporting Information.)

Question 3: What Knowledge and Skills Do Students Bring with Them, and How Do We Determine What Students Already Know?

Once the desired outcomes of the course, and the order in which topics are best developed, have been decided, it is time to turn attention to how the course will be taught and assessed, and, as Ausubel said:[40] "[T]he most important single factor influencing learning is what the student already knows. Ascertain this and teach him accordingly." Students do not arrive at college as blank slates; they have been exposed to chemistry through various sources and often come into a course with knowledge that may or may not be scientifically accurate. There is a vast literature on common "misconceptions" (such as bond breaking releases energy,[41] or the composition of the bubbles in boiling water[42]), and it is increasingly clear that merely telling students the "correct" version rarely changes their understanding for the better. Moreover, many of these ideas are often loosely interwoven into either a somewhat coherent (if incorrect)

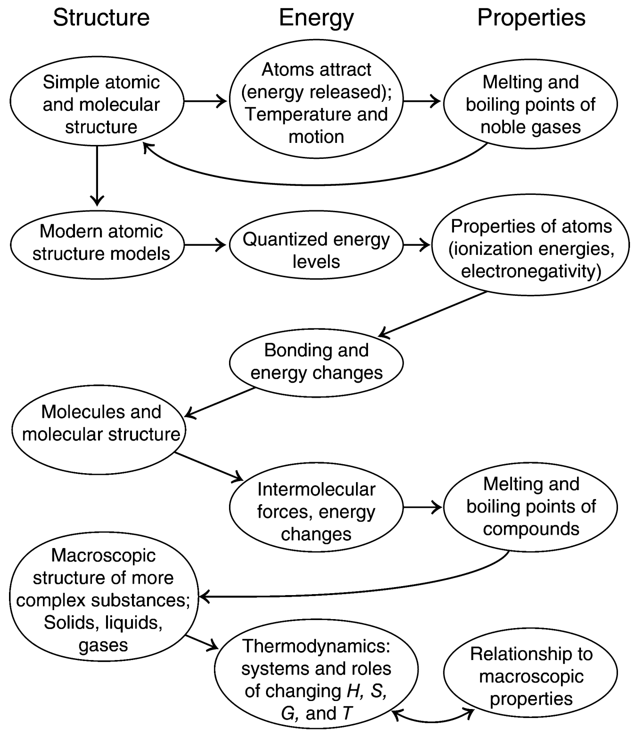

Figure 1. The three core disciplinary concepts and their interrelationship and progression through semester 1.

framework[43,44] or an unstable and context-specific assemblage.[45,46] All too often, students emerge from their chemistry (and physics and biology) courses with their original scientifically problematic ideas largely intact, and perhaps even augmented. For example, we have shown that students who take organic chemistry may incorporate inappropriate content from later courses in their explanations of structure−property relationships.[47]

A number of strategies can be used to elicit student thinking about a particular topic. New topics can be introduced with student worksheets that ask students to "tell us what you know about...", and subsequent activities can be designed to encourage metacognition, the Socratic examination of the assumptions held and the reasons for holding them. For example, we have developed and adapted in-class, clicker-type conceptual questions (sometimes taken from "concept inventories"[48,49]) that are used to provoke in-class discussion. Activities delivered through our beSocratic system[50] often begin by asking an open-ended question on the topic before instruction, and end by asking students to revise their answers (if necessary) after instruction. In addition, major sections of the text of these activities end with Questions to Answer, Questions to Ponder, and Questions for Later, which are designed to serve as catalysts for in-class discussion. It is only by eliciting student understanding of ideas prior to instruction that both learner and instructor can begin to address problematic ideas.

Question 4: What Materials and Experiences Are Most Appropriate for Learning Different Types of Knowledge and Skills?

A fairly wide range of concepts and skills must be mastered by students in general chemistry, yet not all of them are of equal difficulty and not all of them require valuable class time.[51,52] To optimize the use of class time, we have designed CLUE materials to be as flexible as possible. The CLUE text is much shorter than a traditional textbook, has few figures, and does not attempt to teach practices such as problem solving or how to draw structures. We took inspiration from two nontextbooks that we felt captured a readable and engaging style we sought to emulate: Bill Bryson's *A Short History of Everything*[53] and Albert Einstein and Leopold Infeld's *The Evolution of Physics*.[54]

An important note is that the "text" is not and should not be the curriculum. That is: it should not contain all the material that students need to know and do, as there is evidence that (for example) descriptions of how to solve a problem (be it stoichiometry or buffer) or of constructing representations are best presented using more than one mode of input (i.e., not simply reading, but with an audio and video component).[55] Such activities are better learned by watching, listening, and structured practice. We have prepared short videos that are available on YouTube,[56] and we may point students to lectures from places such as the Khan academy,[57] which are useful, particularly if students are required to view these materials critically, and are asked to point out what is missing, incorrect, misleading, or confusing. Students may also explore simulations such as those developed by us,[8] the PhET group,[58] or the Concord consortium[59] to investigate a particular concept. At the same time, such "learning aids" cannot substitute for a coherent curriculum and an effective, constructive learning environment. It is important that learners actively engage with the material and that they understand why they are learning the ideas and skills presented. If a course is built around heuristically answerable questions, it is likely that that is all the students will learn.[60,61] As an example, in prior studies[24] on the difficulties students have in learning to draw Lewis structures, it became apparent that students did not appreciate the value of Lewis structures in terms of understanding why a particular molecule had particular macroscopic properties, arguably the only reason one would want students to draw them in the first place. It was clear that drawing such structures was not meaningful for these students, a fact that contributed to their difficulties with both the task and the course as a whole.

One note of caution is prudent here: We believe that students must be given a consistent message about what is presented as important, what is stressed in course materials (including formative assessments), and what examinations are based on. For CLUE, all the materials were developed by the authors rather than including "supporting materials" that may or may not be relevant to the central themes developed by others. Each of the course components is an integral part of the students' learning experience; the activities are not "mix and match"; rather they are designed to complement one another. A more extended discussion of the materials that were developed for CLUE is provided in the Supporting Information.

Question 5: How Can We Assess Whether Students Have Mastered What We Hoped?

As noted above, assessments drive what is learned.[62] Even the "best" evidence-based curriculum will fail to bring about conceptual mastery if the assessments used focus on recall and algorithmic, heuristic (rather than) concept-based problem solving. If assessments are restricted to short multiple-choice questions focused on memorizable facts, students will rightly understand the implicit message—test performance is more important than understanding—and respond accordingly. Moreover, there is compelling data that merely repeating a large number of similar problems does not produce expertise. Rather, learners need to be challenged with increasingly difficult problems and activities: a procedure known as deliberate practice.[33] At each step learners must be encouraged to reflect on their learning, to communicate their understanding, and to construct representations, explanations, and arguments. It is for these reasons that we developed performance expectations that incorporate both disciplinary knowledge and science practices. That is, the assessments must address both components of the performance expectations, not just disciplinary knowledge.

It has been proposed that the lack of available constructivist assessments is, to some extent, a reason it has been difficult to provide compelling evidence for the efficacy of constructivist curricula.[63] We are aware that the use of student-constructed responses (not just limited to calculations) can be particularly difficult to implement in large-enrollment classes where instructor−student interactions are minimal and most student artifacts must be machine graded; nevertheless, this very real obstacle must be directly addressed if nontrivial performance expectations are to be achieved. In this light, we propose that assessment should be an integral part of the curriculum, not an add-on. Continuous formative assessment, in which students receive useful feedback and have the opportunity to learn (and recover) from mistakes, is crucial for deep, robust learning.[64] For CLUE, we have developed a range of formative assessments that are tightly interwoven with the text narrative and that combine both the content students are learning and the science practices that are emphasized in the course. For example: students are encouraged to provide scientific explanations (i.e., make a claim, using data and evidence, and link the claim and data with reasoning), construct (not merely recognize) models and representations (graphs, structures, molecular-level drawings, etc.), analyze data to find trends, and perform calculations. We provide students with real data to analyze—for example, concentration versus time data—so that students can determine rates and orders of reaction. When students are faced with real data they have to grapple with the kinds of problems they will see later, such as noise, outliers, and ambiguity. These kinds of activities are often an integral component in approaches such as PLTL[15] and POGIL[16] that involve active learning. Materials developed by these groups are an excellent resource for assessment materials, if they fit with the developmental progression and goals of the curriculum. An example of an assessment that can be done in class, during recitation, or online is given in the Supporting Information.

■ A NOTE ON EVALUATION OF NEW CURRICULAR APPROACHES

Researchers face a difficult challenge when attempting to evaluate the impact of a new curriculum in comparison to existing approaches. Issues such as what to assess, what assessments to use, the experimental design and makeup of the comparison groups, and the very fact that there is an inherent conflict of interest when assessing one's own work can all be problematic. However, being cognizant of these factors can help researchers avoid some of the potential pitfalls. For example, while student attitudes and motivation are important, assessments in which students are asked if they "like" the new curriculum are not particularly persuasive. It is important to use validated instruments, and to measure what you believe is important (not what is easy to measure). The "gold standard" for educational experiments is a design in which students are randomly assigned to a control or treatment class, and all other factors (instructor, class size, time, student background and abilities) are kept constant.[63] However, in practice, these kinds of experiments are almost impossible to perform, and some factors simply cannot be addressed: for example, it is highly unlikely that the same instructor teaching both sections will be equally committed to both. This does not mean that curricular comparisons should not be undertaken, but rather that the pitfalls of each experimental design need to be understood and addressed wherever possible.

In our assessment of CLUE, we used a quasi-experimental design[65] to compare two cohorts of students for whom there were no significant differences in any of the measures we used (SAT score, sex, major, TOLT score). We use a number of different instruments and assessment methods to triangulate on a particular learning goal. For example, in our studies on structure−property relationships we used the IILSI,[66] a validated instrument that assesses what concepts student can connect to structural representations, and OrganicPad,[67] a drawing program that allows us to record and grade student free-form chemical structure drawings; we also interviewed students and used open-ended text responses.[68] Other studies using similar methods are underway looking at other aspects of learning in CLUE, yet ultimately strong evidence for change must come from longitudinal studies across multiple types of institutions.

■ SUMMARY

While more active pedagogical strategies are clearly valuable, it is time to think about the curriculum itself, what is important for students to master, and how best to present these ideas and skills.[68] We present a description of the ideas and concepts that guided our development of the CLUE curriculum in the hope that others will critically question the "received curriculum", and seriously consider the benefits, to majors and nonmajors alike, of a more coherent and focused approach to general chemistry (and in fact to all chemistry courses) and how it can be implemented. There is growing evidence using comparative and longitudinal data from our project that an "intelligently designed" curriculum can improve student-learning outcomes. At the same time, we are well aware that many will find it difficult to abandon the traditional general chemistry approach because of institutional pressures and expectations; nonetheless, objective assessment has shown that overburdening students with a poorly conceived curriculum is neither effective nor beneficial, at least if learning is the goal.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Details on how the five questions are implemented in the CLUE curriculum; discussion of how the core concepts are interconnected; sample knowledge statements, science practices, and performance expectations; materials developed for the curriculum; example worksheet. This material is available via the Internet at http://pubs.acs.org.

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Notes

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