

Chemistry, Life, the Universe and Everything: An Evidence-Based, Transformed General Chemistry Curriculum

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Abstract

General Chemistry is a gateway course for many students intending on careers in scientific, engineering and health care related disciplines. While there have been many attempts to improve the outcomes for these students, little has changed over the past 60 years. Recent transformation efforts have focused primarily on incorporating student engagement techniques into the course, rather than considering what it is that is important for students to learn. Chemistry, Life the Universe and Everything (CLUE) is a transformed general chemistry curriculum, developed by an interdisciplinary team of a chemist and a molecular biologist, that aims to bring about evidence based change in general chemistry. CLUE was developed using a design research approach that focuses on scaffolded progressions around four core ideas: structure and properties, bonding and interactions, energy, and change and stability. The course emphasizes causal mechanistic reasoning in order to help students move beyond knowing *that*, to knowing *how* and knowing *why* chemical phenomena occur.

The materials developed include a text (supplied free to students), lecture support materials, workshop/recitation activities, video mini-lectures, and formative and summative assessment materials. We have now taught the course for over five years, and this year all general chemistry students at Michigan State University took the CLUE curriculum. We have assessed the outcomes of CLUE in a number of different ways and find that in general course grades are higher than similar traditional sections, and ACS examination scores are similar. However, when we assess specific skills such as understanding how intermolecular forces operate, or the ability to determine and predict structure-property relationships, we find that CLUE students are significantly better at these tasks than a matched cohort of students from traditional sections. Perhaps even more importantly, these improvements are maintained throughout a year of (conventional) organic chemistry instruction.

Introduction:

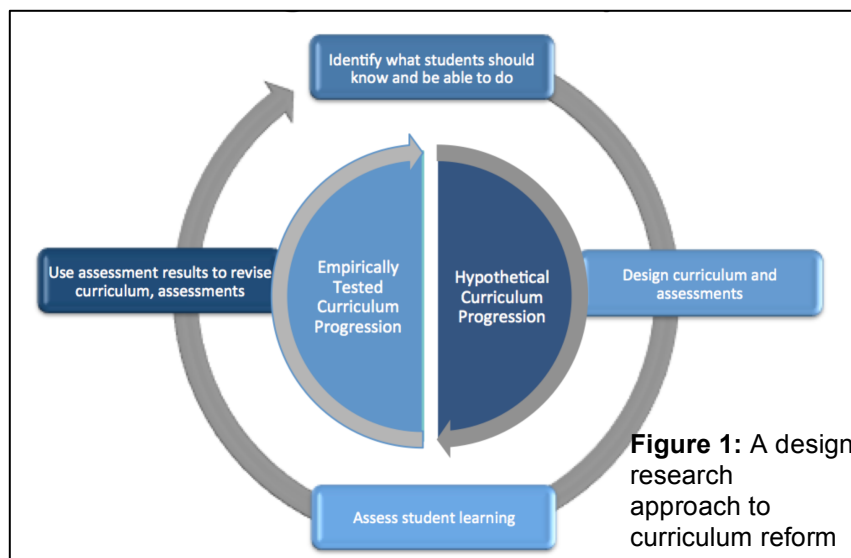
The history of instruction in general chemistry is one of repeated calls for reform, yet from more than 60 years little of substance has changed. Those reforms that have been enacted have focused on engaged pedagogies which have been shown to improve course grades, primarily reductions in failing grades¹. What has not changed is the overall course content and structure, which has remained a vast compendium of disconnected topics and skills that students are expected to master. Yet, there is evidence that such courses pose unnecessary barriers to student engagement and fail to achieve a high level of concept mastery². Chemistry, Life, the Universe and Everything (CLUE) is a transformed curriculum that uses evidence-based approaches to

teaching and learning to structure a more effective approach to understanding chemistry³.

Curriculum Design:

The design of the CLUE curriculum was initially based on two principles: how concepts in chemistry relate to one another and the extant research on how students learn, both generally and in chemistry⁴. We used a design research approach to the iterative development and implementation of the curriculum⁵. We

began with a consideration of the chemistry content that students need, the theoretical curriculum presented as a scaffolded progression around four core ideas (see below). Based on the results of our studies we revised the materials in an iterative process, so that over time, the curriculum has become empirically tested as shown in Figure 1.



Core ideas: It is now well accepted that expert's knowledge is organized around a small set of core ideas that are connected and contextualized so as to be accessible and useful. As discussed in the NRC Framework for Science Education⁶, only if new knowledge is linked to core ideas central to the discipline does it have explanatory power and can be used to approach novel situations. Based on the assumption that students take general chemistry for the broader insights it provides, the goal of CLUE was that it would help students develop a useful transferrable knowledge base. In our initial framing of the CLUE curriculum we chose three core ideas: Structure, Properties and Energy. Based on our own research and that of others^{6,7}, we have come to re-structure CLUE so that it is organized around four core ideas: Bonding and Molecular Interactions, Structure and Properties, Energy (molecular, macroscopic and quantum), and Change and Stability. The topics presented in CLUE are supported and linked back to these core ideas in order to help students develop a more expert-like framework.

Progressions of Ideas: In order for students to develop coherent understanding of these core ideas and how they are interconnected, the new knowledge must be linked and appropriately scaffolded. In more traditional general chemistry courses it is possible to “juggle” the chapters or topics, so that what students learn is not connected to other material. A case in point is the ways that students connect atomic and molecular structure and properties. This is a connection that research evidence suggests is difficult for students². While we might imagine that students use a principled approach that involves drawing a structure, understanding its three dimensional nature, determining molecular polarity, and intermolecular forces, we have found that

conventional course designs leave many students unable to put these steps together². The CLUE curriculum is designed to support these connections.

What should students be able to do with their knowledge? In addition to knowing *that* chemical phenomena occur, it is as (or arguably more) important that students understand *how* and *why* these phenomena occur. That is, if all students can do is to regurgitate facts, apply heuristics, and perform algorithmic calculations, without understanding and connecting their meanings, it is highly unlikely that they will be able to build a useable knowledge base or apply what they have learned to new situations. While pattern recognition and algorithms may enable students to succeed in a traditional course, they will not lead to useful insights. In contrast, our goal in CLUE is to help students develop an understanding of causal mechanistic reasoning that will help them make connections between the ideas that they learning and how to use these ideas. The science practices of constructing models and explanations, as well as analyzing and interpreting data, and mathematical reasoning (as described in the Framework⁶) are central to the design of CLUE and its pedagogical implementation. At each step of the course students are asked to draw diagrams and use them to explain how and why chemical phenomena occur.

Materials and Resources: It has become clear that different materials and resources support different aspects of learning. For example, learning how to perform a procedure (drawing Lewis structures, doing a stoichiometry problem) is best learned by watching and hearing an instructor describe the process⁸. Understanding *why* one should learn such tasks, however, requires materials that supply a relevant and engaging narrative. We have therefore designed a range of integrated materials to achieve this end. The text is relatively short (~210 pages for a two semester course), written in an engaging style, and designed to supply the narrative drive for why ideas are presented in the order that they are and why students should learn them. We acknowledge explicitly that for students to acquire new knowledge in a meaningful (i.e. useable) way it must be i) connected to their prior knowledge and ii) connected to a clear purpose. To engage students we must explain why what they are learning matters to them. To return to the example of structure and properties, if students do not understand why they are learning certain skills, such as drawing Lewis structures, it is unlikely that they will be able to apply their learning to future tasks or even remember how to do the original task.

Other materials that are part of CLUE include lecture support materials, short video lectures on specific skills, group workshop or recitation materials, formative assessment items and summative examinations. All of these have been refined on an iterative basis based on feedback from students, instructors, and our own research findings.

Assessing Student Learning: The aspect of CLUE that has changed most over the implementation of the curriculum is the nature of the assessments that we are developing and using. We have used the ACS conceptual examination for general chemistry and shown that CLUE students are at least as well prepared as their peers according to this measure. We know, however, that students who score very highly on these nationally normed examinations have significant problems when faced with tasks that require them to predict and explain phenomena². By designing assessments that

reveal and monitor the kinds of understanding that we are trying to develop in our students, we have recognized and modified elements of the original CLUE curriculum design.

In particular, we have used beSocratic (NSF DUE #1122472, (1341987)), a web-based system that allows us to post tasks to students where they must write and draw⁹. For example, we ask students to explain why the temperature decreases (or increases) when sodium chloride (or any solute) dissolves in water. We have designed over 60 beSocratic activities (tutorials and formative assessments) to accompany CLUE. We have also developed approaches to designing summative assessments, such as multiple choice items that ask students to choose claim, evidence and reasoning. However we always include constructed response items on examinations.

Implementation: The CLUE general chemistry course has now been offered at two universities, beginning with a pilot section of ~50 students in 2010. In Fall 2015 CLUE was offered in a multi-section large enrollment course to all ~2500 students at MSU. During the past four years, we have conducted investigations on student outcomes, a number of which have already been published (see below). We have also monitored and compared student grades and persistence. Although we do not yet have data for Fall 2015, in Fall 2014 when two sections (~850 students) were taught using the CLUE curriculum and around 1650 students in a traditional curriculum, the DWF rate for CLUE (i.e. the students who cannot continue in STEM without retaking general chemistry) was around 15% compared to a DWF rate of ~33% in the traditional sections. However, while improved grades and persistence are important, it is also important to examine what exactly students know and can do with that knowledge; does successfully completing CLUE lead to improved learning? To this end, we have been designing and carrying out research studies to better monitor how CLUE affects on student understanding of chemistry

Research on Outcomes: Here we summarize a few of the studies we have designed. In these studies we were able to compare cohorts of students matched by demographic information, SAT scores and validated survey responses. We note, however, that as we move forward we have lost our “traditional” cohorts of students for comparisons (since all students are taking CLUE); in future we will rely on design research studies (see future directions).

Study one: a comparison of Lewis structures drawing ability¹⁰:

In this study, we hypothesized that if students understood the rationale of why they were asked to learn how to draw Lewis structures it would lead to measurable improvements in their ability to draw such structures and to make

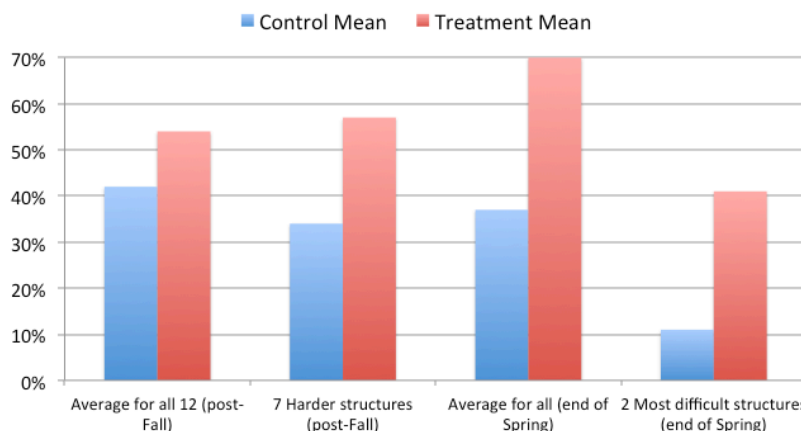


Figure 2: A comparison of two matched cohort of students' correct drawing of Lewis structures.

predications about the physical properties and reactivity of the molecules. Using OrganicPad¹¹, a pre-cursor to beSocratic, we found that CLUE students (N = 99) were significantly better (effect size 0.6) at drawing Lewis structures than the matched traditional cohort (N=127) and that this improvement continued throughout the year, that is into the second semester when drawing Lewis structures was no longer actively taught.

Study two: Do students understand that Lewis structures can be used to predict chemical phenomena?¹² Using a survey that we designed and validated¹³, and a statistical method called survival analysis¹², we investigated how student responses changed over two years of chemistry instruction. The ILSI (the implicit information from Lewis structures instrument), asks students to identify what information they could deduce from a given structure. As shown in Figure 3, CLUE students indicate that they understand this connection earlier, and that this improvement was maintained over four semesters of chemistry (that is, throughout a traditionally structured two semester organic chemistry course). Note that the traditional students never reach the 75% threshold for either physical properties or reactivity.

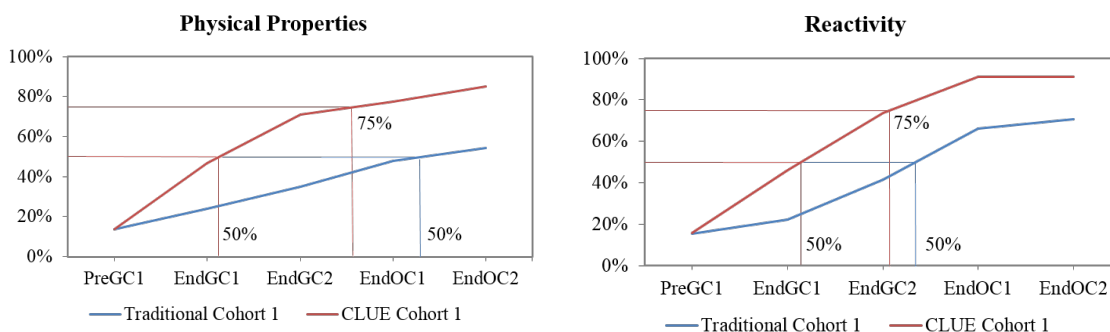


Figure 3: Survival analysis curves for ILSI responses about physical and chemical properties. These studies were replicated (CLUE Cohort 1: N = 88 and CLUE Cohort 2: N = 177, Traditional Cohort 1: N = 125, Traditional Cohort 2: N = 111).

Study three: A comparison of students' understanding of intermolecular forces¹⁴.

The ILSI is a student self report, and while understanding that a connection can be made is an important first step, it is not the same as being able to make a meaningful connection. By the end of two semesters of general chemistry, both traditional and CLUE students in our study indicated that they could determine intermolecular forces from a given structure. Using beSocratic we asked students to draw three molecules of ethanol and indicate where the intermolecular forces (IMFs), hydrogen bonding, dipole-dipole, and London dispersion forces, were located. Because these are small molecules all IMFs occur between molecules. Student drawings were coded as showing IMFs as either within or between molecules (other codes such as ambiguous are not shown here for clarity). There was a large disparity between the drawings for CLUE and traditional students (Figure 4); while the majority of CLUE students drew IMFs as between molecules, traditional students drew them as occurring within molecules. Even more surprisingly, it appears that these differences persist through two semesters of organic chemistry. These findings have been replicated with a second cohort at a different institution. Clearly, if students do not understand how and why molecules interact, it will

be difficult (impossible) for them to develop causal mechanistic explanations for chemical phenomena.

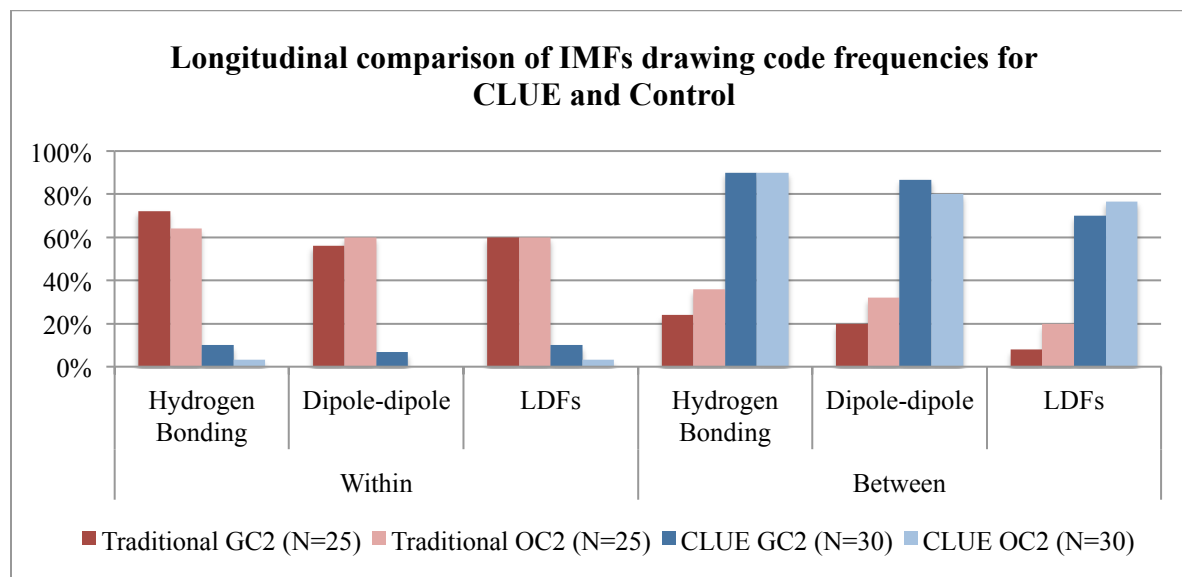


Figure 4: A longitudinal comparison of the ways that students draw intermolecular forces.

Ongoing and future work: All of our previous published studies involved quasi-experimental designs with matched cohorts of students. Our ongoing work is based on design research studies and involves a wider range of investigations, including interactions between light and matter, acid-base reactivity, and the relationship between molecular and macroscopic energy changes. As in our previous work we will use the results of these studies to revise the CLUE curriculum and materials.

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MELANIE COOPER is the Lappan-Phillips Professor of Science Education and Professor of Chemistry at Michigan State University. Her research has focused on improving teaching and learning in large enrollment general and organic chemistry courses at the college level, and she is a proponent of evidence-based curriculum reform for example the NSF supported “*Chemistry, Life, the Universe & Everything*” curriculum for general chemistry. She has also developed technological approaches to formative assessment that can recognize and respond to students free-form drawings such as the *beSocratic* system. She is a Fellow of the American Chemical Society and the American Association for the Advancement of Science, and is on the National Research Council Advisory Board on Science Education (BOSE). She was a member of the NRC committee that produced the DBER report, and is currently a member of the NRC committee on Undergraduate Research Experiences. She was also member of the Leadership team for the Next Generation Science Standards (NGSS). She has received a number of awards including the ACS Award for Achievement in Research on Teaching and Learning in Chemistry (2014), the Norris award for Outstanding Achievement in Teaching of Chemistry (2013), and the Outstanding Undergraduate Science Teacher Award from the Society for College Science Teaching (2011). She earned her B.S. M.S. and Ph.D. in chemistry from the University of Manchester, England.