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Restructuring a General College Chemistry Sequence Using the ACS Anchoring Concepts Content Map

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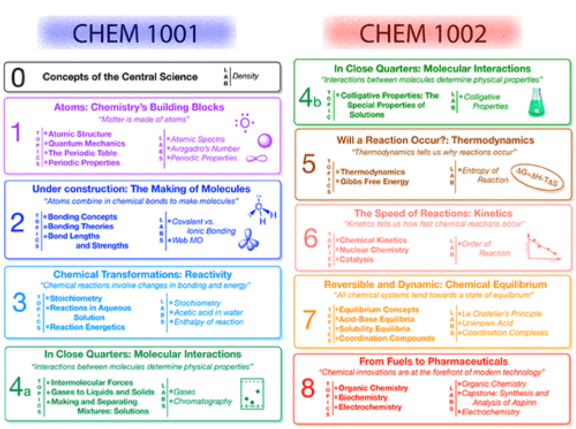
Abstract



Many STEM (science, technology, engineering, and mathematics) disciplines require a two-semester sequence of introductory college chemistry, which are thus critical gateway courses to a variety of majors. Recognizing the benefit to educators of a structure of content learning across the chemistry curriculum, in 2012, the American Chemical Society (ACS) developed the Anchoring Concepts Content Map, or ACCM. The development and subsequent revision of the general chemistry ACCM inspired the restructuring of our first-year chemistry sequence. Thus our CHEM 1001 and 1002 courses, taught in an atoms-first framework, were reorganized into a set of nine modules, each intentionally linked to one (or more) anchoring concept of the ACCM. In this initial effort, we have developed the course modules and subtopics and a set of learning objectives for each module and linked these to the general chemistry ACCM. To facilitate the initial teaching of the courses, the redesign occurred during the academic year, and the courses were taught in summer term 2019 using a flipped classroom design with three weekly 100 min face-to-face discussion meetings and two weekly laboratories for the 6 week long courses. Herein we describe the course design and its mapping onto the ACCM and discuss the results of the initial implementation, with suggestions given for future adaptations.

KEYWORDS:

First-Year Undergraduate, General, Hands-On Learning, Manipulatives, Curriculum, Distance Learning, Self-Instruction, Internet

Introduction

The first-year introductory college chemistry sequence represents a critical gateway for students in a wide array of science-, technology-, engineering-, and mathematics-related (i.e., STEM) disciplines. It is therefore not surprising that the design of the first-year course of study has attracted much interest, and variations in the content and the ordering of content are significant, reflected also in the wide range of available textbooks. Despite calls for reform, it is fair to say that the recent chemical education literature concerning the introductory chemistry sequence has focused as much on course and laboratory pedagogy as on course curriculum, content, or structure, with a continued emphasis on the incorporation of research-based instructional strategies (RBIS) such as flipped classrooms and studio-style courses,(1−6) process-oriented guided inquiry learning,(7) peer-led team learning,(8,9) and learning communities.(10)

Notable efforts in the development of the content and structure of the general chemistry curriculum include the “atoms-first” curriculum(11,12) and studies of the impact of an atoms-first sequencing,(12) a refocusing and restructuring of the curriculum,(13−15) reflections from a redesign of the advanced placement chemistry curriculum,(16) restructuring to encourage higher order thinking using learning taxonomies,(17) teaching introductory chemistry with rich contexts,(18,19) structures centered around key ideas,(20) anchoring concepts,(21) or chemical thinking,(22) the CLUE project,(23) and the recent *Chemistry Unbound* project at Emory.(24) In addition, several models for integrated one-semester courses have been reported.(25−27) Given that the first-year courses are gateway courses for a variety of STEM majors and degree programs and are often taken jointly with introductory biology or physics, efforts have also focused on strengthening connections to concepts in those subjects.(11,28−31)

To provide a coherent framework for knowledge assessment across the undergraduate curriculum, which leveraged the extensive sets of normed exams developed by the American Chemical Society Exams Institute, in 2012 Murphy, Holme, and coworkers reported the Anchoring Concepts Content Map, or ACCM.(21) This map is centered around a framework of 10 anchoring concepts, or “big ideas”, reproduced in Table 1, which are consistent across the undergraduate chemistry curriculum and form the upper level (level 1) of four tiers of levels. Level 2 represents a set of “Enduring Understandings”, which includes some 70 items and is also consistent across the undergraduate chemistry curriculum, whereas levels 3 (∼100 items) and 4 (∼1000 items) drill down into subdisciplinary articulations and content details, respectively.(21) The ACCM was developed over a 3 year period and involved multiple workshops and focus groups to engage the chemistry community.(21)

Table 1. Anchoring Concepts of the ACS ACCM (Reproduced from Reference (21))

Number	“Big Idea”	Anchoring Concept
1	Atoms	Matter consists of atoms that have internal structures that dictate their chemical and physical behavior
2	Bonding	Atoms interact via electrostatic forces to form chemical bonds
3	Structure/Function	Chemical compounds have geometric structures that influence their chemical and physical behaviors
4	Intermolecular Interactions	Intermolecular forces, electrostatic forces between molecules, dictate the physical behavior of matter
5	Chemical Reactions	Matter changes, forming products that have new chemical and physical properties
6	Energy and Thermodynamics	Energy is the key currency of chemical reactions in molecular scale systems as well as macroscopic systems
7	Kinetics	Chemical changes have a time scale over which they occur
8	Equilibrium	All chemical changes are, in principle, reversible, and chemical processes often reach a state of dynamic equilibrium
9	Experiments, Measurement, and Data	Chemistry is generally advanced via empirical observation
10	Visualization	Chemistry constructs meaning interchangeably at the particulate and macroscopic levels

In the same year, the general chemistry ACCM was developed.(32) One immediate application of the general chemistry ACCM(32) was to examine the content assessed by ACS general chemistry examinations.(33) Thus roughly 2000 ACS exam items were aligned to the ACCM. It was found that at the “Enduring Understandings” level (i.e., tier 2), some 17 items had been rarely tested on the exams.(33) These items covered important topics (e.g., noncovalent forces in large molecules) for students in the life sciences and other areas. Overall, this study highlighted the usefulness of the ACCM in identifying conceptual deficiencies (or “holes”) in course content. Subsequently, concept maps for organic,(34) inorganic,(35) and physical chemistry(36) have been published.

Recently, the general chemistry ACCM has been updated.(37) The current version of the content map contains a total 263 articulations (or nodes) through level 4. Whereas we recognize that the ACCM is but one possible scheme for implementing an anchoring concepts framework and was developed with a view toward assessing chemistry majors,(21) the formulation of the general chemistry ACCM inspired us to restructure the first-year chemistry sequence at Marquette, which typically enrolls some 1300 students annually, the majority of which are nonmajors. A separate course sequence (CHEM 1013/1014) exists for chemistry and biochemistry majors. Our CHEM 1001 and 1002 courses, which have been recently taught using an atoms-first approach, were reorganized into a set of nine modules, each intentionally linked to one or more anchoring concept of the ACCM. The goals of this endeavor were two-fold. First, because levels 1 and 2 (anchoring concepts and enduring understandings) are consistent across the chemistry curriculum, our hypothesis is that the realignment of the first-year courses within an anchoring concepts scheme could aid students in identifying and reinforcing key concepts in organic chemistry and beyond, assuming that the corresponding concept maps are implemented there.(34) This is particularly important at Marquette, where roughly 35% of students taking general chemistry are in programs that also require organic chemistry. Second, the alignment of the course learning objectives to the ACCM provides a mechanism to map ACS exam items to course learning objectives and thereby identify conceptual deficiencies in course content and assessments.

In this initial effort, we have developed the course modules and subtopics and a set of learning objectives for each module and linked these to the ACCM. To facilitate the initial teaching of the courses, the redesign occurred during the academic year, and the courses were taught in summer term 2019 using a flipped classroom design with three weekly 100 min face-to-face discussion meetings and two weekly laboratories for the 6 week long courses. Whereas this was the best mechanism for introducing the redesigned courses, the small student populations in these courses precluded a detailed statistical analysis. Thus, in this article, we focus on a description of the course designs and the connection to the ACCM and discuss qualitative results of the initial implementation, with suggestions given for future adaptations. We will also describe the implementation of a revised CHEM 1001 design across all CHEM 1001 sections in Fall 2019.

Course Design and Implementation

Figure 1 shows the set of nine modules (numbered from 0 to 8) developed for the redesigned courses. The advantage of a modular approach is that individual modules could in the future be reordered with little additional effort. Within each module is shown the broad set of topics and associated laboratory exercises and experiments. In the initial course redesign, the laboratory program itself was not modified, although the laboratory experiments were realigned to the new sequencing of topics. The redesign was intended to be textbook agnostic, and no attempt was made to align with a given text.

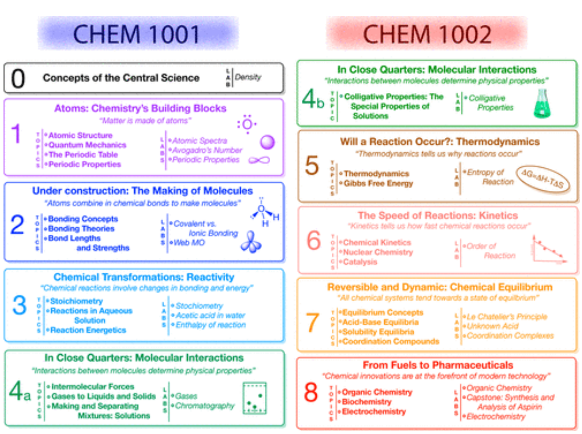


Figure 1. Modules for CHEM 1001 (left panel) and CHEM 1002 (right panel). For each module, the set of included topics and associated laboratory exercises are shown.

Beginning with the first semester course, CHEM 1001, the initial module (denoted Module 0, Figure 1) addressed the scientific method, units, and dimensional analysis. Within the atoms-first sequencing, the remainder of the first-term course consisted of atomic structure and theory (Module 1), chemical bonding and molecular structure (Module 2), and chemical reactivity (Module 3) and closed with intermolecular forces and states of matter (Module 4, part a). Module 4 served as a bridging module into the second-semester course, which began (Figure 1, right panel) with a discussion of colligative properties (Module 4, part b), followed by chemical thermodynamics (Module 5), chemical kinetics (Module 6), and chemical equilibrium (Module 7). The second-term course closed with topics of organic chemistry and electrochemistry (Module 8), which served as a bridging module to Organic Chemistry. Whereas electrochemistry is often incorporated as a component of chemical equilibrium, Module 7 was the largest single module, including topics in chemical equilibrium, acid–base equilibria, solubility equilibria, and coordination compounds and their equilibria. Thus electrochemistry was moved to the final module, coinciding with the final laboratory exercise.

The course modules in Figure 1 were further divided into 40 subtopics, each with a set of learning objectives (187 in total). A goal of the realignment was to connect each module strongly to (ideally) one anchoring concept and thereby link the underlying learning objectives to the general chemistry ACCM. In our analysis, we drilled down to level 3 of the general chemistry ACCM, which included 143 total articulations. The complete set of topics, learning objectives, and the associated ACCM articulations are provided in Table S1. In Figure 2, we show an overview of the primary anchoring concept(s) associated with each module. The number in parentheses indicates the number of level 3 ACCM articulations (nodes) associated with that given module. Individual ACCM items could be associated with more than one module.

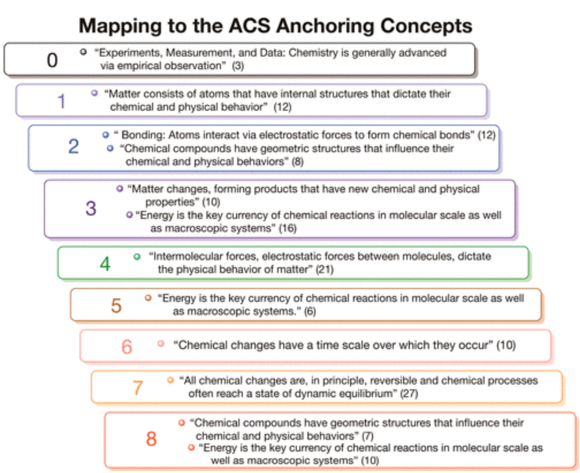


Figure 2. Mapping of the individual modules to the anchoring concepts of the ACCM. The numbers in parentheses give the number of level 3 ACCM articulations mapped onto that module.

In all, nine of the anchoring ACCM concepts were strongly associated with at least one of the course modules. Concept 6 of the ACCM,(37) "Energy is the key currency of chemical reactions in molecular scale as well as macroscopic systems" was the only concept significantly linked to three course modules, Module 3 (Reactivity), which included thermochemistry, Module 5 (Thermodynamics), and Module 8, which included electrochemistry. Whereas this is natural given the importance of energy as a topic, below we suggest modifications to our course structure that might improve the alignment of this concept. Concept 9,(37) “Experiments, measurements, and data: Chemistry is generally advanced via experimental observations”, and its associated articulations were also highly linked with the laboratory portion of the course. Because the summer period did not allow any significant modification of the laboratory component beyond a simple realignment of the experiments, we made no effort here to correlate the ACCM map with our laboratory program. Such an endeavor is planned for the future.

The initial implementation of this course structure was carried out in summer 2019, where CHEM 1001 and 1002 were taught as back-to-back 6 week flipped courses with three 100 min discussion periods (meeting Monday, Tuesday, and Wednesday) and two 3 h laboratory sessions (meeting Monday and Wednesday) each week. The lecture content was delivered as recorded voice-over Powerpoint-based videos, captured and edited using CAMTASIA 2.0 software(38) with a WACOM Bamboo tablet.(39) The edited video lectures averaged 15 min in length, and typically two lectures were assigned for each class period. Each video was paired with a nonadaptive homework set on ALEKS;(40) students were given three chances to complete the homework sets. Before coming to the discussion, students were asked to post a question to the online discussion board. The in-class activities were primarily problem-solving, using the CHEM 101 platform;(41) however, short “microlectures” (one- to two-slide lectures) were often given on specific topics.(42) Participation points were awarded for discussion attendance and for posting questions to the online discussion board. Following the three (Monday, Tuesday, and Wednesday) discussion meetings, a set of adaptive ALEKS objectives was opened; these were typically due on Sunday of that week.

Results and Discussion

We first consider the outcomes of the standardized ACS exams given as the final exams in these courses. Because the summer enrollments were small (20 in CHEM 1001; 26 in CHEM 1002) and only 1/3 of the CHEM 1001 students continued into CHEM 1002, a meaningful statistical analysis of student performance in comparison with prior offerings was not possible. For example, the final ACS exam performance was significantly higher in the Summer 2019 CHEM 1001 course (+5% compared with the national norm with reference to the 70-point scale) as compared with Summer 2018 (−18%); however, as assessed by the performance on the in-semester exams, the overall student cohort was also stronger. Given the specific goals of this effort, it is not assumed that the realigned course should lead to an overall improvement in ACS exam performance. However, once the mapping of ACCM to course learning objectives was completed, it was possible to align ACS exam items to course learning objective and thereby examine detailed student performance in comparison with nationally normed data. As an illustration, in Table 2 we show a comparison of student performance on the final ACS exam in CHEM 1001 across the set of subtopics. The mean score on the exam, a first-semester 70 question general chemistry exam that is not identified here for confidentiality, was 5% above the national mean.(43) The % difference indicates the difference between the observed and the expected score for the set of exam items linked to that topic based on the nationally normed item difficulty metrics. Again, to preserve confidentially, the specific number of linked exam items is not shown; however, typically two to seven exam questions were linked to a given topic.

Table 2. Comparison of ACS Exam Items across CHEM 1001 Course Topics

Module/Topic	% diff in ACS Exam Items[a]
Module 0: Central Concepts of the Central Science	**+13%**
Module 1: Atoms, Chemistry's Building Blocks	**+30%**
Module 1.1: Structure of the Atom	+36%
Module 1.2: A Model of the Atom	+95%
Module 1.3: Orbitals and the Periodic Table	+5%
Module 1.4: Periodic Trends for Atoms and Ions	+29%
Module 1.5: Atomic Masses and the Mole	+24%
Module 2: Under Construction, Making Molecules	**–2%**
Module 2.1: Bonding Basics, Part A	0%
Module 2.2: Bonding Basics, Part B	–8%
Module 2.3: Making Molecules	+2%
Module 2.4: Bonding Theories, Part A	–6%
Module 2.5: Bonding Theories, Part B	+8%
Module 3: Chemical Transformations, Reactivity	**–2%**
Module 3.1: Stoichiometry, Part A	–8%
Module 3.2: Stoichiometry, Part B	–5%
Module 3.3: Reactions in Aqueous Solution, Part A	+4%
Module 3.4: Reactions in Aqueous Solution, Part B	+19%
Module 3.5: Reaction Energetics, Part A	–9%
Module 3.6: Reaction Energetics, Part B	–19%
Module 4a: In Close Quarters	**–11%**
Module 4a.1: Intermolecular Forces	–10%
Module 4a.2: Properties of Gases, Part A	–10%
Module 4a.3: Properties of Gases, Part B	–10%
Module 4a.4: From Gases to Liquids and Solids	0%
Module 4a.5: Solutions: Chemical Mixtures	–25%

[a]% difference of actual versus expected score based on item difficulties.

Viewed across the learning topics, differences between the observed and the expected score can show conceptual holes or gains with respect to the reference set. For example, our students performed well with respect to the national norms across all subtopics of Module 1, dealing with the atomic structure. For Module 3, the aggregate performance was similar to the national norms; however, our students performed more poorly across all questions linked to subtopic 3.6, which examined the enthalpy of reactions, Hess's Law, enthalpies of formation, and bond energies. Similarly, our students performed more poorly across all subtopics of Module 4a, which was the final set of topics covered. Again, the statistics are insufficient to draw out specific conclusions; therefore, the point of this comparison is merely to illustrate how mapping exam items onto course objectives can be used to identify potential conceptual holes or gains in a course design.

A similar analysis was conducted for the CHEM 1002 course, where again a 70 question second-semester ACS exam was utilized. The exam items were mapped onto the course modules and learning objectives. The results are shown, again for illustrative purposes, in Table S2. Here the overall course mean was 3% above the national mean.

We also examined data from student evaluations. Data from the summer CHEM 1001 course was compared with that from flipped courses taught by the same instructor with similar student enrollments in Fall 2018 and Summer 2018. For the CHEM 1002 course, we compared data with a larger enrollment flipped course taught by the same instructor in Spring 2016 because in the latter, there were multiple sections offered, and students self-selected into the flipped course; the comparison here is less than ideal. Student feedback was collected using the standard University Online Course Evaluation, a 15-item 6-level Likert-scale questionnaire,(44) which also contained a free commentary section. The evaluation submission window was opened at the end of the term, prior to the final exam; results were made available after the completion of final course grades. Table 3 provides the results of the key student evaluation metrics.

Table 3. Summary of CHEM 1001 and 1002 Student Evaluation Means

		CHEM 1002		CHEM 1001		
Question	Key a	Summer 2019	Spring 2016	Summer 2019	Fall 2018	Summer 2018
How was this class as a whole?	1	4.5	4.7	5.6	4.6	4.8
How was the content of this class?	1	4.5	4.7	5.6	4.6	4.8
This class positively impacted my problem-solving abilities.	2	5.2	5.1	5.7	4.7	4.6
This class was intellectually challenging.	2	5.8	5.6	5.4	5.5	5.0
Evaluations were consistent with course objectives.	2	5.0	5.1	5.7	4.8	4.8
Relevance and usefulness of lab section content was...	1	4.8	4.2	5.3	4.5	4.4
Coordination between lecture and lab activities was...	1	4.7	4.5	4.6	4.2	4.2
Response rate		40%	59%	35%	57%	38%

[a]Key 1: 6 = excellent, 5 = very good, 4 = good, 3 = fair, 2 = poor, 1 = very poor. Key 2: 6 = strongly agree, 5 = agree, 4 = agree somewhat, 3 = neither agree nor disagree, 2 = disagree somewhat, 1 = strongly disagree.

Addressing first the data from the CHEM 1001 student evaluations (Table 3), the evaluation metrics for the prerealignment courses (i.e., Summer 2018 and Fall 2018) were nearly identical. For the redesigned course, the evaluations were almost uniformly one point higher on the six-point Likert scale, with the exception of the intellectual rigor of the class (similar) and the coordination of lecture and laboratory activities (increased by roughly 1/2 point). Whereas the response rate for all of these courses was relatively poor and the small sample sizes preclude a meaningful statistical analysis, it is fair to say that initial student evaluations of the redesigned CHEM 1001 course were positive in comparison with the prior offerings. For CHEM 1002, the responses were almost uniformly lower than those for CHEM 1001 but were similar to those received in the comparison course. Overall, student comments were in line with the Likert-style questionnaire items and showed that the courses were well received.

Examining the mapping of course learning objectives and content onto the ACCM, we first consider the course learning objectives not explicitly included in the revised general chemistry ACCM (Table S1). These included the following, by module:

- Module 0
    - Describe the components of the scientific method.

    - Differentiate between hypothesis, theory, and law.
    - Differentiate between base and derived scientific units.
- Module 1
    - Define the de Broglie hypothesis and perform calculations of de Broglie wavelength.
    - Describe the uncertainty principle of quantum mechanics.
    - Differentiate between base and derived scientific units.
- Module 2
    - Describe the vibrations of bonds and connect to the absorption of infrared radiation and the greenhouse effect.
    - Identify common polyatomic ions.
    - Define formal charge and use it to assess the relative validity of Lewis structures for a molecule.
- Module 4
    - Describe a and b factors in the van der Waals equation and discuss their origin.
    - Describe the unique features of the phase diagram of water and connect to the physical and chemical properties of water.
    - Define what is meant by amphiphilic and give molecular examples.
- Module 7
    - Compare and contrast heterogeneous and homogeneous equilibria and give examples of each.
    - Differentiate between strong and weak field ligands.
    - Use crystal field theory to predict the spin characteristics of coordination compounds.
- Module 8
    - Differentiate between nucleophiles and electrophiles.
    - Describe different reaction types.

Overall, 170 of the 187 objectives (91%) were strongly linked to the ACCM. In this mapping, we also examined which ACCM articulations or nodes in levels 1–3 were not included in the redesigned courses. These included:

- Concept II.G.2: “A more rigorous model of metallic bonding depicts electrons occupying bands.”
- Concept III.C: “Theoretical models are capable of providing detailed structure for whole molecules based on energy minimization methods.”
- Concept IV.B.1: “Macromolecules, including synthetics polymers and biochemical molecules, are examples of systems where nonbonding forces occur between atoms in the same large molecule.”
- Concept VII.F.1: “When reaction rate is the dominating factor for an observed process, it is said to be kinetically favored. When reaction energy is the dominating factor, it is said to be thermodynamically favored.”

It was surprising to realize that having separated kinetics and thermodynamics into separate modules, we had no explicit discussion of the difference between the thermodynamic and kinetic control of reaction yields. Moreover, whereas a discussion of polymers was included in Module 8, we did not examine noncovalent forces in these systems. Finally, our discussion of theoretical models based on energy minimization for molecular structural elucidation was largely confined to the laboratory and the computational chemistry experiment. These deficiencies notwithstanding, it was satisfying that in this initial effort, 139 of the 143 level 3 articulations could be directly linked to the learning objectives of the realigned courses. It was possible to then link ACS exam items to the learning objectives of the realigned courses. As illustrated in Table 2 and Table S2, this provided the opportunity to examine conceptual deficiencies (or strengths) across the set of objectives.

The alignment shown in Figure 1 is, of course, only one of a number of possible structures. Highlighting the utility of the modular approach, the redesigned CHEM 1001 structure was utilized across all sections of CHEM 1001 at Marquette in Fall 2019 (encompassing some 740 students), with one notable modification. Modules 3 and 4a were flipped, so that the final topic in CHEM 1001 was reaction energetics, which then connects to thermodynamics, an early topic in CHEM 1002. The revised set of CHEM 1001 modules for Fall 2019 is shown in Figure S1. Whereas a different (trial) version of the ACS exam was given in Fall 2019 across all sections to support a study of the effects of a diagnostic exam and intervention program, it is instructive to compare data from student evaluations in the large lecture-based sections taught by the instructor in Fall 2019 versus Fall 2018. This is provided in Table S3. Here the responses are generally similar; however, again the ranking of coordination of lecture and laboratory activities increased by roughly 1/2 point, and the difference is significant at the $p < 0.05$ level. This again is surprising because the only change made to the laboratory program was a simple reordering of the laboratories.

The revised CHEM 1002 structure was not adopted by the faculty teaching the second semester course in Spring 2020. However, on the basis of our experience in Fall 2019, we can suggest a tweak to the curriculum that would move colligative properties, a traditional second-semester topic, into the first semester module encompassing intermolecular forces, gases, liquids, solids, and solutions. Thermochemistry would then become a bridging topic into the initial module of the second-semester course, a structure that would potentially link more closely topics in ACCM Concept 6. This revised structure is shown in Figure S2.

Conclusions

Building upon the development and continued refinements of the general chemistry ACCM,(37) we have used the ACCM to restructure a first-year chemistry sequence. In this initial effort, our introductory sequence was reorganized into a set of nine modules, each with a set of subtopics and learning objectives and each intentionally linked to anchoring concepts of the ACCM. The redesign was carried out in the academic year, and the courses were taught in summer term 2019 using a flipped classroom design. By aligning ACS first-term and second-term general chemistry exam items to the learning objectives of the restructured courses, we could identify conceptual deficiencies (or strengths) across the set of objectives. In the initial implementation, the course enrollments were small, and very few students took both courses. Subsequently, we used a revised course design across all sections of fall 2019 CHEM 1001. In the future, it may be possible to offer the restructured CHEM 1001 and 1002 courses across all of our on-semester sections, which could provide a larger data set for analysis. It is desirable to map the laboratory portion of the course onto Module 9 of the general chemistry ACCM as a guide to restructure the laboratory curriculum.

As emphasized at the outset, an anchoring concepts approach is but one way to logically structure the first-year chemistry sequence. The advantage of this model, in our view, is that the overarching concepts and enduring understandings are consistent across the undergraduate chemistry curriculum, which affords students the opportunity to see the same questions addressed, albeit unpacked in different ways, in different courses. Ultimately, then, the success of such a model may depend on the degree to which it is extended to other courses in the curriculum. Given that the organic chemistry ACCM has been developed,(34) the redesign of the organic curriculum is a logical next step.

The Supporting Information is available at https://0-pubs-acs-org.libus.csd.mu.edu/doi/10.1021/acs.jchemed.9b00950.

- Table S1. Detailed map of the general chemistry ACCM onto the redesigned course learning objectives. Table S2. Comparative data of ACS exam items across topics in the second semester course. Table S3. Comparative data of student evaluation metrics across the lecture-based courses in Fall 2018 and 2019. Figure S1. CHEM 1001 sequencing being used across all CHEM 1001 sections at Marquette in Fall 2019. Figure S2. Revised CHEM 1001/1002 sequence (PDF, DOCX)
- ed9b00950_si_001.pdf (2.55 MB)
- ed9b00950_si_002.docx (6.1 MB)

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