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How Do I Design a Chemical Reaction To Do Useful Work? Reinvigorating General Chemistry by Connecting Chemistry and Society

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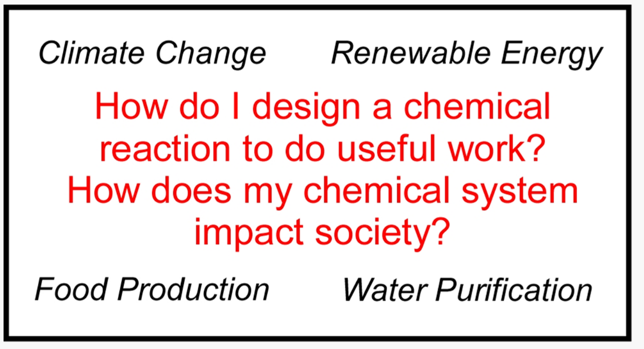
ABSTRACT: Insights and methods from the chemical sciences are directly relevant to global challenges such as climate change, renewable energy generation and storage, water purification, and food production. However, these connections are often opaque to students in general chemistry courses, who may get lost in the weeds of stoichiometry, VSEPR, and gas laws, and fail to see the relevance of their studies to their lives and their communities. Herein we describe a redesigned first-year undergraduate chemistry course that grounds chemical content in relevant societal applications. Students engage in collaborative, inquiry-based learning through an adapted POGIL methodology, and the highly structured class activities help students learn soft skills that enable success in higher education. Significant course revisions sometimes face resistance from key stakeholders, including students, faculty, and administration. We offer a case study in framing broader disciplinary concerns through the lens of institutional values to increase buy-in among key stakeholders.



KEYWORDS: *First-Year Undergraduate/General, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Student-Centered Learning*

■ INTRODUCTION

Recent results from the National Survey of Student Engagement (NSSE) show that today's undergraduates are increasingly interested in activism and working toward change.[1] This mindset seems ideally suited for studying chemistry, since the chemical sciences inform modern approaches to addressing several of the Sustainable Development Goals put forward by the United Nations,[2] including but not limited to clean water and sanitation, affordable and clean energy, sustainable cities and communities, responsible consumption and production, and climate action. Many chemists have offered compelling arguments about how chemistry as a discipline can adapt to help meet these goals.[3−6] While professional chemists understand the breadth and power of chemistry as the central science,[4,5] first year undergraduate students do not always share this experience[7] and may struggle to see how stoichiometry, VSEPR, or orbitals relate to their daily lives and professional goals. This disconnect between the promise of chemistry and its reputation as gleaned from introductory chemistry is a significant missed opportunity, as successfully addressing global challenges relies in part on a scientifically literate citizenry.[8−13] An introductory chemistry course that uses evidence-based pedagogical strategies[14] to integrate modern chemical concepts with their societal impact offers an opportunity to reinvigorate the general chemistry classroom.

The chemistry faculty at Harvey Mudd College (HMC) redesigned the required first-year chemistry course to focus on intersections between chemistry and society. This revised course, Chemistry in the Modern World (Chem 23), presents fundamental chemistry alongside its societal context. The design philosophy, course content, lessons learned from implementation, and strategies for leveraging institutional context to increase buy-in for a new course are described herein.

■ COURSE DESIGN

Integrating Chemical Content and Societal Impacts

There are calls in the chemical literature to reevaluate the general chemistry curriculum[7,14−17] and to draw clear

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Table 1. Course Modules, Societal Impact, and Chemical Content Used in Chem 23 during Academic Year 2018−2019

Module[a]	Societal Impact/Global Challenge	Chemical Content
Fall Course		
1. Can life run on arsenic?	Evaluating scientific claims in the media	Periodic trends; Electron configurations; Lewis structures
2. I only buy organic soap	Chemistry of consumer products with a focus on soap	VSEPR; Organic functional groups; Arrow pushing and esterification; Polymerization reactions; Spectroscopy (NMR, IR); Mass spectrometry
3. Good Haber/Bad Haber	Fritz Haber: the Haber−Bosch process, synthetic fertilizers, and chemical weapons	Thermodynamics; Scientific responsibility
4. Blame it on the rain	Acid rain	Acid/base chemistry; Introduction to equilibria
5. Houston, we have a problem	Water purification system on the International Space Station	Systematic treatment of equilibria; Precipitation reactions and solubility
6. Good ozone/bad ozone	Ozone: smog formation and stratospheric ozone depletion	Chemical kinetics; Catalysis
7. The fuels of today: CO_2 and fuels	What is the "best" fuel? How do we define "best"? How do CO_2 levels fluctuate on a geological time scale?	Ideal gas law; Phase diagrams; Distillation; Thermodynamics; Hydrocarbons and combustion
Spring Course		
8. Gaining a solid understanding	Understanding the arrangement of atoms in solids, laying the groundwork to discuss lithium ion batteries and solar cells	Solid-state chemistry; X-ray diffraction
9. Adventures in the quantum realm: small molecule activation	Moving toward metal-free catalysts and activating H_2	Particle in a box; Molecular orbital theory; Small-molecule activation; Frustrated Lewis acids/bases
10. Tesla vs Toyota smackdown	What will power the car of the future?	Electrochemistry; Batteries, Fuel cells
11. The fuels of tomorrow: 22 TW in your lifetime	Affordable and clean energy	Semiconductors; Photovoltaics

[a]Detailed learning outcomes for each module are provided in Table S1.

connections between chemistry and the broader global community,[3−5,18] and a desire to emphasize the connections between fundamental chemistry and societal issues was a significant motivating factor in redesigning Chem 23. The two-course sequence, which includes a full-semester course in the fall that continues into a half-semester course in the spring, uses modules that are written in-house by faculty members. Each module addresses a specific societal impact alongside the chemical content necessary to understand the issue. Modules are structured to promote the skills and behaviors that are associated with success in higher education, such as reading a textbook and regular, low-stakes practice (see below).[19,20] Table 1 lists the modules, their themes, and their chemical content, and detailed learning outcomes appear in Table S1.

In order to identify global challenges that intersect with course material, the teaching team drew from their individual subdisciplines (materials, organic, atmospheric, organometallic, and bioinorganic chemistry) and read widely. Many of the modules center on sustainability. For example, chemical systems in the atmosphere and the chemistry of greenhouse gases appear in modules 4, 6, and 7. Modules 7, 10, and 11 focus on fuels and the science behind emerging renewable energy sources. The module "Tesla vs. Toyota Smackdown" asks students to consider what will power the cars of tomorrow—batteries or hydrogen fuel cells? Students learn the fundamental electrochemistry necessary to understand both technologies, and since launching this module the department has seen an improvement in student understanding of electrochemistry in major courses (see below). The course concludes with the module "22 TW in your lifetime," wherein students learn about semiconductors and photovoltaic devices. Both modules include dedicated time for class discussions about the political, economic, and psychological barriers and opportunities posed by renewable fuel sources. The Supporting Information includes links to representative modules.

Faculty prioritized building an equitable classroom and using active, inclusive teaching methods that improve outcomes for all students.[21,22] In recent years, HMC has become an increasingly diverse community across all metrics. For example, in 2010, 58% of the student body identified as white; by 2016, this number decreased to 36%. In 2005, the student population was 29% female, and by 2018 this number increased to 49%.[23,24] Considerations of both equity and educational effectiveness led faculty to turn to active learning techniques that help students construct knowledge,[25,26] while being aware of the breadth of educational tools that fall under the umbrella of "active learning."[27] Recently faculty in the HMC mathematics and engineering departments compared the flipped classroom to interactive lecture, and they observed that students achieved comparable outcomes in both class settings.[28] With this finding in mind, chemistry faculty sought to develop a course that includes the advantages of both group work and interactive lecture, and Chem 23 shares many features with POGIL (process-oriented guided inquiry learning) teaching methods.[29,30]

Adapting POGIL to an Institutional Context

Table 2 shows a typical week in the course, which combines individual studying outside of class with guided collaborative work in the classroom.[27] Students prepare for class by completing a guided reading assignment that teaches them to identify important concepts and figures in the textbook.

Table 2. Weekly Course Structure and Assessment

Activity	Monday	Wednesday	Friday
Preparation for class	Guided reading assignment	Guided reading assignment	Guided reading assignment
In-class activities	1. Short interactive lecture	1. Short interactive lecture	1. Short interactive lecture
	2. Guided inquiry exercises in small groups	2. Guided inquiry exercises in small groups	2. Guided inquiry exercises in small groups
	3. Wrap up	3. Wrap up	3. Wrap up
Assessment	Low-stakes 10 min quiz	Minute paper, Problem set due	Minute paper

Students check their answers against a posted key and upload their work to the classroom management system (Sakai). As this is an opportunity for low-stakes practice, students receive full credit for completion rather than accuracy. Each 50 min class period begins with a short interactive lecture that reinforces key ideas from the guided reading exercise and may include sample problems. Then students break into groups of three or four to work on a guided inquiry exercise. During this time the instructor checks in with each of the nine or ten groups in the classroom and responds to questions. When several groups have the same question or misconception, the instructor returns to a whole-class discussion of the relevant concept. The class concludes with a short summary of the main points and a minute paper.[31,32] The spring course retains the structure in Table 2 but does not meet on Fridays.

Research shows that frequent, low-stakes practice with immediate feedback improves learning,[20] and students in Chem 23 have multiple opportunities for practice through daily reading assignments, low-stakes quizzes, and weekly problem sets. Regular, individual assessment proved important in a class that relies heavily on group work (see below). Some students report that they can follow along with their group but struggle to tackle problems individually; weekly quizzes allow students and instructors to diagnose this issue in advance of an exam. Their lowest quiz scores are dropped, which reduces student anxiety. Weekly problem sets often reinforced societal impact as well as chemical content. For example, the "Good Haber/Bad Haber" module focuses on the Haber−Bosch process. The corresponding homework problem asks students to consider the synthesis of H_2 for the Haber−Bosch process by examining natural gas reforming and the water−gas shift reaction. In this way, students practice fundamental thermodynamic calculations while also seeing that the Haber−Bosch process relies heavily on hydrocarbons.

Low-stakes practice also occurs during collaborative in-class work, which provides an opportunity for learning gains.[33−37] HMC students regularly collaborate outside of the structured academic experience through informal study groups in the dormitories. This collaborative culture helps prepare students for their senior capstone project, often consisting of student teams working with an industrial partner, and more broadly for their careers in STEM, which are often team-based.[38−41] However, the practices that facilitate successful teamwork are not always taught in the classroom, which can make it difficult for some first year HMC students to adapt to this culture of collaboration.

To address this problem, Chem 23 includes explicit instruction in group work. Many HMC students seek employment in the tech industry, so faculty use language from Google's Project Aristotle[42,43] to discuss collaboration. This project draws from the social sciences to demonstrate that functional teams are characterized by psychological safety,[44] which is the knowledge that one will be treated with respect by one's teammates. Faculty cultivate psychological safety by providing students with language to deal with disagreements and monitoring the group work experience through formative assessment using qualitative surveys.[32] When a problem arises, the class revisits team norms and ground rules. Assessing group work in the redesigned Chem 23 led to insights into collaborative learning,[32] some of which are reported below in the Lessons Learned section.

Collaboration is just one of many soft skills that contribute to academic success; others include effectively reading a textbook (see above), accessing institutional support structures, and knowing how (and when) to communicate with faculty in office hours. Asking for help is a new experience for many HMC first-year students, and they sometimes hesitate to reach out to faculty. Faculty lower the barrier by giving students an email template[45] on the first day of class to use as a model for contacting professors. Students are also encouraged to attend peer tutoring service meetings through regular in-course advertisements. Chem 23 instructors schedule faculty office hours close to the homework due date and hold these office hours in classrooms, as HMC students are accustomed to studying in the campus teaching building. This setting allows the in-class teamwork to transfer to office hours; students who are waiting to ask questions regularly work with their peers and help one another through difficult problems. This practice has significantly increased attendance at office hours.

ASSESSMENT

The instructional team redesigned the course with the primary goal of emphasizing connections between fundamental chemistry and societal applications, and student understanding of these connections was assessed over three consecutive semesters of Chem 23 through a short essay question administered on a midterm exam. Box 1 shows the essay prompts.

Box 1. Societal Impact Essay Prompts

Essay Mechanics: You are encouraged to write a draft of your response in the open space below, then edit and copy a final version into the box below. If you are pressed for time, you may box your initial response in the open space below. *Only the first 100 words in the box will be read and assessed.* Please write in complete sentences.

Fall Prompt: Consider either the Haber−Bosch process to produce ammonia or the space station water reclamation system. In *100 words or fewer*, explain the societal need this technology addresses, and the impact of this technology upon society.

Spring Prompt: Pick one of the following technologies: thin-film photovoltaics, batteries, or fuel cells. In *100 words or fewer*, explain the societal need this technology addresses, and the potential impact of this technology upon society.

Upon first administering the societal impact essay in the spring of 2017, faculty observed that many students wrote essays describing how a technology works instead of discussing its impact on society. The following semester, an essay question appeared on a midterm exam in the fall of 2017 asking students to consider either the Haber−Bosch process or the water purification system on the International Space Station. As in the spring of 2017, many students wrote essays describing the technology instead of analyzing its impact on society. Faculty provided detailed rubrics (Tables S2 and S3) to students along with faculty-generated sample essays to illustrate what constituted a "partially proficient", "meets expectations", or "exceeds expectations" essay. This approach provided detailed feedback to ~230 students in a way that was not overly burdensome to faculty. When the societal impact essay was administered in the spring of 2018, student performance on the essay question improved, as shown in Table 3. This is attributed to repeated practice along with

Table 3. Average Student Scores for Societal Impact Essay Question

Term	Need for Technology, %	Impact of Technology, %	n
Spring 2017	73	61	139
Fall 2017	62	65	224
Spring 2018	74	74	224

more constructive feedback as compared to spring 2017, as well as more frequent class discussions about both the need for a technology and its impacts on society.

In order to determine how student perceptions changed in the redesigned course, faculty included a question on end-of-term course evaluations that focused on the connections between chemistry and society. This analysis controlled for instructor by considering a single member of the teaching team, who taught ten sections (n = 316) of the previous iteration of the course (a more standard coverage of topics that relied on interactive lecture with less group work) and eight sections (n = 237) of the redesigned Chem 23. Students responded to the statement, "This class encouraged me to make connections between the course material and societal contexts" using a seven-point Likert scale ranging from Very Strongly Disagree (1) to Very Strongly Agree (7). Student responses were analyzed using a t test. The results show the average student response prior to the redesign was 4.69 (SD = 1.36) and increased to 5.89 (SD = 1.34) in the new course ($p < 0.01$, two-tailed test). While the limitations of course evaluations are well-documented,[46−48] an increase of a full point on a seven-point Likert scale suggests that the redesigned course is more effective in highlighting connections between chemistry and society.

In addition to these metrics, the chemistry faculty partnered with HMC's Office of Institutional Research and Effectiveness (OIRE) to evaluate the implementation of this class in real time using summative and formative assessment through minute papers, as described in detail elsewhere.[32]

While the redesigned course prioritized connections between chemistry and society, faculty did not want these connections to come at the cost of fundamental chemistry. Student knowledge of chemical content was assessed through two methods. First, student performance on a diagnostic exam was compared with student performance on quizzes and exams within Chem 23. Second, instructors compared student performance in downstream major courses before and after the redesign.

Incoming first year students complete a department diagnostic exam in the first week of classes to evaluate their knowledge of fundamental chemical concepts such as electron configurations, quantum numbers, and fundamental redox chemistry. Student performance on selected topics was assessed by comparing the percentage of students who answered a diagnostic question correctly with the percentage of students who answered a comparable question correctly on a quiz or exam in Chem 23. The results show a significant improvement in student performance upon completing the course (Table 4).

The department also compared student performance in two downstream foundation courses[49] using ACS division exams as an assessment tool. First, performance in junior-level Analytical Chemistry was assessed through the ACS Division of Chemical Education Exam − Analytical Chemistry Form 2013. Comparing performance of recent students who completed

Table 4. Comparison of the Percentage of Students Answering Correctly on an Initial Diagnostic Exam to the Percentage of Students Answering Correctly on a Comparable Quiz or Exam Question, Academic Year 2018−2019

Topic	Precourse Exam, %	Chem 23 Exam, %
Electron configuration	58	95[a]
Quantum numbers	39	94[a]
Balancing a redox half-reaction in an acidic solution	46	87[b]
Balancing a redox reaction	63	86[b]

[a]For fall semester, n = 236. [b]For spring enrollment in Chem 23, n = 234.

the previous version of Chem 23 (n = 31) and students who completed the redesigned course (n = 6) showed no significant difference in the overall scores between the two groups (p = 0.080, two-tailed test) (Table S4). A more granular comparison yields an interesting result. Student performance on questions about pH, buffers, titrations, and solubility is unchanged between the old and new versions of Chem 23. However, student performance on electrochemistry *improved* from an average of 3.29 out of 5 (SD = 1.13) to 4.33 (SD = 0.67) following the redesign of Chem 23 (p = 0.039, two-tailed test). This result is attributed to teaching electrochemistry in the context of applications ("Tesla vs. Toyota Smackdown"), which increases student engagement in the topic.

The department also assessed student performance in the junior/senior level course in Inorganic Chemistry. Students were divided into two cohorts: those who took Inorganic Chemistry in Spring 2016, 2017, and 2018, and those who took the course in Spring 2019. The first cohort (n = 29) consisted of students who took the previous version of Chem 23, while the second cohort (n = 5) consisted of students who took the revised Chem 23. For the first cohort, the students took the 2014 Inorganic Chemistry Exam. For the second cohort, the students took the 2016 Inorganic Chemistry Exam. While the change in exams precludes a direct comparison of scores, it is informative to compare relative performance on each exam by comparison to the normed exam and the exam percentiles. Table 5 shows the mean score and the standard deviation for each cohort, the mean score and standard deviation for the national norms, and the difference in mean scores for the cohorts to the national norms.

HMC students in the first cohort scored 4.0 points higher than the national average on the 2014 exam, which corresponds to a difference of 14.1 on a percentile basis. Students in the second cohort scored 9.6 points higher than the national average on the 2016 exam, which corresponds to a difference of 32.2 when measured by percentiles.

These results for Analytical and Inorganic Chemistry come with an important caveat regarding the small sample size. The first cohort of students who completed the revised introductory course enrolled in junior-level courses during the 2018−2019 academic year, and this cohort was composed of an unusually small number of chemistry majors. The department continues to assess student performance in these courses.

Together, these results suggest that Chem 23 successfully introduces students to connections between chemistry and society without compromising student understanding of fundamental chemical concepts.

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J. Chem. Educ. 2020, 97, 925−933

Table 5. Comparison of HMC Student Performance on the ACS Inorganic Exam with the ACS Norm

Cohort	HMC Score (Average)	HMC St Dev	ACS Norm	ACS St Dev	Difference	HMC Percentile (Average)	HMC Percentile (St Dev)	Difference
Pre-Redesign (n = 29)	38.1	6.2	34.1	8.8	4.0	64.1	20.5	14.1
Post-Redesign (n = 5)	44.0	3.9	34.4	9.0	9.6	82.2	12.6	32.2

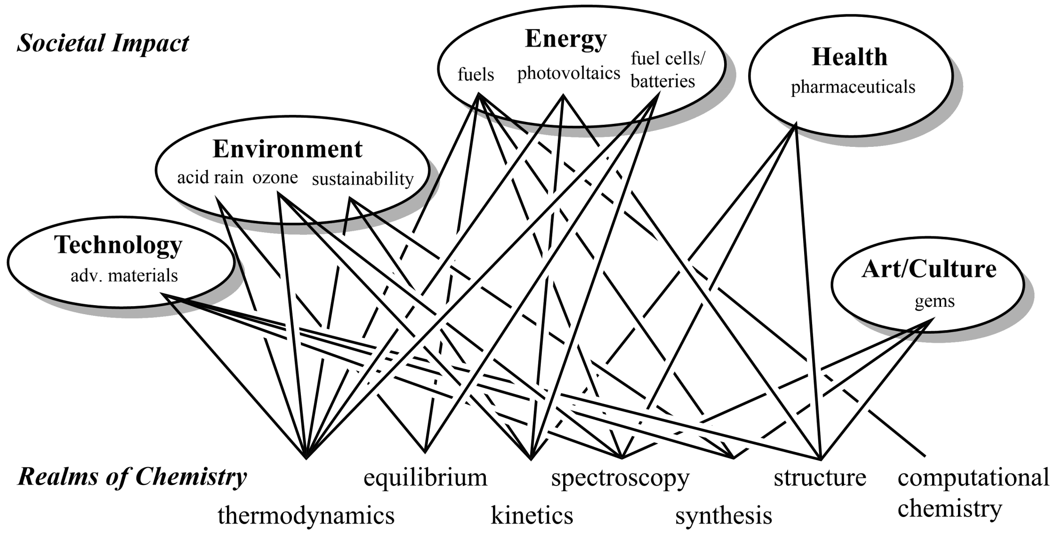

Figure 1. Concept map used in the 2016−2017 offering of Chem 23.

■ LESSONS LEARNED

Overall, the chemistry faculty at HMC observed that the redesigned course successfully taught students to understand the connections between chemistry and emerging global challenges without compromising student understanding of fundamental chemistry concepts. As with any course redesign, several lessons emerged upon implementation.

Leveraging Institutional Values To Build Support for Curricular Redesign

Enacting curricular reform requires buy-in from key stakeholders both within an institution (faculty, students, administrators) and outside (alumni, employers, graduate schools, donors, accrediting agencies, funding agencies).[50] If faculty view the curriculum as part of a larger system, argues Hutchinson, they can more effectively cultivate buy-in by identifying key "leverage points." Considering the curriculum as an interconnected system is a particularly apt way of viewing HMC's vertically integrated Core curriculum. Chem 23 is one of the first classes in the Core, and subsequent classes draw on scientific and academic skills from Chem 23. This leads to downstream implications and corresponding interest from other departments when a Core class is reimagined. Chem 23 serves as a case study for using institutional values as a leverage point to cultivate buy-in among key constituencies.

The chemistry faculty identified the institution's mission statement as a key leverage point in enacting curricular reform. The HMC community is deeply committed to its mission statement: "*Harvey Mudd College seeks to educate engineers, scientists, and mathematicians well versed in all of these areas and in the humanities and the social sciences so that they may assume leadership in their fields with a clear understanding of the impact of their work on society.*"[51] HMC student surveys show that 70% of the student body highly prioritizes "understanding the impact of scientific work on society,"[52] and the chemistry faculty used this data to connect an introductory course to existing student values. Using the mission statement as a lens, chemistry faculty framed disciplinary conversations about general chemistry into two questions that resonated with HMC. First, what does it mean to be well versed in chemistry in the 21st century? Second, how can an introductory course help students understand the impact of chemistry on society in an age where the word "chemical" is often used as a pejorative?

Faculty were mindful of students' trajectories and interests when considering what it means to be well versed in chemistry. As is common,[53] most HMC students do not continue in chemistry and relatively few students at HMC pursue careers in the health sciences. However, as science becomes increasingly interdisciplinary,[54] it becomes more important for STEM practitioners to have some degree of fluency across disciplines. The faculty designed Chem 23 to build the fundamental chemical literacy that will prepare students for interdisciplinary careers in STEM, while still providing a foundation for students who pursue advanced studies in chemistry and biology. In addition, faculty sought to provide all students with the foundational knowledge required to move through the world as informed citizens.

The idea of informed citizens speaks to the second part of the HMC mission statement, namely understanding the impact of one's work on society. Chemistry as a discipline is well-positioned to tackle global challenges that include but are not limited to climate change, renewable energy generation and storage, water purification, human health, and environmental remediation.[5,6] HMC faculty observed that student engagement improved when course material clearly connected to society. As student engagement can foster deep learning,[19] highlighting these connections was an important priority in the redesigned course.

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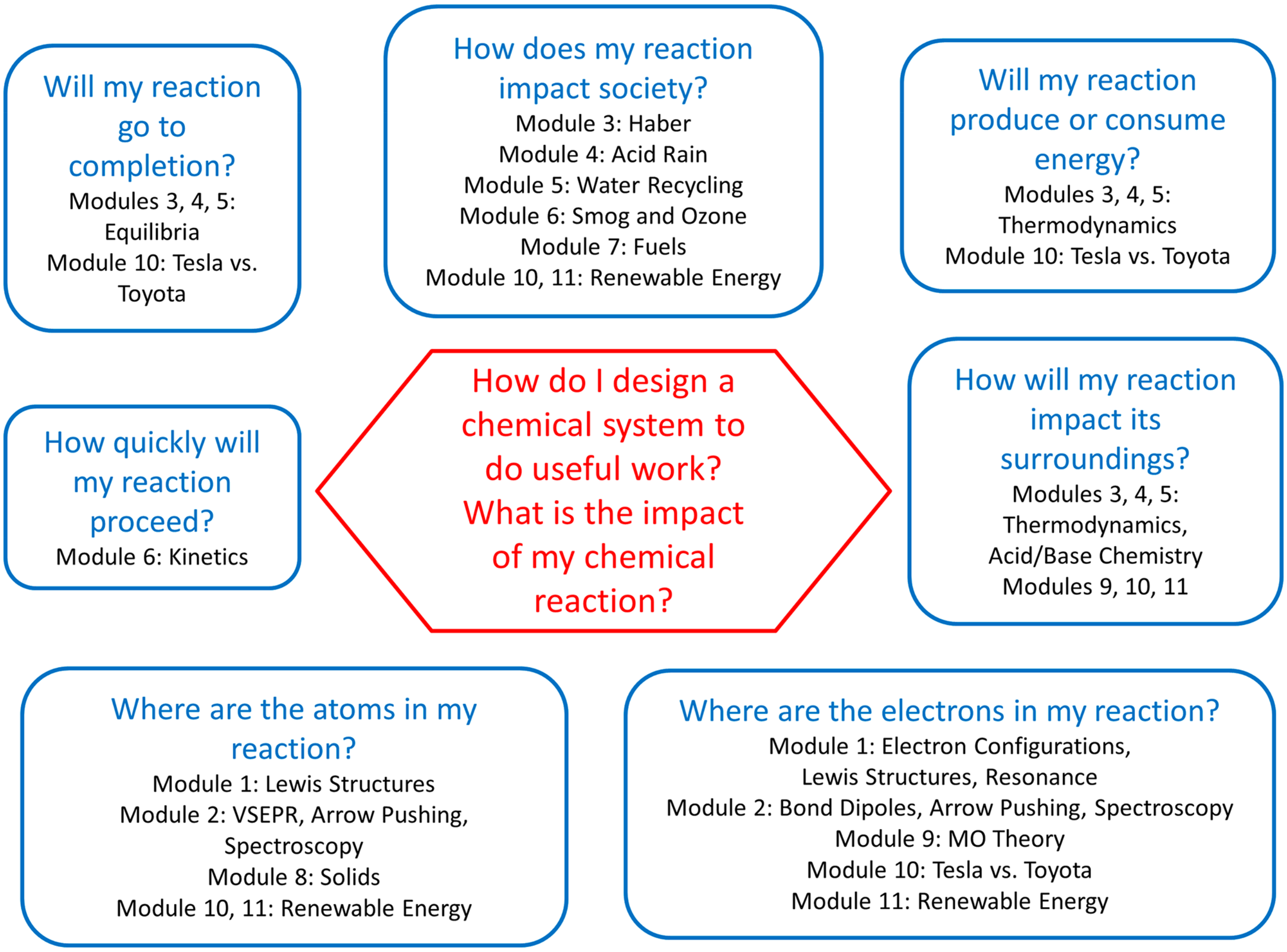

Figure 2. Concept Map used in academic year 2018−2019.

Framing broader disciplinary conversations through the lens of the institution's mission statement proved useful in cultivating support for the redesigned class among key constituencies on campus, including students, the administration, and faculty in other departments. Now that the class is in its third year, the broader community sees the benefits of the redesign. Informal conversations with colleagues in other departments suggest that group dynamics in sophomore courses have improved since Chem 23 began teaching collaborative skills.

This method of framing disciplinary issues through a local lens offers a case study to help chemists engage the broader campus community and increase buy-in among relevant constituencies when redesigning a foundational course.

Using Concept Maps To Create Cohesion and Facilitate Transfer in Modular Courses

While the modular course design allowed faculty to highlight a variety of global challenges, students sometimes struggled to transfer their learning from one module to the next. For example, the module "Blame it on the rain" introduced the concept of solubility through the lens of acid rain dissolving limestone statues. The subsequent module "Houston, we have a problem" centers on the formation of precipitates in the water recycling system on the International Space Station, a problem that relies heavily on solubility. Similarly, the organic chemistry unit covers esterification reactions, which are addressed in soap making (Module 2) and biodiesel fuels (Module 7). However, in both cases, students struggled to see these seemingly obvious connections. Faculty addressed this challenge by designing a concept map for the course to highlight connections between topics. Research shows that novices and experts differ in their ability to integrate new information with prior knowledge.[55] Novices tend to see new material in isolation and "silo" it in their memories, while an expert incorporates new information into a rich mental map of the discipline.

Figure 1 shows the original concept map, which was designed to show how a single fundamental chemical concept touches multiple applications. For example, chemical kinetics does not just apply to ozone (Table 1) but rather is a fundamental property that also applies to fuels, photovoltaics, the Haber−Bosch process, and pharmaceuticals. Instructors used color-coding to show the particular connections relevant to a particular module. However, while this concept map reflects the complex network of connections that are readily apparent to experts[55] and was a valuable tool in designing the course, it proved overwhelming for first-year students. This led to the revised concept map shown in Figure 2 that frames the course through two central questions: "How can I design a chemical reaction to do useful work? What is the impact of my reaction on society?" These are broken up into smaller questions, which highlight the relevant module(s). When this revised concept map was introduced, a student response on the daily minute paper read, "The question 'How do I design a

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J. Chem. Educ. 2020, 97, 925−933

reaction to do useful work?' really resonated with me! As an aspiring chemist that's a question I might have to consider."

In addition to the revised concept map, increased faculty familiarity with the course material also plays a significant role in helping students see the common threads that weave through the course. In the three years since the course launched, instructors have revised the modules, introductory lectures, and concluding remarks to highlight connections between units (Table S1).

Social Dynamics Inherent in Group Work

Recent pedagogical studies highlight the impact of student affect and emotion on learning.[56,57] While group work offers a ready vehicle for active learning, group work can also lead to stressful social tensions. Faculty assessed group work using an adapted 1 min paper administered via Qualtrics, as has been reported in detail elsewhere.[32] Students reported what aspects of group work helped them learn best and what aspects of group work made them most uncomfortable.

Two major themes around discomfort emerged. The first theme came from introverted students who found that interacting with classmates required extra energy and effort as compared to working individually or engaging in interactive lecture. Groups changed approximately every five instructional days to help students meet more of their classmates and to counter the effects of "social loafing," in which a group member relies on their teammates instead of contributing. However, this rapid rate of change sometimes prevented reserved students from finding a comfortable workflow with their group.

The second theme dealt with embarrassment. While HMC admission requirements include a year of chemistry, some students fulfill this requirement through an integrated science course in the first year of high school, while other students complete AP chemistry or an introductory college chemistry class as high school seniors. This often led to heterogeneous groups in Chem 23 with varying levels of chemical background. Faculty intended that students with a strong background could help their classmates and thus reinforce their own learning, and student reports show this did indeed occur frequently.[32] Many students reported the benefits of working through "shared confusion" to arrive at a solution, as well as the learning benefits of explaining a problem or hearing from their peers. However, heterogeneous group composition also led to some well-prepared students disengaging from their groups or expressing impatience with fundamental questions, which resulted in some students reporting embarrassment about their perceived inadequacies in the chemistry classroom. Some faculty were concerned that this embarrassment inhibited learning and pushed students away from chemistry, as negative experiences in group work can interfere with learning.[58]

Faculty addressed this challenge by following the example of HMC's successful computer science department and offering two "flavors" of the course, named Gold and Black for HMC's school colors. The Gold and Black sections cover the same content, use the same quizzes, exams, and homework, and follow the same schedule. Students with a strong preparation in chemistry register for a Black section and students without AP chemistry register for Gold. This resulted in a significant decrease in student reports of discomfort due to embarrassment. Instructors observed an improvement in the classroom culture, as students were more comfortable asking questions during the interactive lecture portion of class and group members worked at a comparable pace. While there are advantages and disadvantages to both homogeneous and heterogeneous groups,[59] in this case homogeneous groups improved the student experience.

Cost and Sustainability

Faculty wrote course modules over the summer and during the academic year. While this resulted in course materials that were tailored to the HMC student population, it was a time-intensive endeavor. The modular course design was intended to allow faculty to readily swap modules from year to year. However, in practice this was hampered by (1) the module's footprint, as a replacement module may not fit in the allotted number of class days and (2) overall course cohesion, which improved when a single faculty member wrote two or three consecutive modules. This continuity in authorship also facilitates building connections between modules (see above). The teaching team found it was important to build some "slack" into the schedule in the form of review days to allow for activities that ran long or time to answer student questions.

The course requires regular and effective communication between the teaching team because the same activities happen in parallel across six different sections led by three instructors. This requires flexibility and a willingness to experiment in the classroom on the part of instructors, as well as the time and energy required to learn new teaching methods. To paraphrase an HMC colleague, team teaching can be both highly effective and highly inefficient due to the requisite frequent meetings. Notably, intensive teamwork is also a new experience for students, and grappling with a new mode of teaching and learning has been a point of shared experience between faculty and students in the course. Regular communication with undergraduate student tutors also facilitates the course, as tutors provide instructors with important information about how first-year students experience Chem 23.

Now that the course is in its third year, students and faculty have acclimated to the new course and developed practices to reduce and manage workload. Overall, faculty have observed significant improvements in student engagement and the classroom climate, and this is sufficiently rewarding to persist with the new model.

LIMITATIONS AND FUTURE STUDIES

The chemical content in Chem 23 does not significantly deviate from the standard general chemistry curriculum, and while the modules are written in-house, the students use the established textbook *Chemical Principles* by Atkins, Jones, and Laverman.[60] The question of the appropriate selection and depth of content in general chemistry is an active question in the chemical education literature.[7,16,53,61,62] In this redesign, institutional context informed content selection. Students complete Chem 23 in their first two semesters of HMC's vertically integrated Core curriculum. Subsequent Core courses in biology, engineering, and physics draw on material from Chem 23, which somewhat limits a complete reimaging of course content. HMC is in the midst of a holistic review of its Core curriculum, and the Chemistry Department is in active discussions about the future content of Chem 23.

CONCLUSION

Framing general chemistry concepts in terms of societal impact led to a reinvigorated course with a concomitant improvement

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in student ability to explain the connections between chemistry and global challenges. Buy-in from key stakeholders, including administrators, faculty, and students, for this curricular redesign comes in part from translating broader questions in the chemical community to the values and priorities of one's local context, in this case using the institution's mission statement as a lens. Similarly, understanding student practices and preferences on campus (for example, recognizing that students tend to study in groups in classrooms and moving office hours to a new location) allowed evidence-based pedagogical methods to be adapted in a way that resonated with students. A holistic concept map was critical to the success of a modular course. Just as group work asks students to step out of their comfort zone and practice the fine art of collaborative learning, so too does this redesigned course ask faculty to experiment with new teaching methods and practice effective communication skills. Overall, in this course students show an improved ability to relate chemistry to important global challenges.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00281.

Detailed learning objectives, rubrics used to evaluate essay questions, links to selected course modules (PDF) (DOCX)

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Notes

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