Title
The Green (Chemistry) Environment: Developing and Assessing Green Chemistry Curricula and Student Outcomes in the General Chemistry Laboratory

Author
Armstrong, Laura B

Publication Date
2021

Peer reviewed|Thesis/dissertation

The Green (Chemistry) Environment: Developing and Assessing Green Chemistry Curricula and Student Outcomes in the General Chemistry Laboratory

by

Laura B. Armstrong

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Science and Mathematics Education

in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor Anne Baranger, Chair
Professor Marcia Linn
Professor Mark Wilson

Spring 2021

The Green (Chemistry) Environment: Developing and Assessing Green Chemistry Curricula and Student Outcomes in the General Chemistry Laboratory

by

Laura B. Armstrong

Abstract

The Green (Chemistry) Environment: Developing and Assessing Green Chemistry Curricula and Student Outcomes in the General Chemistry Laboratory

by

Laura B. Armstrong

Doctor of Philosophy in Science and Mathematics Education

University of California, Berkeley

Professor Anne Baranger, Chair

Climate change and the resulting and related environmental and humanitarian outcomes are some of the fundamental challenges of the 21st century. Green chemistry, a relatively recent addition to the chemistry family, aims to reframe chemistry so that chemistry ethically and responsibly attends to its own environmental and human health impacts and becomes a contributor to sustainable development and innovation within and outside of chemistry. Integrating green chemistry in undergraduate education provides students with an ethical framework for doing chemistry, gives more meaning and relevance to chemical learning, showcases new ways of approaching chemical problems, and allows students to participate in more authentic problem solving and inquiry.

The general chemistry classroom is an ideal yet often underused course for introducing students to green chemistry – especially for non-chemistry majors who may not take any further chemistry courses. One major goal of this dissertation was to develop a robust green chemistry curriculum for the wide-reaching non-chemistry majors' general chemistry laboratory course at UC Berkeley. This was an opportunity to introduce more explicit green chemistry content and practices into the general chemistry laboratory all while utilizing a constructivist learning science framework – knowledge integration – to design a green chemistry curriculum that attended to both content and pedagogy. Additionally, this curriculum work leveraged the Berkeley general chemistry laboratory structure to engage in iterative curricular revision through a utilization-focused evaluation design. Together, this work contributes to a larger understanding of how to develop coherent green chemistry curricular materials and efficiently assess and revise the curriculum by carefully evaluating the implementation process and resulting student outcomes.

The second focus of this dissertation was to develop a series of fixed and free-response items to probe different facets of green chemistry ability (both green chemistry content knowledge and practices) that could be administered and analyzed for thousands of students. While many green chemistry courses do assess student attitudes and self-reported learning more work is needed to measure demonstrated understanding of green chemistry. Even when

methods other than self-reported items are used (e.g., achievement tests, course assignments) they often do not focus on green chemistry outcomes but rather general science or lab technique/skill outcomes. Especially for large enrollment courses, alternative modes of assessment, such as short answer and multiple-choice content questions, are needed to assess green chemistry student learning outcomes more fully. Thus, nearly a dozen fixed and free-response green chemistry items were created to examine how students were able to define and use green chemistry and make green chemistry decisions. Additionally, additional Likert and Guttman items were iteratively designed to measure students' self-reported green chemistry ability, and several open-ended reflection items were used to examine how students valued green chemistry.

Overall, the results of this analysis showed an increased ability to define green chemistry and apply green chemistry concepts to a novel scenario after completing the green general chemistry laboratory course at UC Berkeley. Students reported that their ability to define green chemistry and green chemistry principles, identify and reduce hazards and waste, and identify factors that make a reaction green all increased significantly after completing the general chemistry laboratory course. Many students also reported that green chemistry was the most valuable component and most meaningful connection of this introductory course. However, not all green chemistry terms were equally easy for students to integrate into their existing knowledge schema. More targeted instruction is needed for green concepts that already have usage or meaning in general discourse. Additionally, while students entered the general chemistry course with various levels of prior green chemistry understanding, almost all students made gains in green chemistry understanding after completing the course. These gains were even across gender, underrepresented minority status, and first-generation college status.

Finally, this research showed that both general and organic chemistry students engaged in sophisticated green chemistry reasoning when provided with traditional and green data and metrics. When asked to decide between two alternative methods students used the given data to justify their choice in ways that showed their green chemistry knowledge and modes of reasoning. Overall, both general and organic chemistry students' overwhelmingly chose and correctly justified the 'greener' method choice – showing similar value for and ability in making green chemistry decisions. This was especially impressive given that organic chemistry students received no additional green chemistry instruction through their chemistry courses after general chemistry. The fact that organic chemistry students would choose the green chemistry option on a high-stake summative exam indicated the value they still held for green chemistry and the confidence they had in their understanding of green chemistry principles and practices even two or more semesters after learning about green chemistry.

This dissertation is dedicated to my mother, Pam Schultz.

Thank you for supporting me always, celebrating every success I've had, and letting me know, in words and actions, that I am capable of more than I believe.

Acknowledgements

Throughout my dissertation research and writing I've found it both motivating and comforting to think about all the people who had a hand, either directly or indirectly, in supporting this research. While my name might be the only one to appear on this dissertation it would never have been possible without the guidance, energy, and inspiration from so many others. Research is rarely an individual endeavor and am so thrilled and honored to acknowledge all of those who have contributed to this work over the years – many of whom I consider invaluable colleagues and friends and family.

It feels only right to start this section by recognizing the two people most responsible for my academic journey: Professor Anne Baranger and Dr. Michelle Douskey. I met both during a time in my life when I was adrift and their guidance and unwavering support over the years has made my research, and indeed my life, what it is today. I owe so much of this dissertation to Anne's guidance – as she constantly ensured that I was able to progress and learn – and Michelle's generosity – as she opened her class and curriculum to my research and always was willing to give her knowledge and insight to this project.

To my advisor, Anne – thank you for taking a chance on a former chemistry graduate student and giving me both the flexibility and support to pursue research topics and methods that I loved. You have always been supportive of any academic, professional, and personal opportunity that I've pursued and reminded me that, yes, we're researchers but we also have lives and needs outside of academia. Thank you for making my chemistry education graduate experience one that has been full of discovery, learning, and good memories. It's been a joy to work with and know you these six past years.

Michelle – you are a mentor in every sense of the word and have served as an incredible inspiration to both me and countless other graduate and undergraduate students. You are the reason I even know about green chemistry and could originally imagine pursuing a PhD in chemistry education. Seeing your determination and passion towards education over the years has inspired me to be both a better educator and more involved researcher. I can only hope that once I have settled in my own career I can be half as excellent as you.

To my secondary advisor, Marcia – thank you so much for welcoming me into your research group and providing encouragement and enthusiasm for my research. Your guidance helped design and highlight some of the most interesting and important portions of my research. I always left meetings with you feeling inspired and motivated to continue my work. Thank you also for paving the path that many women in education now walk down. It does not escape me that so many of the professional opportunities I've had in my life were built by many women before me.

I am especially honored to thank the truly exceptional undergraduate researchers that have been an integral part of green chemistry research at UC Berkeley: Mariana Rivas, Zeyi Zhou, Lauren Irie, Kelly Chou, Kailey Sun-Marcus. Working with and knowing each and every one of you has been the absolute highlight of my time at Berkeley. I have loved watching you all progress through Cal and do so much more than I could have ever imagined at your age (or even now). Your tireless work and incredible insights are the reason that so much of this research even exists. Your vision, commitment, and expertise have kept me motivated and focused, and make me believe that the future will be better because of your convictions and actions.

I would also like to thank the many other amazing people I have met during my time at Berkeley and beyond especially Jean Cheng, Victoria Robinson, and Yukiko Watanabe. My life is so much better from knowing every one of you. Jean and Victoria – our work with the Creative Discovery Program gave me a richer and more meaningful graduate experience. It made me a more thoughtful and critical researcher, a more empathetic person, and opened the possibilities of activism and public facing work to me. My experience with the CDF program fulfilled the vision I had of UC Berkeley when I first came here and showed me where my research interests could and should lie. Yuki – I could not have asked for a better mentor at Berkeley or eventual manager than you. I am so thankful to have had the privilege of working with you multiple times over the years. I am constantly in awe of your professionalism, enthusiasm, vision, and expertise and hope to be able to model even a fraction of that in my own work. Thank you for celebrating my successes with me, advocating for me, and letting me learn so much from you.

My chemistry education group members – thank you all for your attention and feedback over the years. A special thanks to MaryAnn Robak, who I spent many wonderful hours designing and formatting many of our now standard green experiments. And many thanks to Alexis Shusterman for helping design and administering a new green chemistry exam question in her course. Thanks also to my qualifying, proposal, and dissertation committee members (Professor Baranger, Professor Linn, Professor Michelle Wilkerson, and Professor Mark Wilson) for your expert guidance and feedback.

My graduate experience was made so much richer from the wonderful friends I've met over these past six years: Emily Harrison, Sara Bourne, Chrissy Stachl, Beatriz Brando, Alex Ramsey, and Geri Kerstiens. Emily – I don't know what I would have done without our weekly rooftop beers (and sushi). You were my anchor during grad school. I cannot imagine going even a single week without talking to you and I cannot wait to finally explore Big Sur and so many other places with you! Sara – I'll never forget the day that Michelle introduced us in the hallway of Latimer. Some of my best memories come from our random chats in Lewis, our trips to the barn, and our absolutely epic hikes. I always knew you were in my corner and that you were just a text away whenever I needed support. Beatriz – thank you so much for being just as big of a data/methods nerd as I am and for championing my dissertation analysis and writing. You were beyond supportive of my dissertation progress and always made me feel like my work was both important and substantial. Alex – thank you for being both my horse and hiking buddy. Going hiking and riding with you grounded me and I will never forget how we crushed Mount Diablo. Chrissy – I am so happy to have met you during my last few years of graduate school and carry that friendship through and beyond Covid. Geri – thank you for being my first chemistry education friend and for introducing me to Hamilton. Lab development would not have been the same without you.

I am so lucky to have the constant support of my family during grad school. I am the person I am today because of their decades of guidance and love. To my mom – Pam Schultz - thank you so much for being my champion since before I can remember. You have been unfailingly supportive of my education and interests and are the reason I even had the opportunity to write this dissertation. Doug Schultz – I feel so lucky to have you as part of our family and be a part of yours. You have brought such joy and richness to my and my family's life. I am so happy to celebrate this dissertation and many future events with you. To my brother – Matthew Armstrong – who has always believed in me even when I have doubted myself. Thank you for watching silly movies with me and always letting me know that I had your support in so many ways. And finally, to my aunt – Beth Quayle – the strongest woman I know. I feel so honored to share a name with you. I love you all so much there aren't enough so's.

Finally, I must thank my partner, Prithvi, for supporting me over these last few months while I completed this dissertation, all while completing the first year of his own medical residency. I'm proud of the dissertation I've written but I am and will continue to be so appreciative of the knowledgeable and empathetic care you provide day in and day out. We both were stretched thin, but your work was a grounding reminder of the stakes and privilege of mine. Even with your demanding schedule you still managed to grocery shop for us, find us amazing food to enjoy, and remind me that it's okay to get out of house occasionally. Thank you for exploring so many amazing trails with me and welcoming our little monster dog, Penny, into our lives. My life is bigger and richer for having met you. Every day with you is one that I value.

Table of Contents

Chapter 1: Introduction to Green Chemistry Practices, Assessment, and Pedagogy

"The best time to plant a tree was 20 years ago. The second best time is now." – unknown

Introduction to Green Chemistry

Climate change and the resulting and related environmental and humanitarian crises have made it clear that the status quo is not tenable. Chemistry and chemical products and processes have both helped and harmed our health, safety, and environment and chemists and chemical engineers, with their unique knowledge and skills, have a critical role to play in developing a truly environmentally just future. From solar panels to carbon capture to prevention of waste and harm instead of remediation so many of the necessary changes and advancements needed for a more sustainable future come from within chemistry. Chemistry as a field and industry needs improve its own sizable environmental impact, but the field also offers many technological and scientific innovations that are critical for sustainable development. Students who enter chemistry courses right now do so at pivotal moment in time. It is not enough to simply instruct them on traditional chemistry content or practices. All students deserve an education that prepares them to not only enter chemistry as it is right now but to have the vision, ethics, and skills to imagine and create chemistry as it should be for their future.

What Is Green Chemistry?

Green chemistry positions itself as the framework for sustainable chemical practices. A relatively recent addition to the chemistry family, green chemistry is a philosophy for all chemistry; it is not a separate field of chemistry, but rather a way of doing chemistry that attends to the safety of people and the environment. Green chemistry is a process that "requires looking across systems and across life cycles to design products and processes that are benign to both people and the environment" (Anastas, 2011). Green chemistry was designed from within chemistry by practicing chemists who saw a need for a different approach to chemistry (Woodhouse & Breyman, 2005). These chemists recognized that chemical processes, by-products, waste, pollution, and industrial chemicals were adversely affecting human health and the environment (Anastas, 2011; Anastas & Beach, 2009). Prior to green chemistry, chemicals were designed without evaluating environmental and health impacts (Iles, 2011) and the chemical industry was (and still is) one of the biggest sources of pollution and environmental hazards (Epicoco et al., 2014; Woodhouse & Breyman, 2005). Green chemists (as they would be come to known) envisioned a new framework for chemistry that would initiate a new relationship between chemistry and the environment and society at large (Bodner, 2016). Green chemistry works within chemistry to move the field towards developing and using renewable feedstocks (Epicoco et al., 2014; Woodhouse & Breyman, 2005), creating chemical processes that are less energy-intensive, and finding and promoting safer alternatives (Epicoco et al., 2014).

Development and Growth of Green Chemistry Education

Mirroring the growth of green chemistry over the past decades, there has been a steady increase in interest and development of green chemistry and sustainability curricula, instruction, and courses (Andraos & Dicks, 2012; Haack & Hutchison, 2016). Within education contexts, green chemistry has been used to improve the cost and safety of instructional laboratory spaces or classes, provide students with an ethical framework for doing and learning chemistry, and/or enhance student learning of or experiences with chemistry. Traditional instructional laboratories are often ideal spaces for green chemistry – both to improve the safety of the physical spaces/experiments as well as providing authentic chemistry contexts, content, and practices for student learning. Many teaching experiments use toxic, carcinogenic, and corrosive substances, which can translate to high costs for waste disposal and ventilated laboratory space (Haack & Hutchison, 2016). Moving towards greener alternatives not only provides students with a safer (and potentially more cost effective) learning environment but also decreases the environmental impact that these teaching laboratories have on the local and global communities.

Ideally, this implicit introduction of green chemistry to courses and laboratories is coupled with explicit green chemistry instruction. Green chemistry allows students to see the impact that chemistry can and should have toward solving some of the grand challenges of sustainability. Green chemistry provides students with an ethical framework for doing chemistry (Andraos & Dicks, 2012), brings relevance to the chemistry classroom (Bodner, 2016), and provides more meaning to chemical learning (Burmeister, Rauch, & Eilks, 2012). Green chemistry can also enhance student thinking and chemistry abilities (Andraos & Dicks, 2012) as it often calls for a comparative analysis between two or more options. Green chemistry allows students to participate in more authentic problem solving and inquiry, as there are often a variety of options that need to be evaluated. There is usually no one correct answer that instructors can offer students. In some cases, there is a range of appropriate green chemistry solutions and, in other cases, the answer is not even known by the chemistry community (Andraos & Dicks, 2012). Authentic green chemistry questions and research require optimizations and tradeoffs (DeHaan, 2009; Kitchens et al.,

2006) and this comparative analysis leads to deeper analyses and richer discussions (Andraos & Dicks, 2012).

Green Chemistry Courses and Curricula

Most green chemistry curricular design has occurred in elective courses or has been integrated into preexisting chemistry courses with occasional cross-curricular implementations of green chemistry principles (Andraos & Dicks, 2012). Stand-alone green chemistry courses are relatively rare since, while they can cover green chemistry topics in detail, they require dedicated instructor time and space within current departmental sequences (Andraos & Dicks, 2012). Integrating green chemistry into preexisting courses does reduce the amount or depth of green chemistry that can be covered but often can reach many more students than an elective green chemistry course. However, most pedagogical materials have been designed for organic chemistry courses (Andraos & Dicks, 2012; Aurandt & Butler, 2011; Beltman et al., 2015; A. E. Marteel-Parrish, 2014; Morra & Dicks, 2016; Roesky et al., 2009), which means that there is still a large population of science, technology, engineering, and math (STEM) majors who are never introduced to green chemistry.

Regardless of the exact placement of green chemistry in the curriculum, the practice of green chemistry involves constantly weighing tradeoffs and making decisions (Burmeister et al., 2012). To allow students to begin making these decisions, many green chemistry courses ask students to change a single aspect of an existing synthesis or process to improve greenness (Guron et al., 2016). These courses are typically designed for novice students and limited to one principle or dimension of green decision making. However, while accessible for novice students, this approach doesn't accurately represent the complexity of green chemistry decisions and doesn't provide students with the real tools or reasoning they need to make these decisions in the future. To bridge this gap, instructors have developed different frameworks of increasing complexity that scaffold the use and application of the *12 Principles of Green Chemistry* to make green decisions (Machado, 2015). However, many educators believe that green chemistry curricula need to extend beyond the *12 Principles of Green Chemistry* to include societal factors (Burmeister et al., 2012). Some courses ground these societal impacts to a local geographic area or introduce students to green chemistry through case studies (Karpudewan et al., 2012c). Others advocate for the application of green chemistry (or related ideas) to social justice problems and the development of humanistic approaches to chemistry (Burmeister et al., 2012; Sjostrom et al., 2016; Sjostrom & Talanquer, 2014).

Barriers to Green Chemistry Education

Green chemistry can face many internal and external barriers to implementation in courses and departments. Typically, when green chemistry is introduced, it is usually the result of a "bottom-up" rather than "top-down" implementation. Without institutional support, these courses are dependent on the motivations of particular instructors and are often dropped once instructors stop teaching the class (Bodner, 2016). Additionally, there's a lack of uniform demand or pull for green chemistry from academic and industrial stakeholders (Haack & Hutchison, 2016), which makes it difficult to develop focused educational materials. The limited number of educational materials combined with few educators with the experience or capacity to implement change in the curriculum (Haack & Hutchison, 2016) means that green chemistry is often introduced in ways that are most convenient, such as incorporating it into existing courses (Bodner, 2016). These courses already cover a large volume of material, which means that green chemistry is introduced at a superficial level. Additionally, the main general and organic chemistry textbooks and the ACS standardized exams have been slow to introduce green chemistry topics or metrics (Haack & Hutchison, 2016) though that has changed over the last five years (*ACS Green Chemistry Module Development*, 2021).

This lack of green chemistry education has real implication for academia and industry. Matus et al. (2012) notes that "while green chemistry has made significant progress, it is unknown or misunderstood by a large number of chemists." Since green chemistry is not part of the standard curricula in most schools (though this is changing) few chemists, and even fewer managers or people working in chemical sales, marketing, or operations have any exposure to green chemistry (Matus et al., 2012). However, it is important to realize that general awareness of green chemistry may not be enough for people or groups to adopt or enthusiastically use green chemistry. Chemists have many different roles, which can influence whether or not they accept green chemistry (Howard-Grenville et al., 2017). For example, some chemists might be attracted to green chemistry because it provides them with practical tools to solve problems. However, green chemistry is often presented as an ethical imperative, which suggests a degree of commitment that is uncomfortable and perhaps impossible for pragmatic chemists (Howard-Grenville et al., 2017). Thus, it is important to not only teach green chemistry, but also consider how green chemistry's values and goals are communicated and framed.

Green Chemistry Assessment

Green chemistry education is a relatively new addition to the chemical education landscape and the assessment of these green chemistry courses and curricula is an even more recent development. Green chemistry assessment has an important role in the iterative improvement of existing courses (Garner, Huwer, et al., 2015; Andraos & Dicks, 2015; Garner, Siol, et al., 2015; Lee et al., 2014; A. E. Marteel-Parrish, 2014; Paluri et al., 2015) and lend validity to new curricula (Aurandt & Butler, 2011; Gron et al., 2013; A. E. Marteel-Parrish, 2014), which can increase buy-in from faculty and students. Green chemistry assessment can also allow instructors and researchers to measure student (self-reported and/or demonstrated) learning of and attitudes towards green chemistry.

Green chemistry curriculum designers and researchers have explored student (and occasionally instructor) knowledge (Gron et al., 2013; Guron et al., 2016; Karpudewan et al., 2012a, 2015a, 2015b, 2016; Mandler et al., 2012; Shamuganathan & Karpudewan, 2017); attitudes, motivation, and values (Guron et al., 2016; Karpudewan et al., 2012a, 2015a, 2015b; Mandler et al., 2012; Shamuganathan & Karpudewan, 2017); and laboratory skills (Gron et al., 2013) in the context of green chemistry courses. Surveys with Likert items, often with an additional free response section are one of the most common methods for assessing green chemistry outcomes (Gron et al., 2013; Guron et al., 2016; Purcell et al., 2016). Some researchers – especially those in smaller (Beltman et al., 2015) to mid-sized (Gron et al., 2013; Lee et al., 2014) enrollment courses – also supplement survey results with student course work as evidence of mastery of the material while others have used interviews or focus groups to provide a more comprehensive picture of student learning and attitudes (Karpudewan et al., 2015a, 2015b; Shamuganathan & Karpudewan, 2017). While this work is valuable there is still a lack of research around student demonstrated – instead of self-reported – understanding of green chemistry principles and practices in large enrollment courses leading to an incomplete picture of how students learn green chemistry.

Dissertation Roadmap

Green Chemistry at UC Berkeley

As outline above, green chemistry is often introduced in elective courses or organic laboratory courses (Andraos & Dicks, 2012) with less focus on introductory general chemistry courses. Although many laboratory experiments have been designed for general chemistry courses (e.g., Purcell *et al*., 2016; Buckley *et al*., 2013), fewer "green" general chemistry lecture (Prescott, 2013) or laboratory (Gron et al., 2013) courses have been developed. Introducing green chemistry into the general chemistry curriculum, rather than a more advanced course like organic chemistry, impacts the broadest range and number of future STEM professionals; at Berkeley, over 50% percent of the total STEM majors on campus complete at least one semester of general chemistry.

In response to this gap and the growing interest in solving complex sustainability and green chemistry issues, the UC Berkeley College of Chemistry developed a new green chemistry focused general chemistry laboratory series. This redesign was initially driven by Dr. Michelle Douskey and Dr. Marty Mulvihill who, with funding from the California Environmental Protection Agency, created several new general chemistry laboratory experiments focused on one or more dimensions of green chemistry. The success of these initial experiments led to the expansion and continued funding of this project by the Dow Foundation. This project eventually expanded to include a team of researchers – professors, graduate students, and undergraduate students – who designed and tested over 30 new green chemistry experiments (Buckley et al., 2013; Purcell et al., 2016). These experiments use green chemistry principles as motivational contexts and cover topics such as biodegradable polymers, extraction and analysis of plant-based antibiotics, ecotoxicity, fuel cells, solar cells, and biodiesel synthesis.

Motivation and Dissertation Scope

This original set of green general chemistry experiments and accompanying curriculum served as the foundation for this dissertation; it was a rich context for iteratively developing and refining additional green chemistry curriculum and assessing student understanding of green chemistry with thousands of students over multiple semesters. As discussed above, general chemistry is an ideal yet underused course for introducing students to green chemistry especially for non-chemistry majors who may not take any further chemistry courses. Additionally, even students that continue with chemistry may not experience more green chemistry instruction unless there is a coordinated green chemistry progression within chemistry courses. Thus, it's important to ensure when green chemistry is introduced (wherever it occurs) both the content and pedagogy are thoughtful and relevant as it might be a student's only chance to learn about green chemistry within a formal instructional setting.

Thus, one major goal of this dissertation research was to assess the implementation and outcomes of the original green chemistry laboratory curriculum and use those results to guide the development of a more robust green chemistry curriculum for this wide-reaching laboratory course. This was an opportunity to introduce more explicit green chemistry content (green chemistry principles, lifecycle and systems thinking components) *and* practices (chemical design strategies, life cycle impacts, hazard and risk assessment) into the general chemistry laboratory with the ultimate goal of supporting students in using green chemistry principles and practices to identify and evaluate the criteria needed to make greener chemical decisions.

It was also an opportunity to engage in more rigorous green chemistry curriculum design and implementation assessment. The *12 Principles of Green Chemistry* (Anastas & Warner, 1998) and systems thinking (Constable et al., 2019) are necessary knowledge components of green chemistry but are not a pedagogy for green chemistry. Many published green chemistry courses and experiments discuss the green chemistry themes, metrics, or principles used in the course (Eissen, 2012; Kennedy, 2016), the assignments used to gauge student learning (Kennedy, 2016; Lee et al., 2014), the projects or experiments that allow students to use or apply green chemistry (Graham et al., 2014; Guron et al., 2016; Lee et al., 2014; Paluri et al., 2015; Purcell et al., 2016), the timelines for content and project development (Graham et al., 2014) , and even staffing needs for these courses (Graham et al., 2014; Lee et al., 2014) – often in service of describing the overall curricular changes that have led to the greener version of the course. However, while these green courses often describe in detail *what* and *why* green chemistry will be taught few describe the pedagogical framework for *how* it will be taught. Some courses and experiments do list learning goals and approaches for instructor and staff technical guidance (e.g., Graham et al., 2014) or discuss inquiry-based teaching and learning (e.g., Paluri et al., 2015) but most do not present an explicit framework for supporting students in developing and integrating new green chemistry ideas and practices into their existing knowledge schema. Developing new curricular materials for this dissertation was an chance to utilize a true constructivist learning science framework – knowledge integration (Linn & Eylon, 2006, 2011) – to design a green chemistry curriculum that attended to both content and pedagogy.

Additionally, many published green chemistry courses and curricula focus on simply describing a single implementation; they do not engage in (or at least publish) the iterative process of curriculum development though there are some exceptions (e.g., Marteel-Parrish, 2014). This dissertation research leveraged the structure of the Berkeley general chemistry laboratory to engage in iterative curricular revision through a utilization focused implementation evaluation design (Patton, 2008). Since chemistry courses are often structured as year-long series it can take several years to fully evaluate multiple implementations of a curriculum. However, the general chemistry laboratory at UC Berkeley is offered every semester (including summer session) which allowed for three curricular iterations within the span of one year. Together, this work contributes to a larger understanding of how to develop coherent green chemistry curricular materials and efficiently assess and revise the curriculum by carefully evaluating the implementation process and resulting student outcomes.

While many newly developed green chemistry courses do engage in assessment of student attitudes (Aubrecht et al., 2015; Eissen, 2012; Guron et al., 2016) and self-reported learning (Eissen, 2012; Graham et al., 2014; Guron et al., 2016; Kennedy, 2016; Purcell et al., 2016) more work is needed to measure student demonstrated understanding of green chemistry especially in large enrollment courses. Even when methods other than self-reported items are used (e.g., achievement tests, course assignments) they often do not focus on green chemistry outcomes but rather general science (Aurandt & Butler, 2011; Karpudewan et al., 2016; Lee et al., 2014; Paluri et al., 2015) or lab technique/skill outcomes (Gron et al., 2013; Lee et al., 2014). Thus, another focus of this dissertation was to develop a variety of fixed and free response items to probe different facets of green chemistry ability (both green chemistry content knowledge and practices) that could be administered and analyzed for thousands of students. While interviews and focus groups provide detailed qualitative information, they are time intensive to conduct and analyze and thus can often only be used with a small number of students. Especially for large enrollment courses, alternative modes of assessment, such as short answer and multiple-choice content questions, are needed to assess green chemistry student learning outcomes more fully.

Dissertation Outline and Research Questions

This dissertation is focused on both curriculum development and assessment of student understanding of green chemistry. The first research chapter (Chapter 2) explores changes in general chemistry student understanding (both self-reported and demonstrated) after completing the original green chemistry laboratory curriculum. It also analyzes the original green chemistry curriculum to identify areas for future curricular development.

Chapter 2
Initial Development of a Green Chemistry Focused General Chemistry Laboratory Curriculum: What Do Students Understand and Value About Green Chemistry?

1. Do students believe they have learned green chemistry? Do students value green chemistry?
2. Does students' understanding of green chemistry increase after completing the general chemistry laboratory, given a limited introduction of green chemistry into the curriculum?
3. Are students with different levels of prior green chemistry knowledge able to reach similar levels of understanding after completing the general chemistry laboratory?

The second research chapter (Chapter 3) builds on the original green chemistry curriculum analysis to iteratively develop a more explicit green curriculum for the general chemistry laboratory (general chemistry green curriculum or GC^2) using the Knowledge Integration framework (Linn & Eylon, 2006, 2011). This chapter also presents the development and validation of a set of fixed response survey items to measure student self-reported understanding of green chemistry. This instrument was then used to measure if students believed they had learned green chemistry after completing the redesigned green chemistry laboratory curriculum.

Chapter 3
Iterative Development of an Integrated Green Chemistry General Chemistry Laboratory Curriculum

1. In what ways does the General Chemistry Green Curriculum (GC^2) need to be modified to better meet the needs of the students and instructors?
2. To what extent are the GC^2 goals clearly defined and aligned between developers and instructors/students?
    a. Do students believe they have learned green chemistry after completing GC^2?
    b. Do students see value in green chemistry outside of the course?

The final two research chapters explore student understanding of green chemistry (Chapter 4) and student green chemistry decision making (Chapter 5) in the context of this new green chemistry curriculum (GC^2). This necessitated the careful selection of assessment methodology as general chemistry at UC Berkeley is large enrollment course with thousands of students. The qualitative methodologies utilized in other studies (e.g., Mandler et al., 2012) were not possible with such a large course while still retaining a representative sample of students. Thus, a combination of fixed and free response green chemistry items was created to assess how general chemistry students were able to *define and use* green chemistry. This work also investigated the impact that student's *background* (gender, first-generations status, underrepresented minority status) and/or *prior chemistry or green chemistry experience* has on the gains they made in green chemistry understanding after completing the new GC^2 laboratory course.

Chapter 4
What's in a Word? Student Beliefs and Understanding About Green Chemistry

1. In what ways do students' abilities to *define and use* green chemistry change after completing a general chemistry green chemistry (GC^2) laboratory course?
2. In what ways do these changes differ based on a student's *background* (gender, first-generations status, underrepresented minority status) and/or *prior chemistry or green chemistry experience*?

The fifth and final chapter (Chapter 5) builds on the analysis and results of the previous chapter (Chapter 4) to explore how students make and justify green decisions when presented with real data and metrics. This chapter includes both general chemistry students (who had just completed the new GC^2 laboratory course) and organic chemistry students (half of whom had previously completed an earlier iteration of GC^2), which allowed for a comparison in green decision making between students who had more and less chemistry experience.

Chapter 5
Assessing the Complexity of Student Green Chemistry Decision Making

1. How do general chemistry students reason about green chemistry choices? In what ways do students use data to support their choices?
2. How do organic chemistry students reason about green chemistry choices? How does this reasoning compare to students who have only completed general chemistry?

Chapter 2: Initial Development of a Green Chemistry Focused General Chemistry Laboratory Curriculum

Introduction

Green chemistry and sustainability are increasingly important components of industrial and chemistry education practices (Benvenuto & Bodner, 2017; Haack & Hutchison, 2016; A. Marteel-Parrish & Newcity, 2017). International sustainable development goals depend on the innovations and solutions offered by green chemistry, particularly to address the global energy and environmental crises. To reach these goals it is imperative that a wide range of professionals understand and use green chemistry principles (Burmeister et al., 2012). Recognizing this need, UNESCO established a Decade of Education for Sustainable Development from 2005-2014 (*United Nations Decade of Education for Sustainable Development,* 2005).

As a result, there has been a growing international effort to develop educational materials focused on green chemistry and sustainability principles; however, the development of green chemistry curricular materials has occurred unevenly. Most green chemistry curricular design has occurred in elective courses or organic laboratory courses (Andraos & Dicks, 2012; Aurandt & Butler, 2011; Beltman et al., 2015; A. E. Marteel-Parrish, 2014; Morra & Dicks, 2016; Roesky et al., 2009) with much less focus on introductory general chemistry courses. Although a number of laboratory experiments have been designed for general chemistry courses (e.g. Purcell *et al.*, 2016; Buckley *et al.*, 2013; Klingshirn *et al.*, 2008; Bopegedera and Perera, 2017; Klara *et al.*, 2014; Rand *et al.*, 2016; Galgano *et al.*, 2012), there have been few comprehensive green chemistry general chemistry lecture (Prescott, 2013) or laboratory (Gron et al., 2013; Henrie, 2017; Klingshirn & Spessard, 2009) curricular designs.

With this gap in mind, the general chemistry laboratory course in the College of Chemistry at the University of California – Berkeley was redesigned around sustainability and green chemistry practices. Over 30 experiments were developed that use green chemistry principles as motivational contexts and include topics such as biodegradable polymers, extraction and analysis of plant-based antibiotics, ecotoxicity, fuel cells, solar cells, and biodiesel synthesis. Introducing green chemistry into the general chemistry curriculum, rather than a more advanced course like organic chemistry, allowed for the broadest range and number of future STEM professionals to be impacted as over 50% percent of the total STEM majors on campus complete this course. The aim was to present green chemistry in the context of real-world problems to deepen student engagement, participation, and connection of the material to their future studies. Ultimately, it was hoped that some of these students would eventually go on to research solutions to sustainability issues and legislate, promote, and/or teach these critical ideas and practices.

General chemistry is a foundational science course that surveys many different chemistry topics and techniques. The curriculum redesign was mindful to maintain canonical general chemistry learning goals alongside the new green chemistry learning goals. This cross-curricular implementation meant that students had a necessarily limited exposure to green chemistry principles. Thus, an objective, in additional to the curriculum design, was to measure the effect this bounded green chemistry curriculum had on student understanding and attitudes towards green chemistry. Systematic assessment of student learning of green chemistry is limited, especially for large enrollment courses like this general chemistry laboratory. Therefore, a series of assessment items were developed that could be efficiently used with thousands of students and still provided valuable and nuanced information about student learning and attitudes.

Green Chemistry Pedagogy and Assessment

The field of green chemistry was developed in the 1990's by chemists who were concerned that processes, by-products, waste, pollution, and industrial chemicals were adversely affecting human health and the environment (Anastas & Warner, 1998). In subsequent years, there has been an increased international commitment to integrate green chemistry and sustainability in industrial practices and educational programs (Benvenuto & Bodner, 2017; A. Marteel-Parrish & Newcity, 2017). To build the next generation of green chemists (and informed consumers and citizens) students must be equipped with the necessary tools to support and promote innovative green chemistry solutions (Burmeister et al., 2012; Kitchens et al., 2006; Rauch, 2015). While students cannot solve environmental or energy crises during their time in general chemistry, they can be introduced to principles and practices that they can ultimately use to make a meaningful impact on these global problems.

In addition to teaching students green chemistry concepts and methods, the integration of green chemistry into the curriculum provides students with an authentic context within which to learn chemistry. Green chemistry is not a separate field of chemistry, but rather an approach to chemistry that prioritizes safety of humans and the environment by considering complex green chemistry metrics and societal factors. (Eissen, 2012; Tucker, 2010). For example, students may be asked to justify which synthesis route to choose in organic chemistry (Graham et al., 2014; Lee et al.,

2014) or to evaluate the green chemistry properties of commercial products (Purcell et al., 2016). There is often no one "right" answer that instructors can offer students, but rather a range of appropriate green chemistry solutions (Andraos & Dicks, 2012; Khuong, 2017; Machado, 2015). This comparative analysis exposes students to a more accurate and nuanced understanding of the nature of science and leads to deeper analysis and greater chemistry understanding (Andraos & Dicks, 2012; Sandoval, 2005).

While green chemistry education has potentially important cognitive and pedagogical significance there is a dearth of systematic assessments of student learning of green chemistry, especially for cross-curricular courses. Most assessments of student knowledge of and attitudes towards green chemistry utilize surveys in which students are asked Likert style questions to self-assess their learning and attitudes towards green chemistry (Armstrong et al., 2018). However, since respondents often overestimate their abilities (e.g. von Blottnitz et al., 2015), it is important to supplement self-assessments with other methods such as student course work or observations. For example, Gron and coworkers (2013) complemented survey results with course results to assess green chemistry in an introductory chemistry majors laboratory course. Karpudewan and coworkers (2015b) were interested in motivational outcomes from green chemistry curricula in secondary teacher education programs and therefore, conducted interviews along with chemistry achievement tests. Mandler and coworkers (2012) assessed a high school chemistry module by asking students to pose four questions of interest about chemistry in an environmental context, before and after completing the module. Although these assessment methods are generally more time-consuming than surveys, it is important to develop an assessment plan that strive to measure the range of desired outcomes of a curriculum accurately and reliably.

Green Chemistry Curriculum Development at UC Berkeley

Goals of Curriculum

Over the past decade there has been a growing interest in solving complex sustainability and green chemistry issues on the UC Berkeley campus. In response to this interest, the College of Chemistry created several general chemistry laboratory experiments focused on one or more dimensions of green chemistry. The success of these initial experiments led to the redesign of the entire the general chemistry laboratory sequence around green chemistry and sustainability principles.

This new laboratory curriculum targeted several outcomes: 1) to educate students about sustainable practices applicable to their future work in the chemical sciences in academia and in industry, 2) provide students with a knowledge of exciting chemical applications and problems that are relevant to their interests, and 3) give students a more authentic experience of chemistry. The course was redesigned so that green chemistry principles were integrated into each multi-week experimental module while still retaining traditional general chemistry laboratory learning goals. These multiweek modules allowed the curriculum to progressively build towards more complex concepts and skills while retaining the same learning context week-to-week. The multiweek and modular structure also gave instructors the ability to customize their laboratory schedule as best fit their teaching practices.

Description of Original Green Curriculum

The development of the new curriculum followed an iterative design process involving a team of undergraduate assistants, graduate students, and faculty members. A constructivist framework (Bodner, 1986) was used to create guided-inquiry experimental modules (Farrell et al., 1999; Spencer, 1999) with the Model–Observe–Reflect–Explain (MORE) thinking framework used as a guide for the new laboratory curriculum (Rickey & Stacy, 2000). All of the new experiments asked students to use their data or pooled class data to answer novel questions while a subset of experiments allowed students to create their own hypotheses and experimental procedures (Fay et al., 2007). The use of multiweek experiments progressively built towards more complex concepts and skills while retaining the same learning context. Green chemistry was used as both a motivational context for the experiments and informed the criteria for selection of reagents and procedures utilized in the course (Anastas & Warner, 1998). Nearly every experiment now uses non-toxic (or less hazardous) chemicals and reduces waste production or produces non-toxic waste (e.g., using food dyes instead of heavy metals). Many of the experiments are presented in green chemistry contexts and ask students to connect green chemistry to the experiment they are completing.

In addition to green chemistry experimental procedures, a written curriculum that covers many green chemistry principles was created. An introduction to green chemistry is included at the beginning of the laboratory manual, which describes the goals of green chemistry, the *12 Principles of Green Chemistry*, and explicitly lists the principles that apply to each experiment they will complete during the semester. Each experiment includes a paragraph in the introduction outlining the relevant green chemistry principles. When needed, additional sections introduce green chemistry content or methods (e.g., dose response curves, LD_{50}). Finally, most experiments include at least one green chemistry focused prelab or postlab questions. Table 2.1 illustrate the chemistry and green chemistry principles that apply to each general chemistry laboratory module.

For example, one of the longest running modules is a three week biofuels unit that was inspired by published procedures (Levy, Irv, 2017; Thompson, 2013). During the first week of this module, students are introduced to toxicology, including the use and limitations of LD_{50} values. They make standard dilutions of several biofuels and prepare a simple radish seed germination assay to quantify the potential ecotoxicity of each of the fuels. The ecotoxicity assay allows students to appreciate the subtlety of *designing safer chemicals* and to see that even though all the fuels come from *renewable feedstocks*, that they have significantly different effects on radish seed germination.

Students also synthesize biodiesel from soybean oil during the first week of the module and then isolate their biodiesel sample through separation, aqueous extraction, and drying during the second week. They measure the viscosity of their fuel and compare it to the starting materials. In addition to introducing techniques of synthetic chemistry, this experiment focuses on concepts of stoichiometry, limiting reagents, and reaction yield. The discussion of reclaiming used cooking oil introduces a *waste prevention* strategy as well as using *renewable feedstocks*. The *base-catalyzed* transesterification reaction is both *solvent-less* and *atom economical*. In the final experiment of the module, students determine the heat of combustion of their synthesized biodiesel using a simple soda can thermometer. This introduces heat transfer and asks students to consider the relationship between the heat of combustion of a fuel and efficiency of a fuel. Soybean-based biodiesel has a much lower flash point than other alcohol-based biofuels, making the combustion reaction *inherently safer*. Measuring the heat of combustion allows students to evaluate the *energy efficiency* of biofuel and compare it to other fuels.

The module themes are synthesized in a final argumentation worksheet. Students write a short paper comparing biodiesel and one other biofuel as alternative transportation fuels. They use the data they collected over the last three weeks along with supporting information from scientific sources to support their argument for the best fuel. This argumentation exercise gives students a chance to reflect on what they have learned, engage in critical scientific discourse, and consider how green chemistry applies to the energy challenges facing our society.

Table 2.1. Experimental Module, Chemistry Principles, and Green Chemistry Principles for Each Redesigned Experiment Used in the General Chemistry Laboratory Course at UC Berkeley

Module (# of Weeks)	General Chemistry Principles	Green Chemistry Principles
How the nose knows (1)	Functional groups, physical properties, formal charges, bond-line notation, VSEPR	Designing safer chemicals, renewable feedstocks
Polymers: Properties and Applications (1)	Functional groups, density, solubility, structure-function relationship, dissolution, hydrolysis	Waste prevention, designing safer chemicals, design for degradation
Polymers: Cross-Linking and Toy Design (2)	Cross-linking reactions, intermolecular interactions, bonding, mass ratios in mixtures	Inherently safer chemistry, safer solvents, renewable feedstocks, atom economical
Polymers: Density of Liquids and Solids (2)	Precision and accuracy, systematic and random error, solubility, experimental design, polymer structure	Waste prevention, designing safer chemicals, and designing for degradation
Biofuels (3)	Transesterification, combustion and calorimetry, solubility, extraction, C_{cal} and H_{comb}	Designing safer chemicals, renewable feedstocks, catalysis, safer solvent, atom economical, inherently safer chemistry, energy efficiency
Spectroscopy: Food dyes and riboflavin in beverages (1)	UV-Vis and fluorescence spectroscopy, Beer's Law, extinction coefficients, calibration curves, error propagation	Inherently safer chemistry
Extraction of curcumin and spectroscopic analysis (1)	Transmission, absorbance, extraction and separation, calibration curves, linearity of data	Safer solvent, energy efficiency, waste prevention
Equilibrium (1)	Solubility, acid/base equilibria, gases, Le Châtelier's Principle, pH measurements	Renewable feedstocks, safe solvents and auxiliaries, designed for degradation
Depolymerization and Titration (2)	Ester hydrolysis, dimensional analysis, ICE tables, indicator and potentiometric titrations	Renewable feedstocks, designed for degradation
Acids in the Environment (3)	Solubility equilibria, acid/base titrations, gases and equilibrium, Le Châtelier's Principle, buffers	Real-time analysis for pollution prevention, less hazardous chemical syntheses, waste prevention
Extraction from Thyme Leaves (2)[a]	Extraction, IMFs, polarity, chromatography, diffusion, extraction, standard addition, uncertainty	Waste prevention, design for degradation, use of renewable feedstocks
Extraction and Analysis of Limonene (2)[b]	Chromatography, boiling points, sublimation, triple point, polarity, mass spectrometry, standard calibration curves, uncertainty	Pollution prevention, safer solvents, energy efficiency, renewable feedstocks, design for degradation, safer chemistry and solvents
Methanol/Glucose Fuel Cells and Dye-Sensitized Solar Cells (2)	Electrochemistry, galvanic cells and batteries, catalysis and enzymes, cell potentials, net free energy calculations	Energy efficiency, catalysis, renewable feedstocks, design for degradation, inherently safer chemistry
Kinetics: Bleaching Organic Dyes and H_2O_2 Decomposition (2)	Catalysis, reaction rates, kinetics, reaction order, method of initial rates, visible spectroscopy, Beer's Law	Catalysis, designing safer chemicals, inherently safer chemistry
Computational and experimental investigation of pesticides (2)	MO theory, computer-based molecular modeling, solubility, UV-Vis and fluorescence spectroscopy	Waste prevention, designing safer chemicals, real-time analysis for pollution prevention

[a]See Buckley et al., 2013. [b]See Klingshirn et al., 2008.

Assessment of Student Learning

The new general chemistry laboratory curriculum provides a green chemistry context for each experiment, outlines the green chemistry principles relevant to each experiment, and asks the students to evaluate complex green chemistry outcomes while maintaining most of the traditional general chemistry learning goals and chemistry content. However, developing the new curriculum was only the first step; the next step was to determine whether this targeted introduction of green chemistry into a traditional general chemistry laboratory would lead to an increase in student understanding of green chemistry.

The *12 Principles of Green Chemistry* (Anastas & Warner, 1998) and systems-thinking (Constable, 2017) served as the framework for the green chemistry assessment design. The item design and administration were refined over the years with input from course instructors, curriculum designers, graduate students, and undergraduate students both within and outside of the course. The purpose of this research was to 1) understand students' attitudes towards their own green chemistry knowledge and 2) measure how students' understanding and application of green chemistry concepts and principles changed after completing the redesigned general chemistry laboratory course. Specifically, this work was designed around the following research questions:

1. Do students believe they have learned green chemistry? Do students value green chemistry?
2. Does students' understanding of green chemistry increase after completing the general chemistry laboratory, given a limited introduction of green chemistry into the curriculum?
3. Are students with different levels of prior green chemistry knowledge able to reach similar levels of understanding after completing the general chemistry laboratory?

The choice of assessment methodology had to be carefully considered due to the number of students who take general chemistry laboratory each year. Since over 2000 students complete our laboratory course each year it was impossible to personally interview or observe every student. Online surveys and in-class assignments and exams were important data sources for evaluation of student attitudes and learning. These tools allowed every student to be evaluated while not requiring an enormous investment in research time. When possible, fixed response items were utilized for faster analysis, but certain assessment questions required open-ended student responses or interviews with students to answer. This approach allowed efficiently assessment of thousands of students, while still gaining valuable and nuanced information about student learning and attitudes.

Methods

Study Design

This study focused on the first semester of general chemistry for non-chemistry majors laboratory (Chem 1AL). This course is divided into a lecture (Chem 1A) and laboratory (Chem 1AL) course with separate instructors. Chem 1AL has a weekly lab lecture from an instructor, weekly lab experiments, and an end of term written lab exam. Chem 1AL is offered year-round and has an approximate enrollment of 100 students in summer, 800 students in spring, and 1200 students in fall.

This study focused on Chem 1AL for the Fall 2013-2017 semesters and the item design and administration underwent iterative updates over these semesters. First, an online survey that contained several green chemistry items was administered at both at the beginning and end of each semester. After collecting and analyzing this data for several semesters, additional free-response survey and in-class items were added for the Fall 2016 semester. The research was approved by the university's Institutional Review Board, and all student participants consented to participate. Each student was assigned a pseudonym to report any specific examples or findings.

Administration of Assessment Items

Online Survey

Students completed a comprehensive online survey at the *beginning* (first three weeks) and *end* (final two weeks) of the semester using either SurveyMonkey or Qualtrics. This survey covered a range of questions probing student chemistry concept and technique knowledge, green chemistry knowledge, attitudes towards chemistry, confidence in chemistry abilities, and demographic and course evaluation information.

Students were incentivized to complete the survey for two course bonus points. If they did not wish to complete the survey, they could complete an alternate assignment. The survey had, on average, a 65% response rate after removing duplicate respondents and students who declined to provide identifying information to verify enrollment in the course (Table 2.2).

Table 2.2. Response rates for administered surveys in Chem 1AL

Semester	Total number of students in course	Response Rate	
		Pretest	Posttest
Fall 2013	1,108	552 (50%)	958 (86%)
Fall 2014	1,158	578 (50%)	678 (59%)
Fall 2015	1,121	690 (62%)	836 (75%)
Fall 2016	1,053	686 (65%)	824 (78%)
Fall 2017	1,197	687 (57%)	986 (82%)

Four items from the online survey were used to measure student familiarity with and attitudes towards green chemistry (Table 2.3). These questions allowed for quick assessment of students' self-reported green chemistry knowledge and attitudes. Of these, three free response items were iteratively refined during the initial semesters of this project and were finalized during the Fall 2016 and 2017 semesters.

Table 2.3. Online Survey Items Relevant to Student Self-Reported Green Chemistry Knowledge and Attitude toward Green Chemistry

Green Chemistry Survey Item	Response Type	Pretest/Posttest	Semesters analyzed
I know what the term Green Chemistry means.	Fixed response[a]	Both	Fall 2013 – Fall 2017
What will you take from this course into other classes or life?	Free response	Posttest	Fall 2016, Fall 2017
What was the most valuable thing you gained from lab?	Free response	Posttest	Fall 2016, Fall 2017
Describe a connection that was meaningful to you.	Free response	Posttest	Fall 2017

[a]The fixed-response categories are Strongly Disagree, Somewhat Disagree, Somewhat Agree, and Strongly Agree.

Student chemistry content knowledge was measured using 21 fixed response survey items (Appendix I). Sixteen Likert items were used to measure students' self-assessment of their chemistry content knowledge and technique ability and five multiple choice chemistry content question were used to measure students' knowledge of core general chemistry concepts (e.g., intermolecular interactions, absorbance, titration curves). These items were analyzed for the Fall 2016 semester concurrent with the green chemistry item analysis.

In-class Green Chemistry Assignment

In addition to online surveys, students also completed an in-class green chemistry assignment at the *beginning* and *end* of the Fall 2016 semester. Students were asked to respond to the question: ***In your own words, define green chemistry***. Students were given 10 minutes to complete this written assignment during the first laboratory lecture of the semester and during the last laboratory section of the semester. They were advised that this assignment would be graded based only on effort and that if they did not know what the term green chemistry meant, they should state "I don't know what green chemistry is, but my best guess is…."

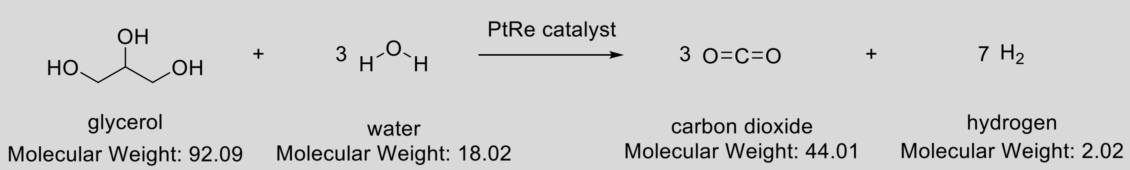
Nearly every student enrolled in the course completed these assignments (1,086 students completed the pretest and 1,017 students completed the posttest). Administering this question in-class assessed student understanding of green chemistry without access to search engines or other outside resources.

Exam Question on Green Chemistry

Students also completed a green chemistry question on their laboratory exam during the Fall 2016 semester (Figure 2.1). This was a closed book exam administered in-class at the end of the course. Students were given 90 minutes to complete 25 free response and multiple-choice questions. The green chemistry question was worth 4% of their overall grade for the exam. All of students enrolled in the course completed this exam.

This question assessed students' use of higher-order thinking strategies and green chemistry understanding through the exploration of a novel real-world problem that included the primary sustainability themes taught in the laboratory course. The question allowed us to discern student proficiency of green chemistry in their own words, without access to search engines or other outside resources.

Glycerol can be converted to hydrogen gas using a new PtReC based catalyst. The reaction is performed at high temperatures using water as a solvent.



Why is this exciting from a green chemistry perspective?

Figure 2.1. Green chemistry question included on the Fall 2016 exam

Student Interviews

Students were asked on the online survey if they were willing to be contacted for interviews. All students who were willing to be interviewed were emailed an invitation to schedule an interview. Students were chosen based on scheduling constraints and promptness of response. Interviews were conducted with 12 Chem 1AL students during the final two weeks of the Fall 2016 semester. Out of the 12 students interviewed, there were seven male and five female participants. There were three Asian, two Latinx, and five White participants; two students did not provide ethnicity data. Interviews lasted no more than 30 minutes.

The purpose of the interviews was to validate the administered green chemistry items. Students were asked to reflect on their responses to the in-class green chemistry assignment. They were prompted to describe what they were thinking when they answered the question and why their answer changed or stayed the same between their pretest and posttest responses.

Analysis of Assessment Items

For all items results were considered significant at the 95% level. Respondents with missing data and those who did not consent to participate in the research study were dropped from the dataset. All analysis was completed using StataSE 14.2.

Fixed Response: Online Survey

The fixed response green chemistry item (Table 2.3*)* was assigned numerical values for further analysis. *Strongly disagree* was assigned a value of 0, *somewhat disagree* a value of 1, *somewhat agree* a value of 2, and *strongly agree* a value of 3. The means and standard deviations for each semester for the pretest and posttest were calculated. Paired two-sample t-tests were used to compare the mean pretest and posttest scores for each item.

Free Response: Online Survey

Three free response online survey items (Table 2.3) were coded for green chemistry themes. These questions did not directly prompt students to discuss green chemistry but after coding a subset of responses it became clear that green chemistry (and related topics such as biofuels, chemical safety, energy, and sustainability) were common response topics. Three main themes arose after this initial coding: explicit inclusion of green chemistry, connections to the environment/climate, and direct mentions of the green chemistry focused experiments used in the course (biofuels, ocean acidification). An additional round of coding revealed three more common categories related to energy/catalysis, waste/byproducts, and material lifecycle.

From this initial coding, subcategories with detailed inclusion criteria were developed for each of the main themes. The number of times each of these criteria were mentioned (words or phrases) for each response were counted using Excel. The validity of this coding was confirmed against a human coder for the first 50 responses. The Excel text analysis was refined until 100% agreement was reached with the human coder. This text analysis allowed for quick coding of thousands of student responses over two semesters.

In-class Green Chemistry Assignment

A randomized sample of 50 student responses was qualitatively coded, and several emergent themes arose including minimizing hazards, minimizing waste, energy, material lifecycle, and research and development. This coding scheme was applied to additional student responses and discussed with a larger group of researchers. Several categories were added including discussing green chemistry philosophy and mentioning buzzwords (words or phrases that students used that were not connected to actual green chemistry content, e.g., 'efficiency' or 'environmental friendliness').

To refine the coding scheme, two researchers independently coded approximately 25 student responses and then discussed their results to achieve 100% coding agreement. The main categories, inclusion criteria, and exclusion criteria were revised and clarified based on these results. This process was repeated until no more changes to the codebook were produced. The two researchers then independently coded 20% of the student responses and achieved a high rate of agreement (Cohen's κ of above 0.90 for all coding categories). The two researchers then each individually coded half of the remaining responses. Any responses that were ambiguous to an individual researcher were flagged and discussed by both researchers until agreement was reached.

A total item score was assigned to each response by summing the individual coding categories. A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 point plus 1 point for each specific green chemistry category present in the response. Thus, a response that only mentioned "green buzzwords" received a score of 1 while a response that discussed reducing chemical hazards and laboratory waste would receive a score of 3. McNemar's test for paired dichotomous data was used to compare the pretest and posttest proportions for each coding category. Paired two-sample t-tests were used to compare the mean pretest and posttest total item score.

Exam Question on Green Chemistry

A randomized sample of thirty student responses to the green chemistry exam question (Figure 2.1) were qualitatively coded and four emergent themes arose: hazard reduction, waste prevention, renewability, and catalysis. This coding scheme was applied to 20% of the total student responses and discussed with additional researchers. The main themes were revised and divided into "general" (e.g., "reduced damage to the environment") and "specific" (e.g., "water as a safer solvent") subcategories. Several categories for common incorrect responses were also added.

Using this new coding scheme, two researchers independently coded an additional set of student responses and discussed their results to achieve 100% agreement. The inclusion and exclusion criteria were revised based on these results. This process was repeated until no additional changes to the codebook were produced. The remaining student responses were coded by both researchers and disagreements were discussed until consensus was reached. A total green exam question score was assigned to each response by summing the correct general (1 point each) and specific (2 points each) categories and subtracting the number of incorrect (1 point each) categories.

Prior Understanding of Green Chemistry

For the Fall 2016 semester, students were divided into two groups based on their total definition score for the pretest in-class green chemistry assignment. Students were categorized as having "low prior green chemistry knowledge" if they had a total item score of 1 or lower and as having "high prior green chemistry knowledge" if they had a score of 2 or higher. A total item score of 0 indicated a blank or off-topic/irrelevant response while a score of 1 indicated a correct but non-specific definition. A score of 2 or above indicated that the student definition included at least one specific green chemistry category. Independent sample t-tests were used to compare the mean posttest total item scores of the low and high prior green chemistry knowledge groups.

Student Interviews

Student interviews were audio recorded and then analyzed in a qualitative manner of data inspection and thematic analysis.

Results and Discussion

General chemistry at UC Berkeley serves thousands of students each year. These students come from diverse backgrounds and thus, capturing the growth in their knowledge and experiences was an important feature of this study. Given the size of the course and the challenge of teaching green chemistry, the assessment focused on student self-evaluation of their green chemistry knowledge, demonstrated knowledge of green chemistry, and spontaneous discussion of green chemistry. This approach illustrated the impact of the redesigned curriculum on student confidence in their green chemistry knowledge as well as their demonstrated green chemistry ability.

Course and study demographics. Chem 1AL is the first semester general chemistry laboratory course at UC Berkeley and is typically taken by incoming non-chemistry majors. Students in Chem 1AL have diverse backgrounds and prior chemistry experience. The students encompass a wide range of intended majors including, but not limited to, life sciences, bioengineering, nutrition science, public health, and civil engineering. Typically, the majority (~75%) of students come from middle to upper-middle class households and about half of them have at least one parent with a graduate degree. Nearly every student has taken at least one semester of chemistry prior to their entry into the university. About half of the students have completed two semesters and ~40% have completed four or more semesters of chemistry before entering Chem 1AL. Approximately half of the students have taken honors chemistry (55%), AP chemistry (46%), and/or AP physics (44%). The course typically has more female (60%) than male (40%) students. Most students are of Asian descent (~45%) with White (~25%), Latinx (~15%) and African American (~2%) students comprising the remainder of the class. The gender and ethnicity of the study respondents is representative of the course demographics with detailed demographic data presented in Appendix II.

Do Students Believe They Have Learned Green Chemistry and Value Green Chemistry?

Student Self-Assessment of Green Chemistry Knowledge

One of the main goals for the curriculum redesign was to teach students green chemistry principles and applications. As with many large-scale course changes, it was important to check that the goals of the curriculum were readily apparent to the students (Meyers & Nulty, 2009) and that students left the course believing they gained green chemistry knowledge. The students were asked how much they agreed with the statement "I know what the term Green Chemistry means" at the start and end of the course. This fixed response item allowed student self-assessment of green chemistry knowledge to be quickly measured for thousands of students over many different semesters. As hoped, students' self-reported understanding of green chemistry increased significantly between the beginning and end of the semester (Table 2.4). This trend held across many semesters with different instructors, TAs, and experiment orders.

Table 2.4. Mean Student Response Scores to the Question "I Know What the Term Green Chemistry Means" before and after Completing Chem 1AL

Semester	Pretest[a]	Posttest[a]	Significance		
			p-Value	*t*-Value	Degrees of Freedom
Fall 2013	1.35	2.19	$p < 0.001$	–17.45	385
Fall 2014	1.34	2.11	$p < 0.001$	–17.34	397
Fall 2015	1.93	2.17	$p < 0.001$	–6.23	554
Fall 2016	2.13	2.49	$p < 0.001$	–9.31	416
Fall 2017	1.93	2.31	$p < 0.001$	–8.93	466

[a]This scale was used for responses: 0, Strongly Disagree; 1, Somewhat Disagree; 2, Somewhat Agree; 3, Strongly Agree.

While all semesters showed a significant increase in students' self-reported understanding of green chemistry there were differences in mean pretest scores between different semesters of the course. Differences in instructor pedagogy may help explain these variations. Students in Fall 2015-17 courses had much higher mean pretest scores than the Fall 2013-14 semesters. The Fall 2015-17 instructor was one of the designers of the new green chemistry curriculum and thus was intimately familiar with not just green chemistry but the purpose and structure of each new experiment. Her first lab lecture introduced students to the *12 principles*, explained the redesign of lab curriculum, and gave an example of new green chemistry lab experiments. Students interviewed at the beginning of the Fall 2015 semester confirmed this description of the first lab lecture and stated that they had complete the initial survey after attending the first lab lecture.

Students Reported That Green Chemistry Was Meaningful to Them

In addition to students' increased confidence in their green chemistry knowledge, a goal of the course was to give students tools to bring to their future classes, research, and careers. Several free response survey items were used to investigate whether students found the curriculum meaningful and would consider applying what they learned to future courses and professions. These questions probed what students' value about the course and what they will bring with them to future courses (Table 2.3).

None of these questions directly asked students about green chemistry and yet many students, unprompted, mentioned green chemistry in their answers. When asked, 'What will you take from this course into other classes or life?' one quarter to one third of students in Fall 2016 and 2017 semesters, respectively, stated that they planned to use green chemistry in their future courses or daily life (Figure 2.2). Surprisingly, when asked, 'What was the most valuable thing you gained from lab?' close to 10% of students from both years identified green chemistry as the most valuable thing they gained. That even a fraction of students decided that green chemistry was the most valuable part of the course, instead of basic laboratory skills, is evidence of the impact of green chemistry in the curriculum.

Based on results from these questions, a new item was added in the Fall 2017 semester to determine *what connection in the course was most meaningful* to students (Figure 2.2). Once again, this question did not specifically ask students about green chemistry and yet three quarters of the students stated that green chemistry was the most meaningful connection from the course. Together, these results indicate that students highly value learning green chemistry in Chem 1AL and plan to use these green chemistry principles and methods in future courses or in their daily life.

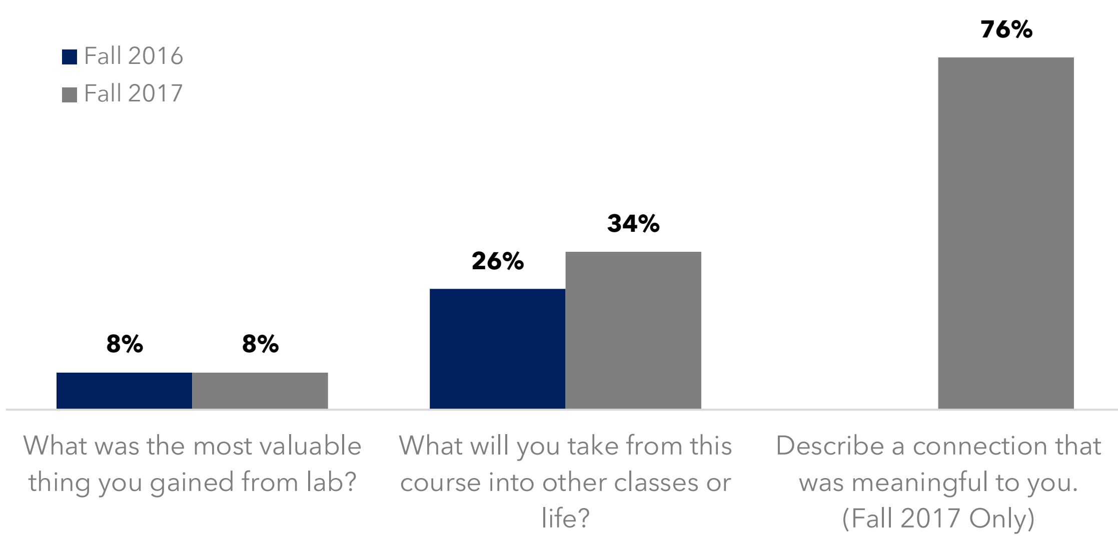


Figure 2.2. Percentage of student responses that included green chemistry (or related words/phrases) after completing Chem 1AL (N = 750 for Fall 2016, N = 715 for Fall 2017)

To What Extent Do Students Understand Green Chemistry?

In-Class Green Chemistry Assignment

While it was encouraging that students believed they understood green chemistry after completing Chem 1AL, it was important to ensure that they were also truly improving their green chemistry abilities especially since self-assessment of knowledge is often not a reliable measure of cognitive learning (Davis et al., 2006; von Blottnitz et al., 2015) and is instead a better measure of affective components (Sitzmann et al., 2010). Thus, the open-ended question "*In your own words, define green chemistry*" was used to measure green chemistry understanding. The open-ended structure of this question allowed respondents to demonstrate a wide range of green chemistry knowledge. Additionally, this item was ideal as a pretest because it did not assume prior chemistry knowledge. Students were encouraged to make it clear if they were guessing on their response which provided a measure for their confidence in understanding green chemistry.

Student responses were first analyzed for correctness, guessing, and only mentioning "buzzwords" (Figure 2.3). "Buzzwords" were defined as words students may have heard in their daily life without any surrounding green chemistry content, such as "sustainability" or "environmental friendliness." At the beginning of the semester, 80% of respondents stated their response was a guess, 32% only mentioned "buzzwords," and 25% gave an incorrect definition. Responses such as "I'm not sure but my best guess is that it's the chemistry of organic compounds" or "My best guess is that green chemistry is chemistry that is good for the environment" were emblematic of the level of confidence and green chemistry understanding students were able to exhibit. However, after completing the new general chemistry laboratory curriculum students were wholly confident in their definitions of green chemistry; no student stated that they have guessed for their posttest response. This confidence was well earned since no students gave an incorrect definition of green chemistry at the end of the semester.

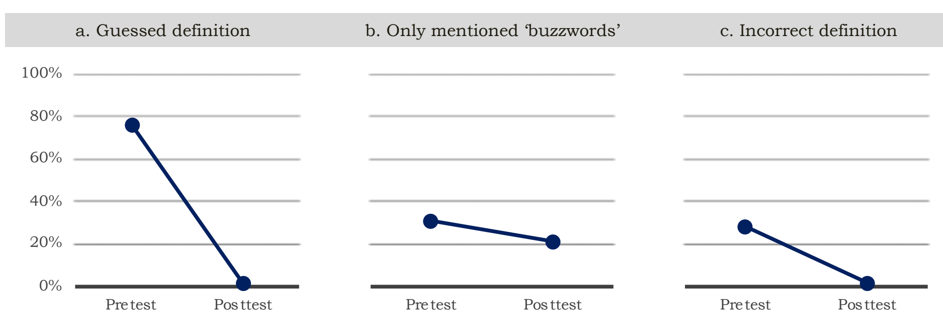


Figure 2.3. Percentage (N = 801) of pretest and posttest response categories for the question "In your own words, define green chemistry." McNemar tests showed that the pretest and posttest proportions were significantly different for each category, $p < 0.001$ (exact). A solid line (–) represents a statistically significant difference from pretest to posttest.

Students not only gave more correct definitions of green chemistry, but also showed an increased level of sophistication as they were able to identify and describe more components of green chemistry (e.g., reducing waste, minimizing hazards, material lifecycle considerations) after completing Chem 1AL (Figure 2.4). In contrast to students' pre-semester responses, of which 52% were incorrect or only mentioned buzzwords, student's post-semester responses mentioned at least one specific component of green chemistry 77% of the time. Minimizing hazards, material lifecycle considerations, and minimizing waste were the most common green chemistry components discussed in student responses. There were significant differences in all three of these categories between the pretest and posttest proportions ($p < 0.001$).

While less common than the previous three categories, students also demonstrated an increased understanding of the practice and philosophy of green chemistry. At the beginning of the course, very few students understood that green chemistry strives to create new technologies, methods, and other innovations (*research and development*) but by the end of the course 22% of students were able make this connection. Similarly, at the start of the course only 3% of students acknowledged that green chemistry targets all aspects of a chemical process (reactants, reaction, products/byproducts), but by the end of the semester 14% of students considered multiple components of the reaction. Additionally, after completing Chem 1AL, 11% of students discussed how green chemistry is a philosophy for all chemistry – not just a niche topic – demonstrating a more nuanced understanding of green chemistry as a metadiscipline.

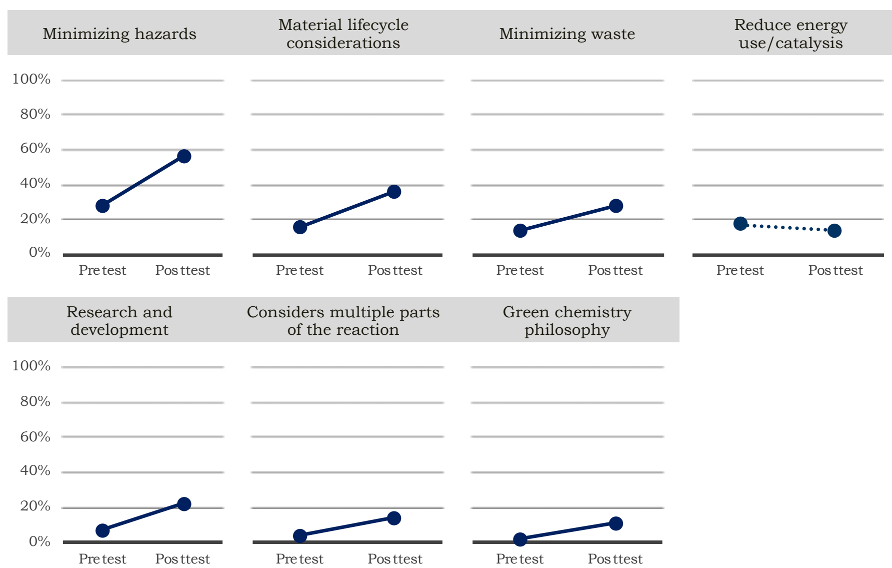


Figure 2.4. Percentage (N = 801) of pretest and posttest response categories to the question "In your own words, define green chemistry." McNemar tests showed that the pretest and posttest proportions were significantly different for each category ($p < 0.001$, exact) except for *Reduce energy use/catalysis* ($p = 0.061$, exact). A solid line (–) represents a statistically significant change and a dashed line (• • •) represents a non-significant change from pretest to posttest.

Comparing one student's pre- and posttest responses illustrates how students were able to build more sophisticated definition of green chemistry after completing Chem 1AL. Penny's pretest response emphasizes the idea that green chemistry should not harm the environment, but does not contain specific components of green chemistry:

> *Green chemistry means sustainable chemistry. It aims to teach chemistry practices that do not harm the environment. Green chemistry aims to benefit the environment and not contribute to global warming.*

After completing Chem 1AL, Penny was able to add and integrate more specific components of green chemistry into her original understanding of what green chemistry encompasses:

> *Green chemistry involves performing environmentally friendly tasks while in the lab. This includes minimizing waste, preventing toxic substances from leaving the lab, and also exploring ways in which to perform experiments that do not harm the environment. Another goal of green chemistry is to spread knowledge of environmentally friendly chemistry practices and also to inspire scientists to formulate ways to help the environment. For example, in this lab course, we learned about alternative fuels sources in our biofuels lab and how green chemistry can be applied to the real-world concept of fuel usage. In summary, green chemistry is the promotion of environmentally safe practices to help steer towards a greener and safer and more sustainable future.*

She was able to name specific components that promote environmental friendliness in a chemistry laboratory (*minimizing waste, preventing toxic substances from leaving the lab, and exploring ways in which to perform experiments that do not harm the environment*) and provide an example for how scientists can use green chemistry practices to innovate. She also shows a complex understanding that green chemistry involves both practical and innovative principles.

While not all students had as sophisticated a posttest response as Penny, 66% of students gained at least one point from their pre to posttest scores. Students, even those with a strong understanding of green chemistry, were not expected to include all the coding categories in their definition of green chemistry. The coding scheme was created to capture the breadth of categories that could be included in a definition. Nevertheless, a total item score was created to compare how student's ability to define green chemistry changed from the beginning to the end of the course. A total item score was assigned to each student's responses by summing the individual coding categories. A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 plus 1 point for each specific green chemistry category present in the response.

The mean pretest score was 1.50 points indicating that, on average, students did not include a specific green chemistry category in their definition. However, by the end of the semester the mean total item score had increased significantly to 2.79 ($p < 0.001$, $t = 19.97$, d.f. = 800) showing that students were able to integrate, on average, nearly two specific green chemistry categories into their definition. These results show that not only do students believe they know more about green chemistry after completing Chem 1AL, but they have also gained demonstrable green chemistry knowledge.

Interviews with 12 students were also conducted at the end of the semester to qualitatively explore the responses to this in-class green chemistry assignment. All interviewees stated that they believed their understanding of green chemistry improved after completing Chem 1AL. Eight of 12 students stated that they had a general understanding of green chemistry at the beginning of the semester, relating it to “buzzwords” such as “environmental friendliness”, but at the end of the semester they had a more specific knowledge of green chemistry. Students also talked about how they were able to learn about green chemistry by reading the laboratory manual and applying green chemistry principles and concepts in the experiments they completed in Chem 1AL. Many of them were able to give examples of green chemistry principles during the interviews (such as atom economy) and how they used these principles in specific Chem 1AL experiments (such as the biofuels module), which is consistent with our quantitative assessment results.

Exam Question on Green Chemistry

Improving students’ understanding of green chemistry is one of the fundamental goals of Chem 1AL. Instructors often include green chemistry questions on their final written laboratory exam to assess student mastery. During the Fall 2016 semester, students were asked to analyze why a particular reaction, shown in Figure 2.1, was exciting from a green chemistry perspective. This question was an excellent complement to the Fall 2016 dataset because it probed students’ use of higher-order thinking strategies and green chemistry understanding of the primary sustainability themes taught in Chem 1AL through a novel real-world scenario. This question also allowed assessment of student proficiency of green chemistry in their own words, without access to other outside resources.

There were multiple correct approaches to answer to this question and thus analysis of this item aimed to descriptively capture the variety of ways students responded to this problem (Figure 2.5). The responses were first categorized the *general* statements students provided. These ranged from statements that the materials involved in the reaction were less hazardous/toxic (e.g., "*CO_2 is a greenhouse gas, but it is not radioactive or extremely dangerous*") to the broad idea that using a catalyst is in alignment with green chemistry principles (e.g., *"This reaction is exciting because it uses a catalyst").* Most students (77%) made at least one general statement in response to this question though a minority (22%) included multiple general statements in their response.

Additionally, 64% of the student responses included at least one *specific correct* reason for why this reaction was exciting from a green chemistry perspective and approximately a quarter of the respondents (27%) were able to provide two or more *specific correct* ideas. There are multiple *specific* reasons this reaction is exciting including 1) it utilizes a safer solvent (water), 2) it utilizes a waste product from biofuel synthesis (glycerol), 3) one of the reactants (glycerol) can be sourced from renewable feedstocks, and/or 4) it utilizes a catalyst which can reduce the energy/pressure/temperature needed for the reaction and is superior to stoichiometric reagents.

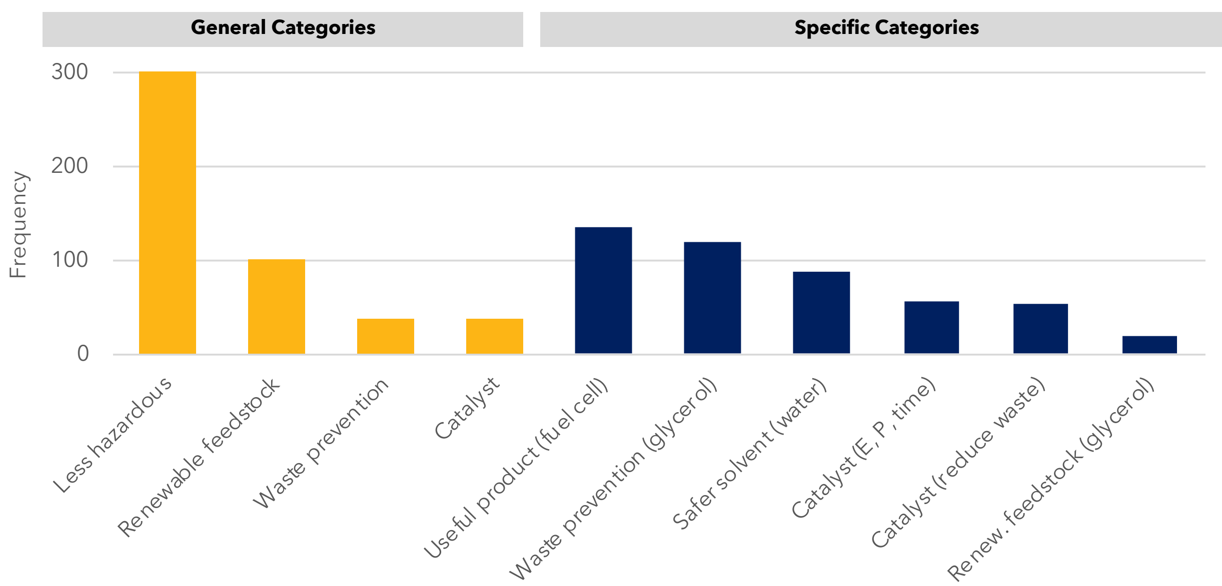


Figure 2.5. Frequency of major general and specific categories included in student responses to the green chemistry final laboratory exam question (N = 495)

The most common student response (45%) included both *general* and *specific* statements about the green chemistry properties of this reaction. A minority (32%)

only mentioned *general* categories while an even smaller proportion (19%) only included *specific* statements. For example, Cami covered multiple *specific* (renewable feedstock – glycerol, useful product – fuel cell, catalyst – E, P, time) and *general* (less hazardous reagents) ideas in her response:

> *Glycerol can be derived from renewable resources (as we showed thru our biofuels extraction using vegetable oil). This is a greener way to isolate H_2 molecules that can be used in hydrogen fuel cells that can power engines, like cars. Using H_2 in cars is a much cleaner option, as it doesn't emit harmful molecules like NO_x and SO_x. Using a catalyst in this reaction reduces the amount of energy needed for it to happen, which is also green.*

She was also able to connect this this new reaction to an experiment she had completed earlier this semester showing an ability to transfer learning from the laboratory to a novel situation.

Most students (63%) mentioned that this reaction was exciting because it was less hazardous than traditional reactions (e.g., *"Because these reagents are cheap and safe to use, this reaction is economically efficient and safe to perform which means it can be performed in a variety of lab settings")* with 17% specifically discussing that water was a safer solvent. (e.g., *"This reaction only requires water, a safe and inexpensive reagent, to convert glycerol, another cheap and safe reagent, into the desired product."*). Students also recognized that hydrogen was a useful product for fuel cell vehicles (26%) and that one of the reactants (glycerol) was a waste product from biofuel synthesis (24%). Encouragingly, only 22 respondents (<1%) had completely incorrect answers. This indicated that most students were able to not only define but also apply green chemistry principles to a novel scenario.

Approximately 20% of the total respondent population incorrectly applied the principle of atom economy to this reaction (this reaction was not atom economical, but students stated it was, e.g., *"one mole of glycerol leads to seven moles of h2* [sic] *which is efficient")*. However, the most interesting and unanticipated issue arose from the presence of CO_2 as a product. Nearly 16% the students either explicitly or implicitly stated that the production of CO_2 was benign or even beneficial with 40 students (8%) stating that CO_2 was a beneficial/desired product and 37 (7%) arguing that the products were natural and therefore beneficial. For example, Dax tries to justify the production of carbon dioxide by saying it can be used by plants. While this is not an untrue statement it is certainly not a reason that this reaction is exciting from a green chemistry perspective:

This is exciting from a green chemistry perspective because the reactants and products used are safe for human use and do not have a negative impact on the environment. Water is safe and necessary for life, CO_2 can be used by plants, the desired product (H_2) is made, and excess reactants can be safely disposed of since H_20 and glycerol are safe compounds.

The unexpected prevalence of this justification may indicate that students still have difficulty understanding that tradeoffs are inherent to green chemistry decision making. As Andraos and Dicks (2012) state "the evaluation of 'greenness' is a relative comparison and not an absolute one" yet these students seem to have been viewing the reaction through an absolute perspective. This may indicate that students need more opportunities within the course to grapple with real (and complex) green chemistry scenarios.

Are students With Different Levels of Prior Green Chemistry Knowledge Able to Reach Similar Levels of Understanding After Completing Chem 1AL?

Chem 1AL is a large and diverse class with students from many different backgrounds. Students enter the general chemistry laboratory with widely varying levels of prior green chemistry knowledge. Some students have already completed environmental or sustainability focused chemistry courses while others have never heard of the term green chemistry. The outcomes of both high and low prior knowledge students were compared to assess whether the new curriculum could close the gap in knowledge between these students. Based on their pretest responses to the question ***"In your own words, define green chemistry"***, students were grouped into two categories: low and high prior green chemistry knowledge. Students were categorized as low prior knowledge if they answered this question incorrectly (total item score of 0) or with a superficial response (total item score of 1) on the pre-test.

After completing the redesigned general chemistry laboratory, low prior knowledge students were able to define green chemistry at the same level as high prior knowledge students (Figure 2.6) At the beginning of the semester, the difference in means between the high and low prior knowledge groups was estimated as 2.22 with a 95% confidence interval from 2.04 to 3.91 ($p < 0.001$, $t = 25.03$, d.f. = 260). However, by the end of the semester this difference in means was estimated as only 0.15 with a 95% confidence interval from -0.20 to 0.50; there was no longer any significant difference in the mean scores for these two groups ($p = 0.4078$, $t = 0.92$, d.f. = 260). Additionally, both low and prior knowledge groups made gains from pretest to posttest scores though only the low prior knowledge group had statistically significant gains ($p < 0.001$, $t = 16.52$, d.f. = 134). The low prior knowledge group saw an estimated 2.27-point increase from the mean pretest to posttest scores with a 95% confidence interval from 2.00 to 2.55.

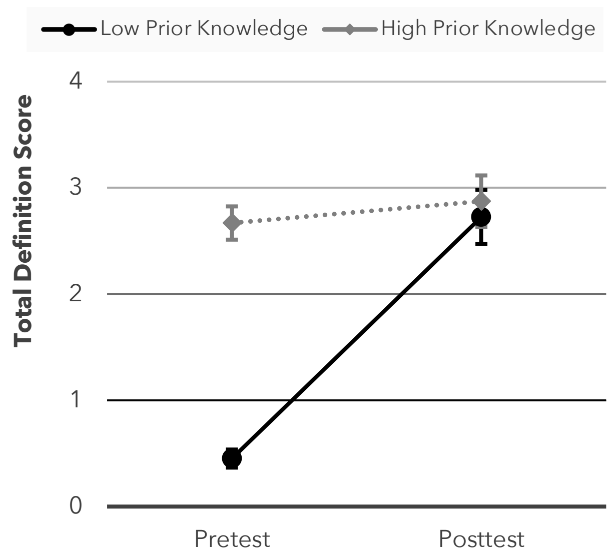


Figure 2.6. Pretest and posttest total definition score for low and high prior knowledge students. Based on their responses to the pretest question "In your own words, define green chemistry", students were grouped into low and high prior green chemistry knowledge categories. The gap in ability to define green chemistry between low (N = 135) and high (N = 127) prior knowledge students was significantly reduced after completing Chem 1AL. A solid line (–) represents a significant change and a dashed line (• • •) represents a non-significant change from pretest to posttest.

Similar results were found for student performance on the green chemistry exam question. There was no significant difference in the mean scores on the green chemistry exam question between the low and high prior green chemistry knowledge groups ($p = 0.4078$, $t = 0.923$, d.f. = 260). The difference in means was estimated as 0.41with a 95% confidence interval from -0.06 to 0.87. Together, these results show that regardless of prior green chemistry knowledge, students reach similar levels of green chemistry understanding after completing Chem 1AL.

Conclusions

The new general chemistry laboratory curriculum was developed to introduce students to the concepts and skills of green chemistry while maintaining traditional chemistry content. The green chemistry context of each experiment, introductory materials, and laboratory lecture material were designed to familiarize students with green chemistry concepts and practices, while the pre-lab and post-lab questions provided opportunities students to integrate and apply that knowledge to relevant chemistry problems. The integration of green chemistry into the curriculum provided students with an authentic context within which to learn chemistry. Green chemistry expands the boundaries of traditional 'reductionist' chemistry (Constable, 2017); it is not a separate field of chemistry, but rather a philosophy to chemistry that prioritizes safety of humans and the environment by considering complex green chemistry metrics and societal factors (Eissen, 2012; Tucker, 2010). The systems-thinking approach of green chemistry allowed students to see chemistry as an interconnected system that has uses and impacts outside of their classroom laboratory (Constable, 2017).

The new general chemistry laboratory curriculum succeeded in providing an environment in which students learned green chemistry concepts and realized that chemistry has connections to their future courses and professions. Recognition of the value and relevance of green chemistry content is predicted to be important for long term sustained interest and learning (Savery & Duffy, 1995). A quarter to a third of the students identified green chemistry as concepts they would take to another class, while three quarters identified green chemistry as a connection that was meaningful to them. This was achieved without significantly reducing the traditional learning goals for general chemistry laboratory. However, further longitudinal studies are needed to determine if green chemistry remains relevant to students as they progress through their education.

In addition to students' self-reported gains, it was also important to measure the degree to which students learned green chemistry from the necessarily limited introduction of green chemistry principles and practices into the course. The goal was to introduce green chemistry concepts and skills so that students could begin approaching chemical issues from a systems-thinking approach. Students entered the course familiar with certain general terms related to sustainable practices, such as eco-friendliness or efficiency. Importantly, most students were aware of the weakness of these answers and identified them as guesses. After completing the course, most students offered correct or partially correct specific definitions of green chemistry and a smaller percentage included practices and philosophy related to green chemistry. In contrast to students' starting green chemistry definitions, over 75% of student's final definitions of green chemistry mentioned at least one *specific* green chemistry component.

Additionally, students also demonstrated their ability to apply green chemistry principles to a novel scenario through a green chemistry exam question. This high stake assessment ensured that students put their best effort into preparing for and answering this question. More than three quarters of the students included a general, correct statement, more than half included a specific correct statement, and more than a quarter of the students included two or more specific correct statements. In general, students moved towards a more holistic systems thinking approach in their final responses. After completing the course, they shifted from focusing only on isolated chemical reactions to sourcing and end of life consideration as shown in their definitions of green chemistry (e.g., waste, hazards, total reaction, material life cycle) and their responses to the green chemistry scenario exam question (end of life/waste).

Importantly, students with little prior knowledge of green chemistry ended the course with a similar level of understanding as those students who started the course with a better understanding of green chemistry. In a general chemistry non-majors laboratory course student usually enter the course from high school with highly variable backgrounds. Not surprisingly, some students entered the course with a stronger green chemistry background, while most others had little prior exposure to green chemistry. It is important that all students are served by the newly developed curriculum. Thus, an important finding is that the gap in students' understanding and ability to apply green chemistry principles was closed by the end of the semester. Students who entered the course with little knowledge of green chemistry ended the course with the same level of understanding of green chemistry as those students who had significant prior green chemistry knowledge.

After completing the redesigned laboratory course students better understood green chemistry concepts and applications and highly valued the introduction to green chemistry. This is especially impactful as over 2000 STEM majors complete the general chemistry laboratory at Berkeley each year. The hope is that students can use the principles and practices they learned during their time in general chemistry to ultimately make a meaningful impact on both large and small scale environmental and energy issues and be more informed citizens. Green chemistry presented in the context of real-world problems will hopefully deepen student engagement, participation, and connection of the material to their future studies. While students cannot solve environmental or energy crises during their time in general chemistry, they can be introduced to principles and practices that they can ultimately use to make a meaningful impact on these global problems.

Next Steps

Overall, the new general chemistry laboratory course succeeded in providing an environment in which students learned green chemistry concepts and realized the connection of green chemistry to chemistry and their future course and profession. This was achieved without significantly reducing the traditional learning goals for general chemistry laboratory. However, this assessment also showed that there are still additional opportunities to add depth to student knowledge and increase the impact of the curriculum. Students often discussed only select green chemistry principles (for example, reducing hazards, material lifecycle, waste prevention), suggesting the need for more exposure to green chemistry in a diverse range of situations and more opportunities for comparative analysis to support a more nuanced understanding (Andraos & Dicks, 2012; Sandoval, 2005). Students also had trouble reconciling the tradeoffs associated with green chemistry, which suggested that students need more exposure to more real green chemistry scenarios and metrics and the idea that there is no single "right" answer to a green chemistry problems (Andraos & Dicks, 2012; Khuong, 2017; Machado, 2015).

Additionally, even though it was an intentional design choice to introduce a limited amount of green chemistry content into the redesigned general chemistry laboratory curriculum, an analysis of the green chemistry content of the curriculum did show room for improvement. The original goal of this curricular redesign was to integrate "sustainability and green chemistry concepts into every aspect of the curriculum." This was accomplished by situating each experiment in a green context and including introductory material explaining the green chemistry principles relevant to each experiment, with the goal of highlight the inherent interconnectedness of chemistry to other systems and disciplines (such as toxicology).

However, green chemistry was only one of the learning goals for the course; the chemistry content and technique outcomes for this course remained in place to prepare students for their future coursework and research positions. Additionally, many different faculty, graduate students, and undergraduate students were involved in the design of the curriculum. Therefore, once the written curriculum was finalized, it was important to critically examine the final written laboratory curriculum to ensure this curriculum was in alignment with the original design goals.

For each experiment used during the Fall 2016 semester, every prelab question, procedural prompt, and postlab question was coded for instances when students demonstrated knowledge of green chemistry content or methods of analysis. This analysis showed that 11% of the prelab and postlab questions in the written curriculum focused on green chemistry (Table 2.5). Seven of these questions addressed toxicity and nine addressed waste disposal. However, only one question explicitly mentioned green chemistry (see Appendix III for a detailed description of each curriculum question). Overall, students complete 175 questions during the semester with only 20 of these questions covering green chemistry content or practices.

This analysis highlighted the mismatch between the original curriculum design goals and the implemented laboratory curriculum. While many of the Chem 1AL laboratory experiments used greener reagents or had green chemistry contexts (e.g., biofuels) there wasn't the corresponding explicit introduction of green chemistry concepts and metrics in the written laboratory curriculum. This finding, coupled with the gaps in student green chemistry outcomes, prompted a redesign of the green chemistry learning outcomes for Chem 1AL and the creation of new green chemistry curriculum for the Fall 2018 and future semesters.

Table 2.5. Percentage of questions that address green chemistry in each Chem 1AL experiment during the Fall 2016 semester. The Fall 2016 curriculum was representative of the curriculum used for the past five years.

Experiment	Green chemistry questions (%)	Total # of questions	Total # of green chemistry questions
Biofuels 1	58%	12	7
Biofuels 3	20%	10	2
Developing a Model Airbag	14%	7	1
Polymers: Crosslinking and Toy Design 1	13%	16	2
Acids in the Environment 1	11%	18	2
Acids in the Environment 3	11%	18	2
Polymers: Crosslinking and Toy Design 2	8%	13	1
Biofuels 2	5%	20	1
Acids in the Environment 2	5%	20	1
Extraction of Curcumin and Spectroscopic Analysis	4%	27	1
How the Nose Knows	0%	14	0
Total # of Questions		**175**	**20**

Chapter 3: Iterative Development of an Integrated General Chemistry Green Curriculum

Introduction

For the past 25 years, there has been both a growing interest in using green chemistry to solve complex sustainability issues and a parallel concerted effort to develop educational materials focused on and around green chemistry and sustainability principles (Andraos & Dicks, 2012; Haack & Hutchison, 2016). In response to a growing interest and need, the undergraduate general chemistry laboratory curriculum at Berkeley was iteratively redesigned to focus on sustainability and green chemistry principles starting in 2008. Over 30 new experiments were developed using *The Twelve Principles of Green Chemistry* (Anastas & Warner, 1998) as a guiding framework for experiment context and content. These experiments aimed to introduce students to green chemistry principles within the context of authentic green chemistry contexts such as biodegradable polymers, extraction and analysis of plant-based antibiotics, ecotoxicity, fuel cells, solar cells, and biodiesel synthesis.

Introducing green chemistry into general chemistry was a deliberate choice; green chemistry curricula are usually designed for elective or organic laboratory courses (Andraos & Dicks, 2012) with much less attention paid to introductory general chemistry courses. Although a number of laboratory experiments have been created for general chemistry courses (e.g., Buckley et al., 2013; Purcell et al., 2016), far fewer "green" general chemistry lecture (Prescott, 2013) or laboratory courses have been developed. General chemistry serves the largest and broadest range of future STEM professionals; at UC Berkeley over 50% percent of the total STEM majors on campus complete general chemistry. Targeting general chemistry as a site for green chemistry education, rather than more advanced courses like organic or inorganic chemistry, means that the greatest number of students will have the opportunity to learn about a vitally important topic.

This first phase (2013-2017) of introducing green chemistry into the UC Berkeley general chemistry laboratory showed many positive student outcomes (as discussed in detail in Chapter 2 and Armstrong et al. (2019)) as well as several areas for curricular improvement. Greening the UC Berkeley general chemistry laboratories was a substantial undertaking that spanned nearly a decade with many different faculty, graduate students, and undergraduate students involved in the design, testing, and refinement of a written lab manual and experimental procedures. While all the experimental procedures used greener reagents (e.g., safer/no solvents, innocuous reactants/products) and/or green chemistry contexts (e.g., biofuels, acids in the environment) the laboratory manual only implicitly touched on green chemistry. Out of over 180 total questions, only 11% of the prelab and postlab questions in the written curriculum focused on green chemistry and only a single question explicitly said the words "green chemistry."

The original goal of introducing green chemistry into the Berkeley general chemistry laboratory, as stated in the original grant application to the California Environmental Protection Agency, was to "integrating sustainability and green chemistry concepts into every aspect of the curriculum" and yet the implemented laboratory curriculum only briefly introduced green chemistry concepts and metrics and had few opportunities for students to build, explore, and demonstrate their green chemistry understanding. Thus, the next phase of this project aimed to achieve the original goal of this curriculum more fully by redesigning the laboratory manual to explicitly integrate green chemistry into the prelab questions, in-lab observation prompts, and postlab questions.

Iterative Curricular Redesign Process

How can a general chemistry laboratory curriculum be developed that 1) utilizes green chemistry as a relevant context for learning and doing chemistry and 2) connects and integrates green chemistry and chemistry concepts and practices into a coherent laboratory curriculum? These were the guiding questions for the redesign of the green chemistry general chemistry laboratory curriculum. Starting from the original (2013-2017) green chemistry curriculum, the green chemistry portion of the general chemistry laboratory curriculum for non-chemistry majors (Chem 1AL) was reimagined (Figure 3.1). Through discussion and collaboration with a variety of stakeholders at Berkeley and from the larger green chemistry community, three goals were chosen to help structure the green curriculum redesign:

1. Expose students to a wider range of green chemistry principles and provide them with more opportunities to grapple with the tradeoffs (or comparative analyses) inherent to green chemistry.
2. Ensure that new green content introduces students to normative green chemistry ideas while also valuing their prior knowledge and giving them opportunities to evaluate the new ideas they encounter.
3. Use green chemistry contexts and practices to show students the value of (green) chemistry both inside and outside of the classroom.

These outcomes along with the KI framework (Linn & Eylon, 2011) were used to guide the development of new green chemistry laboratory curriculum: **General Chemistry Green Curriculum (GC²)**.

GC² was built on the foundation of the original (2013-2017) green chemistry laboratory curriculum whenever possible and utilized the same green chemistry laboratory procedures. GC² was piloted during the Fall 2018 semester (GC² v1a) along with a new mixed method study design that included a green chemistry focused student and graduate student instructor (GSI) survey, student interview protocol, and in-class assessment items (to be discussed in Chapters 4 and 5). The new green chemistry curriculum was iteratively refined based on student and instructor feedback for the Spring 2019 semester (GC² v1b) and later more extensively revised for the Fall 2019 semester (GC² v2).

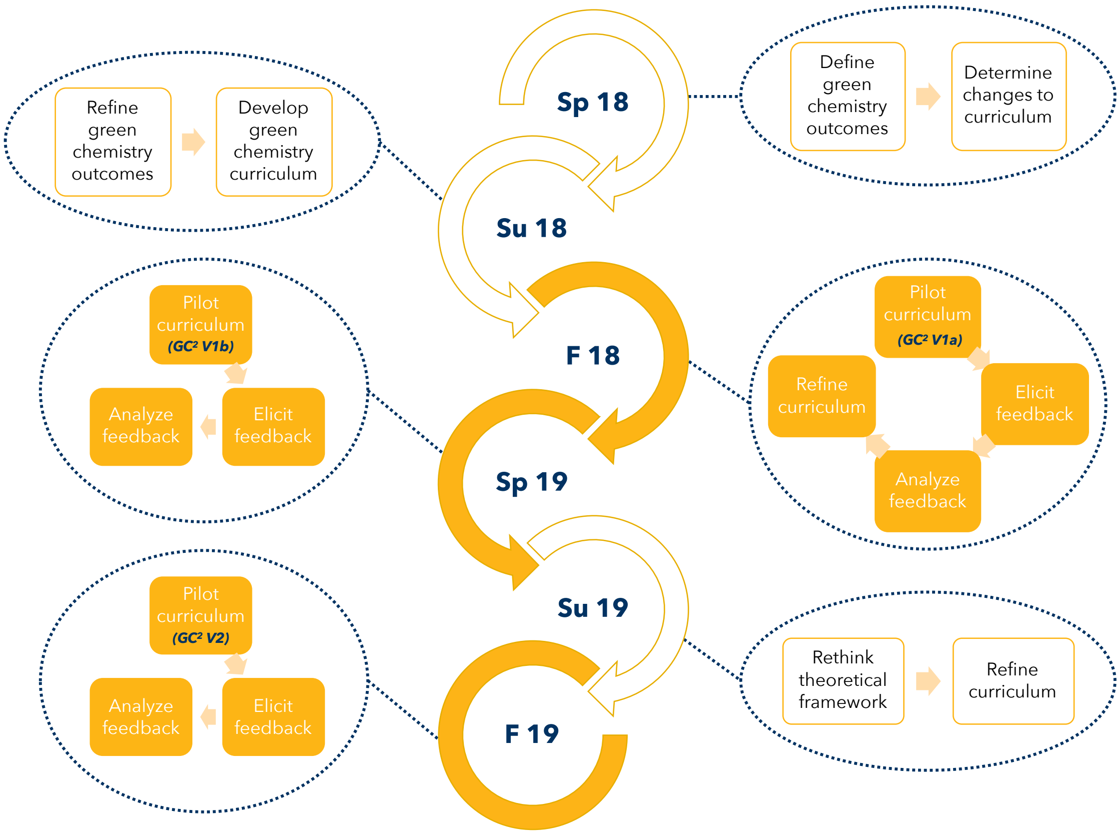


Figure 3.1. Overview of development and refinement of the General Chemistry Green Curriculum (GC²) for Chem 1AL. All redesigned curricula were based on the original (2013-2017) Chem 1AL green chemistry curriculum. The first version of the General Chemistry Green Curriculum (GC²) was piloted during the Fall 2018 semester (GC² v1a), updated for the Spring 2019 semester (GC² v1b), and finalized for the Fall 2019 semester (GC² v2).

Theoretical framework

The Issue of Context and Relevance

Chemistry instructors often struggle with aligning their curriculum and pedagogy with the needs of their students. This is especially true for students who, in the future, will not be chemistry researchers but will need a strong scientific background to become scientifically literate citizens (Hofstein, Eilks, & Bybee, 2011) and pursue science, technology, engineering, or math (STEM) careers. Chemistry curricula often suffers from an overload of chemistry content, a lack of coherence and relevance, and an inadequate emphasis for future learning (Gilbert, 2006). This emphasis leads students to view science as a series of isolated facts with little relevance to their daily lives. As a result, students aren't able to apply this knowledge outside of the classroom and participate in socioscientific discussions (Gilbert, 2006; Hofstein et al., 2011). Additionally, this lack of perceived relevance decreases student motivation and interest in chemistry (Hofstein et al., 2011).

Some chemistry curricula have attempted to address this deficit in coherence and relevance by contextualizing chemistry (Bennett & Lubben, 2006; Schwartz, 2006), but there are still many different ideas of what constitutes a *good* context for chemistry learning. Duranti and Goodwin (1992) define context as "a focal event embedded in its cultural setting" while others are more specific that contexts should introduce "authentic societal debates of a controversial character to increase the relevance of science" (Sjöström & Eilks, 2017). Gilbert (2006) states that in order for contexts to be used effectively they need to be chosen such that they cover the most important chemistry topics and "provide the basis for the development of coherent 'mental maps' of the relationship between these concepts by students."

Regardless of the specific context chosen it should be a *relevant* context. However, what is considered relevant can vary widely between times, places, personal backgrounds, ages, prior knowledge, etc. For example, Van Aalsvoort (2004) provides four categories for relevance: 1) personal relevance—connecting science to students' lives, 2) professional relevance—connecting science to possible professions that students can pursue in the future, 3) social relevance—connecting science to human and social issues, and 4) personal/social relevance—connecting science to being responsible citizens. Similarly, Stuckey et al.'s (2013) three dimensions of relevance include 1) the individual dimension—matching students' interests and teaching useful skills for their daily live and futures, 2) the societal dimension—helping students develop skills to be responsible participatory citizens and contribute to sustainable development, and the 3) vocational dimension—preparing students for future professions and careers or further academic or vocational training.

Determining which dimensions or categories are most relevant depends on both the course content and student population, which is especially challenging for large classes with diverse student interests and needs like UC Berkeley's general chemistry laboratory curriculum for non-chemistry majors (Chem 1AL). Chem 1AL serves thousands of non-chemistry major students each year who will go on to pursue many different degrees (e.g., biology versus engineering) and careers (e.g., dentists, pharmacists, doctors, engineers, biologists, researchers). Additionally, it is important to remember that what is relevant to an instructor or curriculum developer may not be (as) relevant to students (Hofstein et al., 2011).

Green Chemistry as a Relevant Context

Green chemistry, in addition to being vital content and practice for chemistry in the 21st century, also serves as a viable *relevant context* for introductory chemistry education. While chemistry majors may be intrinsically motivated to learn chemistry concepts and practices, non-chemistry majors don't necessarily share this same drive. Teaching chemistry within the context of green chemistry helps non-chemistry majors see how chemistry is relevant to their personal, professional, and/or societal interests (Bodner, 2016). Green chemistry expands the boundaries of traditional chemistry by asking students, instructors, and researchers to consider how the entire lifecycle of their work impacts human health and the environment. It requires looking at chemical reactions and processes as interconnected systems with far reaching impacts and affordances (Anastas, 2011; Anastas & Allen, 2016; Anastas & Beach, 2009; Constable, 2017). It allows students to work towards solving some of the grand challenges of sustainability through the use of chemistry (Haack & Hutchison, 2016) and often aligns with their personal ethics regarding stewardship of the environment (Bodner, 2016; Haack & Hutchison, 2016).

Ultimately, using green chemistry as a relevant context for introductory chemistry serves two goals: 1) to increase student motivation and interest in chemistry *and* 2) to increase student understanding of green chemistry. Green chemistry introduces students to ideas, skills, and practices that support them in engaging critically with socioscientific issues in their current lives and hopefully in their futures as responsible citizens, researchers, and professionals.

Curriculum Framework: Knowledge Integration

Knowledge integration (KI) was used as the theoretical framework for redesigning the original (2013-2017) green chemistry curriculum and assessing the resulting student outcomes. When used as a guide for curriculum development, this framework helps ensure that the curriculum elicits students' prior knowledge in order to build on their ideas, promotes discovering and distinguishing between prior knowledge and/or new ideas, and supports reflection on newly constructed knowledge (Linn & Eylon, 2006). Students who are taught using a curriculum built on a KI framework learn by building on their knowledge and exploring new content in the context of their initial ideas. Knowledge integration encourages students to make valid and coherent connections between scientific concepts, using evidence and reasoning (Linn & Eylon, 2011).

Knowledge integration is an ideal framework for curriculum development as it necessitates that curriculum designers value and leverage the prior knowledge and experiences that student bring to the course. One of the challenges with using green chemistry as a relevant context is that not all contexts are equally relevant and interesting to students due to their unique backgrounds and future aspirations. Knowledge integration allows for (and indeed expects) that students come into the classroom with different backgrounds and that those backgrounds are powerful building blocks for learning.

Additionally, a curriculum built using knowledge integration provides opportunities for students to add, distinguish, and reflect on their prior ideas and new knowledge. This prioritization of connections between new and old ideas can help students find relevance between their prior interests and knowledge and the context and content of their classroom. This emphasis also allows students to iteratively form connections within and between chemistry concepts and green chemistry concepts, practices, and applications within a curriculum.

Implementation Framework: Utilization-Focused Evaluation

The design of GC^2 was guided by the KI framework while the evaluation of the implementation of GC^2 was derived from a utilization-focused evaluation (UFE) framework (Patton, 2008). UFE centers on ensuring that the evaluation results/data are useful for the intended users, which means it is critical to identify and engage users early and often. Patton argues that users are more likely to use evaluation findings if they understand the evaluation process, which is built through active involvement. Thus, “by actively involving primary intended users, the evaluator is preparing the groundwork for use” (Patton, 2008).

There were many intended users of the redesign of the general chemistry general chemistry laboratory curriculum, but the primary intended users were the course instructor, graduate student instructors (GSIs), and enrolled students. Thus, the redesign the green chemistry curriculum was conceptualized as a multi-semester iterative process that would necessarily involve participation and feedback from instructor, graduate student instructors (GSIs), and students in the course each semester. Ultimately, some of these participants would go on to implement the next phase of the green chemistry curriculum the following semester. The involvement of a wide range of stakeholders helped to both better understand the implementation process of the curriculum and ensure that the evaluation findings were utilized by the instructor for each subsequent semester.

Guiding Implementation and Outcome Evaluation Questions

Derived from utilization-focused evaluation, two guiding questions were used to focus the iterative evaluation process each semester:

Implementation phase (Fall 2018 and Spring 2019 semesters)

- In what ways does the General Chemistry Green Curriculum (GC^2) need to be modified to better meet the needs of the students and instructors?

Outcome phase (Fall 2019 semester)

- To what extent are the GC^2 goals clearly defined and aligned between developers and instructors/students?
    - Do students believe they have learned green chemistry after completing GC^2?
    - Do students see value in green chemistry outside of the course?

General Methods

Iterative Curriculum Redesign Overview

The General Chemistry Green Curriculum (GC^2) was iteratively developed and refined over the Spring 2018 – Fall 2019 semesters. The first version of GC^2 was piloted during the Fall 2018 semester (GC^2 v1a), updated for the Spring 2019 semester (GC^2 v1b), and finalized for the Fall 2019 semester (GC^2 v2). Approximately 50 new prelab and postlab green chemistry questions were created using the KI framework (Linn & Eylon, 2006), which were later refined to approximately 40 questions over 10 experiments. New green chemistry content was also created for the lab manual introduction and for the introduction to each experiment. GSI notes and solutions were provided for all new content and questions.

During the Fall 2018 semester (GC^2 v1a) student and GSI surveys, individual student interviews, and weekly feedback from the course instructor and GSIs were used to refine the questions/content for the subsequent Spring semester. This led to the creation GC^2 v1b for the Spring 2019, which had more introductory material covering green chemistry principle and metrics, several new in-lab observation prompts focused on green chemistry, and the clarification of several postlab question sets.

During the Spring 2019 semester, student and instructor input was once again used to refine GC^2, which led to the design of new green chemistry introductory content, the replacement of several postlab green chemistry question sets with more integrated content, the restructuring of the layout of the entire postlab report sheet, the development of dozens more green chemistry in-lab observation prompts. The KI framework was once again used to design these new questions and prompts with the goal of helping students link and reflect on the chemistry and green chemistry concepts they learned or experience during their in-lab experience. This work culminated in the final version of the GC^2 used during Fall 2019 (GC^2 v2).

Course Context

General Chemistry at UC Berkeley

This iterative curriculum redesign took place within a general chemistry laboratory course for non-chemistry majors (Chem 1AL) at UC Berkeley between the Fall 2018 – Fall 2019 semesters. Chem 1A/L is divided into a lecture (Chem 1A) and laboratory (Chem 1AL) course with separate instructors. Most students take the two courses simultaneously, but students can complete the courses sequentially. Chem 1AL includes a 1-hour laboratory lecture (taught be the course instructor) and a 3-hour laboratory section (taught by a GSI) each week. Chem 1AL has approximately 1200 students in Fall and 800 in Spring.

Original (2013-2017) green chemistry curriculum

The redesigned General Chemistry Green Curriculum (GC^2) was built upon a base set of general chemistry experiments (Table 3.1) developed between 2008-2013 and the original green chemistry laboratory manual (2013-2017) for Chem 1AL. Sustainability and the *12 Principles of Green Chemistry* (Anastas & Warner, 1998) were used both to 'green' the Chem 1AL laboratory experiments (e.g., use of safer reagents, reducing waste) and as motivational contexts for the experiments.

Table 3.1. The experimental module, chemistry principles, and green chemistry principles for the base set of experiments used in the general chemistry laboratory course at UC Berkeley (Chem 1AL)

Module (# weeks)	General Chemistry Principles	Green Chemistry Principles
How the nose knows (1)	Functional groups, physical properties, formal charges, bond-line notation, VSEPR	Designing safer chemicals, renewable feedstocks
Polymers: Properties and Applications (2)	Functional groups, density, solubility, structure-function, dissolution, hydrolysis	Waste prevention, designing safer chemicals, design for degradation
Polymers: Cross-Linking, Toy Design (2)	Cross-linking reactions, intermolecular interactions, bonding, mass ratios in mixtures	Safer chemistry, safer solvents, renewable feedstocks, atom economical
Biofuels Synthesis and Combustion (3)	Transesterification, calorimetry, solubility, extraction, C_{cal} and H_{comb}	Designing safer chemicals, renewable feedstocks, catalysis, safer solvent, atom economical, safer chemistry, energy efficiency
Extraction of curcumin and spectroscopic analysis (1)	Transmission, absorbance, extraction, calibration curves, linearity of data	Safer solvent, energy efficiency, waste prevention
Equilibrium (1)	Solubility, acid/base equilibria, gases, Le Châtelier's Principle, pH measurements	Renewable feedstocks, safe solvents and auxiliaries, designed for degradation
Acids in the Environment (2-3)	Solubility equilibria, acid/base titrations, equilibrium, Le Châtelier's Principle, buffers	Real-time analysis for pollution prevention, less hazardous chemical syntheses, waste prevention

Data Collection and Analysis

Participants

Participants were mainly general chemistry students in Chem 1AL during the Fall 2018, Spring 2019, and Fall 2019 semesters. Consent rates were high with more than 90% of students consenting to be part of the study (Table 3.2). Additionally, during the Fall 2018 semester 21 Chem 1AL GSIs (out of a total of 29) participated in the curriculum implementation study. The instructor for the course (consistent across all three semesters) also provided feedback on the current implementations of the curriculum and collaborated on the initial design (GC^2 v1a) and subsequent refinement (GC^2 v2) of the green chemistry curriculum for the course. All research was approved by the university's Institutional Review Board (Protocol ID 2012-09-4666).

Table 3.2. Number of general chemistry laboratory students involved in study during Fall 2018 – Fall 2019 semesters

Semester	Number of students in course	Number of students in study
Fall 2018	1086	1010
Spring 2019	598	582
Fall 2019	1031	1040[a]

[a] The total number of students in the study acceded the total number of students in the course due to attrition during the semester. The total number of enrolled students is calculated at the end of the semester while the number of students in the study comes from both the pretest and posttest surveys.

Description of Evaluation Tools

Online student survey. Online pretest and posttest survey were used to assess student self-reported green chemistry understanding. These surveys covered a range of topics including green chemistry (13 fixed response items) and chemistry knowledge (20 fixed response items), green chemistry and chemistry attitudes (12 fixed response items), green behaviors (10 fixed response items), demographics and prior green chemistry experience (11 fixed response items), and course feedback (18 fixed and 6 free response items). The attitude and behavior sections were inspired and adapted from the Environmental Attitudes Inventory (Milfont & Duckitt, 2010) and the New Environmental Paradigm Scale (Dunlap, 2008). Course feedback questions were only included on the post survey and demographic questions were only included on the pre survey. A mixture of fixed response (Likert, Guttman, and multiple choice) and free response questions were used (see Appendix IV for an example of the surveys used during the Fall 2019 semester).

Student interviews. A semi-structured interview protocol was developed for current Chem 1AL students during the Fall 2018 semester. This protocol (Appendix IV) asked the student to reflect on their overall impressions of the course, the amount of time they spent on coursework, their impression of the green chemistry curriculum, and the usefulness of the resources provided to support the curriculum

GSI written questionnaire. A short written GSI questionnaire (Appendix IV) that covered topics such the length of the lab section and prelab lectures, the most common interactions GSIs have with their students in lab, GSI usage of green chemistry both during and after their lab sections (i.e., office hours), and GSI prior experience with green chemistry was administered during the Fall 2018 semester.

Course instructor debrief. An in-person debrief was held with the course instructor near the end of each semester along with other informal feedback opportunities throughout the semester. This debrief unstructured (i.e., no interview protocol was used) though each course experiment was sequentially reviewed by the instructor and lead researcher of this project.

Data Collection

Online student survey. The online student survey was administered using Qualtrics. The link to the survey was distributed through a personalized bCourses announcement. The course instructor was also asked to announce the survey during their lectures if possible. Two reminder announcements were posted for each survey – one several days before the due date and one the day the survey was due. The respondents had between 7 – 10 days to complete the survey. The pretest survey was administered during the first two weeks of the semester and the posttest survey was administered during the last two weeks of the semester. All respondents received course bonus points for completing the online survey. If students did not want to complete the survey but still would like to receive the course bonus points, they could instead write a one-page essay on a recent green chemistry innovation.

Student interviews. Interviews were conducted with 11 Chem 1AL students approximately two-thirds of the way through the Fall 2018 semester. These students had a diverse range of prior chemistry/lab experience (seven students had taken AP chemistry, two had taken IB, one was a community college transfer, and one had only taken high school chemistry) though all had above average scores in Chem 1AL at the time of the interviews. All interviews were 30 minutes. Interviewees were assured that their course instructor and GSI would not be privy to any information divulged in the interview. Students were not offered any incentive for completing this interview.

GSI written survey. A written questionnaire was administered to the Chem 1AL GSIs during their last GSI meeting of the Fall 2018 semester. GSIs were not required nor incentivized to complete this survey but it was communicated that their feedback would be used to improve the course for the next semester. The majority of the GSIs (26 out of 30) completed the questionnaire. GSIs were not offered any incentive for completing this questionnaire.

Course instructor debrief. An in-person debrief was held with the course instructor near the end of each semester along with other informal feedback opportunities throughout the semester. This debrief was unstructured but typically lasted at least one hour. The course instructor shared their any notes from each GSI meeting and student office hours that pertained to the new green chemistry content and question in the laboratory manual. The instructor also shared their own impressions of the new content as well as their perceptions of GSI and student response to the curriculum.

Data Analysis

Online student survey. All fixed response survey items were assigned numerical values for analysis (e.g., *strongly disagree* was assigned a value of 0, *somewhat disagree* a value of 1, *neither agree nor disagree* a value of 2, *somewhat agree* a value of 3, and *strongly agree* a value of 4). The means and standard deviations for the pretest and posttest scores were calculated and Wilcoxon signed rank sum tests were used to compare changes in pretest and posttest scores. For all analyses, results were considered significant at the 95% level for all items. Respondents with missing values and those who did not consent to participate in the research study were dropped from the dataset. All analysis was completed using StataSE 14.2.

Student interviews. Hand-written notes were taken for every student interview conducted during Fall 2018. Common responses and themes were noted from these notes and used to inform quantitative survey results and helped inform curricular changes for the next semester.

GSI written survey. All the fixed response questions on the GSI questionnaire were quantified and the free response items were categorized. The 23 unique responses were categorized based on topic (e.g., the frequency of questions or discussions, and what prompts discussions) and sentiment (e.g., positive, negative).

Course instructor debriefs. Notes were taken for each instructor debrief conducted during Fall 2018 – Fall 2019. These notes, along with the instructor's own running notes from the semester (shared with the lead researcher on this project), were compared to student and GSI responses and together were used to inform curricular changes for the next semester.

Assessment of Initial Curriculum Implementation

Curricular Design for GC^2 v1a in Chem 1AL

The implementation and assessment of the original (2013-2017) green chemistry curriculum during the Fall 2016 semester showed room for growth within the curriculum. The original goal of greening the general chemistry laboratory courses was to “integrate sustainability and green chemistry concepts into every aspect of the curriculum.” While the principles of green chemistry had certainly been used to develop each new general chemistry experiment these design choices were not made explicit to the students who completed the course.

In the original curriculum, explicit green chemistry content had been added in ways that least disrupted the original structure and goals of a traditional laboratory course (i.e., traditional chemistry content was privileged over the introduction of new green chemistry content), which is documented phenomena in green chemistry education (Bodner, 2016; Burmeister et al., 2012; Haack & Hutchison, 2016). While this approach has the benefit of directly contributing to sustainability (by, for example, reducing chemical waste) it doesn’t explicitly teach students skills to contribute towards sustainable development (Burmeister et al., 2012).

Thus, the redesign of the original green chemistry laboratory curriculum focused on explicitly teaching students the basic chemical principles behind sustainable and green chemistry, which would also highlight the chemical principles inherent to every day processes making chemistry more meaningful to students (Burmeister et al., 2012). This redesign, termed the General Chemistry Green Curriculum or GC^2, built off the original green experiments leading to a curriculum that not only contributed to sustainability through the experiment design but also endowed students with knowledge and practices to eventually contribute themselves.

Learning Goals for GC^2 v1a

The first step in the curriculum redesign process was to critically review the green chemistry learning outcomes for the general chemistry laboratory to ensure that they met the needs of the course and learners. The original (2013-2017) green chemistry learning outcomes for Chem 1AL spanned a range of green chemistry content and practices:

1. Identify, evaluate, and minimize the use of hazardous chemicals.
2. Understand the origins and the fate of chemicals in the environment.
3. Design safer and more efficient chemical reactions and processes.

4. Gather data and effectively use both qualitative and quantitative metrics.
5. Communicate scientific data and concepts to both experts and the public.

These learning outcomes covered both specific green chemistry practices (learning goals 1-3) to more general chemistry practices (learning goals 4-5). The first three learning outcomes did cover the majority of the *12 Principles of Green Chemistry* (Anastas & Warner, 1998) but were overly ambitious about what one could reasonably accomplished with a one-unit introductory laboratory course. For example, students would not be able to design safer reactions (outcome 3) until they had taken more advanced courses such as organic chemistry and, while they might understand that one should minimize the use of hazardous chemicals (outcome 1), they did not have the power to change the reagents used within Chem 1AL.

Thus, new learning outcomes were developed by soliciting feedback from a wide variety of stakeholders (chemistry education professors, post-docs, graduate students, and undergraduate students) on what they believed were important and reasonable green chemistry outcomes for a general chemistry course. Additionally, the implicit green chemistry content of each experiment was used to inform which principles of green chemistry could be easily introduce throughout the laboratory course. Together this led to a first draft of new green chemistry outcomes for Chem 1AL. These were then shared with the course instructor who added two additional main outcomes: lifecycle and hazard analysis.

The outcomes were further informed from the ACS Green Chemistry Institute Design Principles for Sustainable Green Chemistry and Engineering (ACS Green Chemistry Institute, 2015) and the rise of systems thinking within green chemistry education (Aubrecht et al., 2019; Constable et al., 2019; Dicks et al., 2019; Hutchison, 2019; Mahaffy et al., 2019; Orgill et al., 2019). Generally, systems thinking is defined as "the ability to understand and interpret complex systems" (Evagorou et al., 2009) which has made it popular among green chemists and educators as a way of explaining and understanding the numerous complex and interrelated factors involved in both practicing green(er) chemistry and educating learners (Mammino, 2019). Thus, the final updated green chemistry outcomes focused on three main categories:

1. Maximizing resource efficiency and using life cycle thinking (including sourcing, reaction, products, and waste)
2. Eliminating or minimizing hazards and pollution
3. Understanding that (green) chemistry is a complex system

Each outcome had several sub-outcomes that ranged from simple awareness to identification and finally evaluation (Table 3.3). These outcomes were specifically designed to match the constraints of a first-semester general chemistry laboratory course. For example, one of the original learning goals for the course was for students to "identify, evaluate, and minimize the use of hazardous chemicals." This is a worthwhile goal aligned with many green chemistry principles, but it was more appropriate for an upper-division class or as a terminal degree outcome. The framework of this outcome was kept but clarified that students should first understand what it means for chemicals/experiments/reactions to be less hazardous, then identify and/or compare hazards, and finally suggest ways to make something less hazardous. These outcomes were specifically designed to allow them to be built upon as the laboratory course progressed.

New Curriculum Design for GC^2 v1a

The updated green chemistry learning outcomes were used to create new green chemistry prelab and postlab question and introductory material (Table 3.4). This new content not only covered a range of green chemistry principles and introduced students to normative chemistry and green chemistry ideas but also gave students meaningful contexts to learn chemistry and allowed them to grapple with interesting green chemistry data and issues.

The updated green chemistry learning outcomes were mapped to each relevant experiment in Chem 1AL and used to determine what material (prelab questions, postlab questions, and/or introductory material to the written experimental procedure) needed to be added or revised to address these outcomes appropriately. Then, a specific green chemistry context that was most relevant for that learning outcome was chosen. Often, the context was the experiment itself (e.g., biofuels, acids in the environment) but related topics were also identified to help illustrate green chemistry principles or connect the experimental context to a relevant real-world issue. For example, students design a polymer-based children's toy in the third and fourth week of the laboratory course. This provided an opportunity to also introduce them to the wide range of polymer applications including plastics and plastic waste.

Table 3.3. Redesigned green chemistry learning outcomes for Chem 1AL

Learning outcomes *(applicable green chemistry principle)*	**Students should be able to…**
Maximize resource efficiency and use life cycle thinking	1. [Awareness] Understand that chemistry has far reaching effects (humans + environment) 2. [Awareness] Understand that material and energy inputs should be renewable and minimize the depletion of natural resources 3. [Awareness] Understand that chemistry research should go beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability
Sourcing (renewable resources)	1. [Awareness] Understand that reagents have economic, environmental, human health impacts 2. [Awareness] Understand that a raw material or feedstock should be renewable rather than depleting whenever technically and economically practical 3. [Identify/compare/evaluation] Identify the environmental impact, human health and safety factors, and/or economic impact of obtaining a given reagent
Reaction (atom economy, catalysis, design for energy efficiency, alternatives, derivatives)	1. [Awareness] Understand what it means for a reaction to be 'green' or 'greener' 2. [Identify/compare] Identify factors that make a reaction 'green' and measure greenness of a reaction 3. [Evaluate] Suggest improvements to make a specific reaction greener
Product and Waste (atom economy, prevention, design for degradation)	1. [Awareness] Understand that waste should be minimized/prevented (not cleaned up or treated) 2. [Awareness] Understand what happens to waste and how to monitor waste 3. [Identify/compare] Identify what waste is produced from each experiment 4. [Evaluate] Suggest ways to minimize or prevent the generation of waste
Eliminate and minimize hazards and pollution (inherently safer chemistry, less hazardous synthesis, designing safer chemicals, safer solvents, persistence, prevention)	1. [Awareness] Understand what it means for chemicals/experiments/reactions to be less hazardous 2. [Identify/compare] Identify and/or compare hazards (environmental and human health and safety) 3. [Evaluate] Suggest ways to make something less hazardous
Systems-thinking	1. [Awareness] Understand the purpose of green chemistry 2. [Awareness] Understand the connections between different (green) chemistry principles/goals 3. [Awareness] Understand boundaries of chemistry/green chemistry 4. [Awareness] Understand who gives feedback and how feedback influences chemistry

Table 3.4. Overview of new green chemistry content for Chem 1AL (GC^2 v1a and v1b)

Experiment	# of GC Prelab Qs	# of GC Postlab Qs	New GC material	Guiding GC question(s) for prelab	Guiding GC question(s) for postlab
Developing a Model Airbag	No prelab	5	Yes		What does it mean for a reaction to be green?
How the Nose Knows	No prelab	5	Yes		What does it mean to sustainably source chemicals?
Polymers: Crosslinking and Toy Design 1	2	3	Yes	How do you identify and dispose of waste?	What happens to the waste after it leaves the lab room? How can we better manage waste in our daily lives?
Polymers: Crosslinking and Toy Design 2	2	5	Yes	How do you reduce waste before it occurs? How do you balance safety and performance when designing a product?	How do you balance safety and performance when designing a product?
Biofuels 1	3	4	Yes	How do you quantify hazards/toxicity?	What additional metrics, besides LD50, are used to describe hazards/toxicity?
Biofuels 2	3	2	Yes	What chemical properties can be used to model environmental harm?	What chemical properties can be used to model environmental harm?
Biofuels 3	3	3	Yes	What does it mean for a reaction to be energy efficient?	What does it mean for a reaction to be energy efficient? What does it mean for a reaction to be green?
Acids in the Environment 1, 2, 3	6	8	Yes	What contributes to acids in the environment?	How can real-time analysis be used to reduce pollution?
Extraction of Curcumin and Analysis	4	3	Yes	What health and safety information are available for different chemicals?	What are the components of a green extraction?

Once green chemistry learning goals and a relevant context were chosen, the specific curricular materials or questions for each experiment or multi-week experimental module were created using the KI framework (start by eliciting student ideas, allow students to add and evaluate ideas, and have them reflect on their new understanding). This entire process is shown in Figure 3.2 and an example of one postlab question redesign and revision using the KI framework is shown in Appendix V. Appendix VI shows a summary of all the new green chemistry questions and details all the green chemistry curriculum questions for Chem 1AL in the Spring 2019 and Fall 2019 semesters.

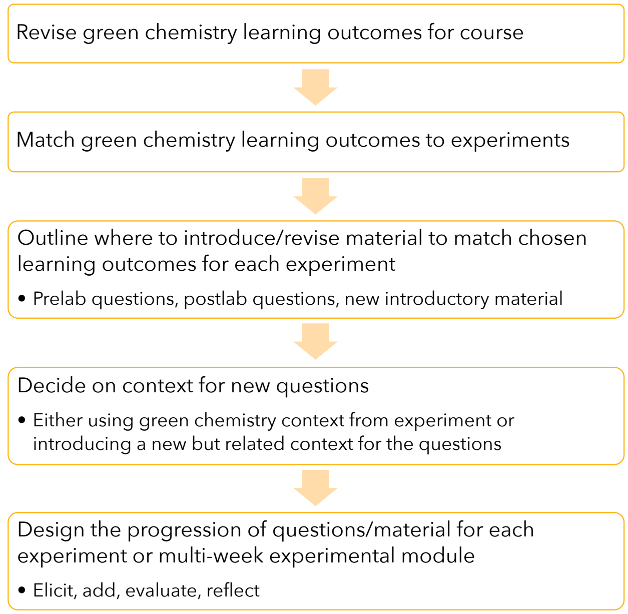


Figure 3.2. Design process for new green chemistry curricular materials with the goal of producing more coherent and relevant curriculum

Methods: Implementation of GC^2 v1a in Chem 1AL

Implementation

The first version of GC^2 was piloted during the Fall 2018 semester (GC^2 v1a) with approximately 1100 students (1010 of whom consented to be a part of this study), 30 GSIs, and one lab instructor. Approximately 50 new prelab and postlab green chemistry questions and in-lab observation prompts were created using the KI framework (Linn & Eylon, 2006) and new green chemistry content was created for the lab manual introduction and for the introduction to each experiment (see Appendix VI for a summary of the green chemistry content for GC^2 v1a). Instructor notes and solutions were provided for all new content and questions.

The curriculum was provided to the course instructor several months before the Fall 2018 semester for review and feedback. The GSIs were given the laboratory manual with instructor notes/solutions one week before the start of the semester during their orientation week. The course instructor held weekly GSI meetings to introduce the new experiment and answer questions about the previous and upcoming experiments. The lead researcher for this project attended each of these meetings to first introduce the study and then introduce the new green chemistry curricular questions and answer any specific green chemistry questions that arose each week.

Each week students attended a lab lecture given by the course instructor, which introduced the upcoming experiment content and techniques; the course instructor would highlight certain green chemistry contexts and practices present in the experiments (e.g., biofuels, atom economy). Students also received a GSI prelab lecture at the start of each weekly 3-hour long laboratory experiment. This prelab lecture typically focused on procedural aspects of the experiment (e.g., where to get reagents, dispose of waste, how to use equipment). Students then completed their weekly in-lab experiment with a student partner.

Students also completed weekly prelab and postlab questions before and after they attended their laboratory session respectively. Students completed prelab questions through an online system that allowed for automated and immediate feedback on multiple choice questions. Students were allowed three attempts on their prelab questions with the highest overall score counting towards their course grade. Students then completed more detailed free response postlab questions after finishing their laboratory procedure. These questions were completed individually and turned in one week after the experiment they referenced. GSIs graded each postlab question and provided students with written feedback. Students completed one 90-minute summative in-class exam after completing all their laboratory experiments.

Guiding Assessment Questions

Derived from utilization-focused evaluation (Patton, 2008), one main guiding question was used to focus the iterative implementation evaluation process each for GC^2 v1a (Fall 2018):

- In what ways does the General Chemistry Green Curriculum (GC^2) need to be modified to better meet the needs of the students and instructors?

During the Fall 2018 semester (GC^2 v1a) student and GSI surveys, individual student interviews, and weekly and summative feedback from the course instructor were used to explore this question and ultimately revise the curriculum for the next semester.

Data Collection and Analysis

Student survey. As detailed in the "General Methods," an online survey was administered to students near the end of Chem 1AL. One free response item asked students “What would you want to change about the green chemistry portion of this course?” and was coded for green chemistry themes to better understand the student green chemistry experience within the course. A total of 842 responses were received for this item and 20% of these responses were randomly chosen to be coded and analyzed.

Initial coding showed two major areas of focus: 1) course/experiment organization/instruction and 2) lab manual organization/content. Further coding revealed additional common categories related to students desiring more real-life application of green chemistry, revised pre/postlab questions and introductory green chemistry content, and better integration of green chemistry into the course/experiment (e.g., “Instead of separating the sections between green chemistry and the lab, I would recommend integrating as a vital part of the lab."). A subset of responses also desired more green chemistry emphasis in the course while another subset desired the reduction/removal of green chemistry from Chem 1AL. And finally, even though this question explicitly asked students about desired changes to the course, some responses stated that the green chemistry portion of the course was already satisfactory and they would not recommend any changes. A detailed coding scheme for this item can be found in Appendix VII.

Student interviews. As detailed in the “General Methods”, 11 student interviews (30 minutes) were conducted approximately 2/3 of the way through Chem 1AL during the Fall 2018 semester.

GSI questionnaire. As detailed in the “General Methods”, a questionnaire was administered at the end of the semester to all the GSIs who taught Chem 1AL.

Results: Assessment of GC^2 v1a in Chem 1AL

In What Ways Does GC^2 v1a Need to be Modified to Better Meet the Needs of the Students and Instructors?

Student survey. Student feedback on what could be improved about the green chemistry portion of Chem 1AL were varied but responses overwhelmingly provided constructive criticism and suggestions (**Figure 3.3**). Only 7% of responses said that green chemistry should be removed or reduced from Chem 1AL (with the majority wanting it reduced and not eliminated) while 79% of responses provided suggestions for improvement and 17% said that the green chemistry content in Chem 1AL was already satisfactory.

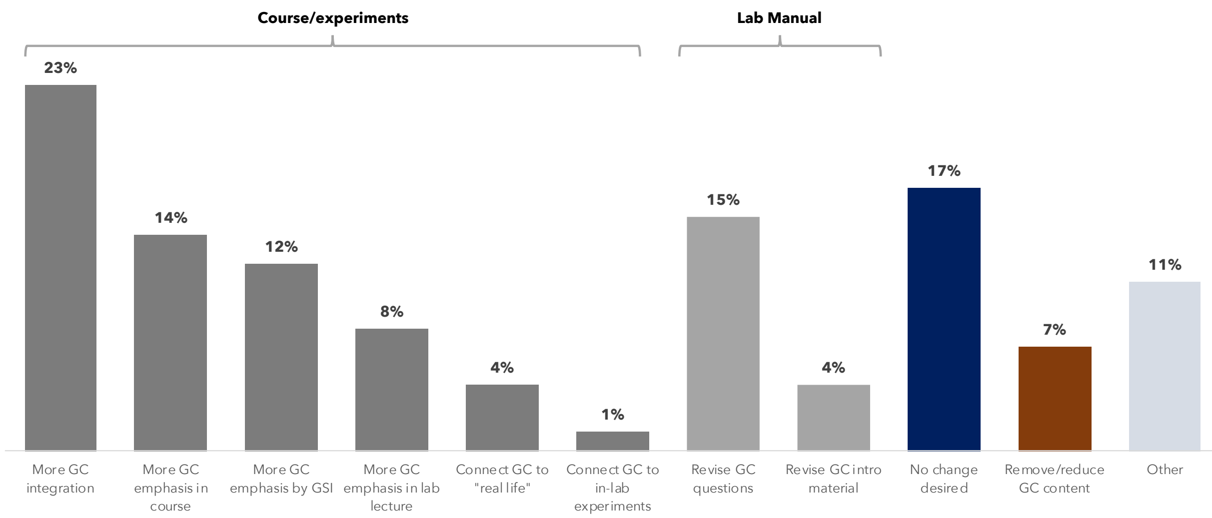


Figure 3.3. Coded Chem 1AL student survey responses to the end of semester survey question "What would you want to change about the green chemistry portion of this course?" for the Fall 2018 semester (N = 168)

Feedback revolved around two main categories: the overall course/experiments and the written laboratory manual. Many students (14%) expressed a desire for a larger green chemistry emphasis or focus within the course (e.g., "add more emphasis on green chemistry concepts and include them on the exam") or explicitly stated that they wished their GSI or course instructor had discussed green chemistry more often or in more detail (e.g., "I believe it should be more a part of the lab lecture part of lab, when the GSI is first talking about the lab for that day").

However, the most frequent comment came from students wishing that green chemistry was better integrated into the course. Nearly a quarter of responses indicated that green chemistry should be better connected to specific experiments or to the overall course material. For example, one survey responses said:

> *I think the green chemistry in the course can be reapplied to be more integrated within the course rather than just [postlab] questions at the end of the report. For example, the biofuels labs were a really good application of this, but for labs such as acid rain, we simply did titrations, which was only tied into green chemistry in the [postlab] extension questions.*

Additionally, students provided feedback on the written laboratory manual. Student responses (15%) mainly focused on the prelab or postlab green chemistry questions; feedback was usually vague but focused on clarifying, shortening, and/or making questions more relevant/connected to a given experiment's purpose/theme. Some students (4%) also suggested revisions to the green chemistry introduction for each experiment; most of this feedback was vague (e.g., "Make the green chemistry of each experiment more clear [sic] in the lab introduction. Ex. 2 paragraphs isn't enough in my opinion.") though some responses did focus on specific green chemistry topics or practices (e.g., atom economy, LD_{50}) they would like to see introduced or explained in more detail.

Student interviews. Interviews with 11 Chem 1AL students were conducted during the latter half of the Fall 2018 semester. Overall, interviewees appreciated the experiment context/order and the lecture/instructor with five of the 11 students mentioning how they enjoyed the type and order of the experiments used in Chem 1AL. Student feedback on green chemistry was varied but most stated that green chemistry made chemistry more interesting and relevant. Students thought that green chemistry was "better than just chemistry" as it provided motivation and real-world application and was linked to their personal interests or majors (e.g., environmental science, sustainability). One student stated that it was a "new perspective and they plan to use in their own research" and another said that it was "cool focus since most other schools don't have it."

However, as seen in the student survey responses, interviewees also stated that they would like to see green chemistry more fully integrated into each experiment especially for the experiments at the beginning of the semester. They also wanted to see better integration of *12 principles* in each experiment procedure/postlab, green chemistry observation prompts within the actual experimental procedure, and more green chemistry content in GSI prelab lectures. Most students found the green chemistry postlab questions easy to answer and interesting, liked that there was no single 'correct' answer, and that these questions helped contextualize the experiments. However, some interviewees also mentioned how this could lead to confusion (what does the GSI want to hear? what is the question trying to ask?).

GSI questionnaire. GSIs completed a questionnaire at the end of the Fall 2018 semester that covered, among other items, their experience teaching green chemistry that semester. Responses showed that GSIs most often discussed green chemistry during their prelab lectures with 61% of the GSIs discussing green chemistry during at least one prelab lecture and 35% discussing it during another time while in-lab with the students (Figure 3.4). However, the vast majority of GSIs only discussed or explained green chemistry topics or questions for a single experiment or module. The majority (11 GSIs) discussed green chemistry only during their prelab lecture(s) for the biofuel module. Additionally, when asked about their experience with green chemistry prior to Chem 1AL, 57% (13 of 23 GSIs) said that they had never heard or used green chemistry prior to being a GSI for this course.

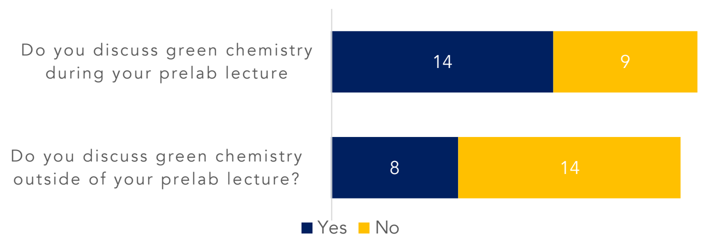


Figure 3.4. GSI responses to questions about green chemistry in Chem 1AL, Fall 2018 semester (N = 23)

Course instructor debrief. The feedback provided by the course instructor covered many of the same themes seen from GSI and student feedback. During student interviews, several specific green chemistry postlab questions were identified as confusing/redundant which was confirmed by the instructor's own conversations with students during office hours. Additionally, the instructor identified several additional question sets that had been unclear or confusing to GSIs and/or students. The instructor provided suggestion for redesigning these questions and reviewed all updated green chemistry question sets before they were implemented the following semester.

Discussion: Revisions for GC^2 v1a in Chem 1AL

Student response to the new green chemistry curriculum (as seen through surveys and interviews) was generally positive though there was room for improvement. Students recognized that course lab manual emphasized green chemistry principles and practices and wanted to see their instructors mirror at least a portion of that content. This was supported by feedback from the GSIs as most GSIs said they only discussed green chemistry during one of their prelab lectures and nearly 40% of GSIs never mentioned green chemistry at all.

Additionally, one of the most common pieces of feedback from students (and several GSIs) for GC^2 v1a was that they wished there was a greater green chemistry emphasis in the course (14%) and that there were more connections between green chemistry and the rest of the course concepts and themes (23%). This desire for better green chemistry integration was seen in both student survey and interview responses and often focused on the idea that the green chemistry prelab and postlab questions seemed 'tacked on' to the non-green chemistry questions. Indeed, the green chemistry questions were the last section on the prelab and postlab report sheets and often focused on extensions of the laboratory experiments instead of connecting directly to the experiment the students had just completed.

Additionally, students noted that they were rarely prompted to think about green chemistry during their laboratory experiment. Instead, they only encountered it before and after their in-lab section when they completed their prelab and postlab questions. An analysis of the GC^2 v1a showed that there were no green chemistry in-lab prompts that asked students to connect green chemistry contexts or content *while* they were collecting data or making observations in lab. The majority of green chemistry questions were either asked before or after students were in lab – not while they were actually performing the experiment. While there were 25 in-lab green chemistry prompts they all asked the same three questions about laboratory waste (e.g., proper disposal, reducing waste).

Curriculum Revisions

Based on student, instructor, and GSI feedback GC^2 v1a was revised for the Spring 2019 semester. First, specific green chemistry questions were revised or removed based on specific feedback from students, GSIs, and the course instructor (see Appendix VI for all Spring 2019 green chemistry questions). Next, student concerns about green chemistry integration for each experiment was addressed through the addition of 19 new green chemistry in-lab prompts. These prompts were situated within the written procedure for each experiment and were immediately relevant to what students were doing for that procedural step. Students weren't required to write responses to these prompts but they were encouraged to discuss them with other students and their GSI during the lab section.

Additionally, new green chemistry introductory material was added to the first several experiments in the laboratory manual, which had been noted by interviewees as having especially low green chemistry integration. This material introduced both local and global laboratory waste production and disposal (e.g., the 5.5 million metric tons of plastic waste generated from bioscience labs in 2014) before asking students to consider how they could reduce their own waste footprint in the laboratory. Finally, each experiment's introductory green chemistry section was rewritten to ensure that the green principles highlighted in these sections were clearly connected to the experiment at hand.

To increase GSI discussion of green chemistry during their laboratory sections, new GSI notes were added to the instructor version of the laboratory manual. Since nearly half of the GSIs for the Fall 2018 semester had no prior experience with green chemistry it was important to provide instructor material that helped support GSI integration of green chemistry into their teaching practices. These instructor notes gave suggestions for green chemistry topics to introduce or review during prelab lectures.

Curricular Updates for GC^2 v1b in Chem 1AL

Based on the Fall 2018 curriculum pilot and resulting data collection and analysis, a new version of GC^2 was developed for the subsequent semester. GC^2 v1b maintained the same overall structure, green chemistry outcomes, and question design as GC^2 v1a but built upon the previous curriculum. The main changes (as detailed in the previous section) were the addition of introductory material covering green chemistry principle and metrics, the addition of 19 new in-lab observation prompts to help student reflect on the green chemistry topics or practices present in their experiments (or different variables they could optimize to make their experiment greener), and the clarification of several postlab question sets (Appendix VI provides a summary of these changes). Additionally, suggestions for green chemistry topics and questions for the GSIs to cover during their prelab lectures were provided.

Methods: Implementation of GC^2 v1b in Chem 1AL

Implementation

GC^2 v1b was piloted during the Spring 2019 semester with approximately 600 students (582 of whom consented to be a part of this study), 20 GSIs, and the same lab instructor as for the previous semester. The overall course structure remained the same as the previous semester.

Guiding Assessment Questions

As for GC^2 v1a (Fall 2018), the main guiding assessment question focused on curricular improvement for GC^2 v1b: In what ways does the curriculum need to be modified to better meet the needs of the students and instructors? An online student survey and end-of-semester feedback from the course instructor were used to explore this question and produce revisions to the curriculum for the subsequent and final semester of this project.

Data Collection and Analysis

Student survey. As detailed in the "General Methods" and in the previous section for GC^2 v1a, an online survey was administered to students near the end of Chem 1AL. One free response item asked students "What would you want to change about the green chemistry portion of this course?" This question was coded for green chemistry themes as described in the previous section for GC^2 v1a. A total of 356 responses were received for this item and 20% of these responses were randomly chosen to be coded and analyzed.

Course instructor debrief. As for the Fall 2018 semester, a debrief session was conducted with the course instructor at the end of the Spring 2019 semester. The instructor reviewed and shared their notes from conversations with GSIs and students over the course of the semester that were pertinent to the green chemistry curriculum. The instructor was actively involved in green chemistry question redesign during Summer 2019 and reviewed all updated green chemistry question sets before they were implemented the following semester.

Results: Assessment of GC^2 v1a in Chem 1AL

In What Ways Does GC^2 v1b Need to be Modified to Better Meet the Needs of the Students and Instructors?

In contrast to the previous semester, the new GC^2 version showed significantly different student feedback to the post-survey question "what would you want to change about the green chemistry portion of the course?" (Figure 3.5). The desire for better green chemistry integration with the rest of the course materials decreased by over 15% from the previous semester, as did the suggestions to revise/update the prelab or postlab green chemistry questions. This indicated that the changes made to create GC^2 v1b were effective at addressing student concerns around these areas. Additionally, the percentage to students who said no change was desired for the green chemistry curriculum increased by 5% from v1a (17%) to v1b (22%).

However, there were three main feedback categories that increased in prevalence during the second iteration of the curriculum. Most noticeably, students desired more connection between green chemistry and their in-lab experiments. In contrast to the previous semester, most of these responses indicated that they didn't simply want to hear or read about green chemistry during their experiment but rather wanted opportunities to engage in green chemistry practices during their in-lab experiments (e.g., "There should be a portion of every lecture that specifically addresses what can be improved on in terms of chemistry from lab to lab.") or improve the 'greenness' of the reactions or procedures they were using (e.g., "Get more into the green chemistry with using materials [during the in-lab experiment]. I had used so many plastic pipettes and solutions and it was very wasteful.").

Additionally, while students found the green chemistry curriculum more integrated with the rest of the course material, they still expressed a desire for more GSI attention towards green chemistry, often connecting it to the desire for more green chemistry emphasis during their in-lab experiment (e.g., "I want the gsi [sic] to discuss what [green chemistry] principles we are using for each lab, before lab so we can keep them in mind as we do lab.") This was mirrored in student comments about revising the green chemistry introductions for each laboratory experiments. Students still desired more explicit pedagogy around green chemistry and suggested that more green chemistry related readings might help bridge that gap either alone (e.g., "More outside articles like the excerpts from biofuel unit. Pro and anti biofuel [sic]. They were very informative.") or in combination with additional instructor focus (e.g., "More detailed definitions and examples of each principle in Green Chemistry. We can also go over the concept during the lecture or spend more time talking about it during lab.").

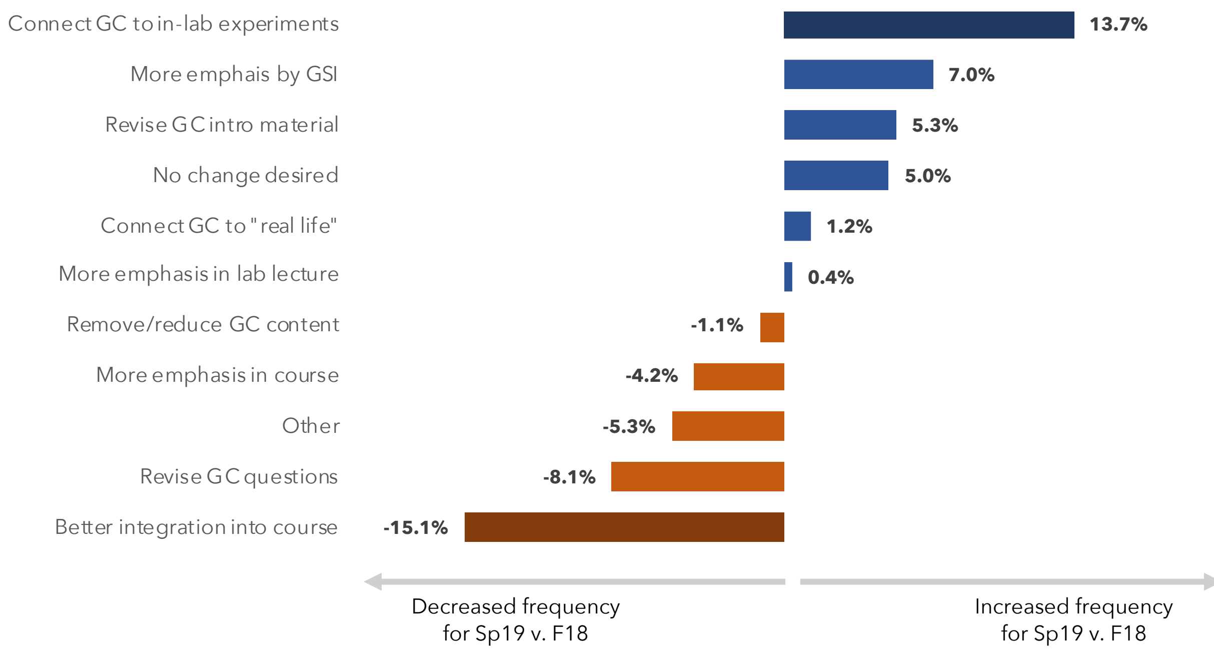


Figure 3.5. Changes from Fall 2018 (N = 168) to Spring 2019 (N = 74) semester for coded Chem 1AL student survey responses to the end of semester survey question "What would you want to change about the green chemistry portion of this course?" A positive increase change indicates that category was coded more often for Spring 2019 compared to Fall 2018 while a negative change indicates that category was coded less often for Spring 2019.

Discussion: Overall Revisions for GC^2 v1a and v1b in Chem 1AL

Designing the General Chemistry Green Curriculum (GC^2) was an iterative process that relied heavily on stakeholder involvement from the course. Derived from utilization-focused evaluation (Patton, 2008), the one main guiding question that was used to focus the iterative implementation evaluation process revolved around the ways in which the curriculum could and should be modified to better meet the needs of the students and instructors. Thus, feedback from the instructors and students in the course was critical for the development and improvement of the curriculum.

Student responses showed just how critical it is to holistically integrate green chemistry into the curriculum (and course) in order for students to view it as a valuable and useful practice. Students don't just want to think about green chemistry during their prelab and postlab questions; they want to see green chemistry in action during their in-lab experimental procedures and learn about it from their instructors. While curricular changes (e.g., increased in-lab green chemistry prompts) did improve student perceptions of green chemistry integration, students still desire more green chemistry connections during the in-lab experimental procedures and from instructor/GSI discussions. Thus, two new potential approaches were identified for the final version of GC^2 for the Fall 2019 semester:

- **Distribute the green chemistry questions throughout the prelab and postlab question sets instead of having a separate 'green chemistry' section at the end of each question set.** For GC^2 v1a and v1b, the last section of each prelab or postlab question set consisted of the 'green chemistry extension' questions. Since most of the green chemistry questions were developed with a focus on real world relevance they often served as a bridge between the experiment content and a current societal or environmental issue. This made them an appropriate coda to each experiment while also explicating naming the green aspects of each experiment. However, this structure segregated the experiment into green chemistry and chemistry sections and may have made the green chemistry extensions appear ancillary since they were positioned at the end of each experiment.

- **Provide additional support so GSIs can cover more green chemistry topics during their prelab lecture each week.** One piece of student feedback, consistent across both semesters, was the desire to have their instructors talk more about green chemistry. Introducing additional green chemistry content and revising the existing content to the lab manual is important but not wholly sufficient, as the lab manual is only one aspect of a course. Instructor buy-in and use of the new green chemistry curriculum is a key component to obtain true green chemistry integration into every aspect of the course. This makes it critically important to support GSIs in including green chemistry practices in their pedagogy. However, GSIs already cover many different chemistry content and technique topics to prepare their students for each experiment so adding additional content to their lecture is challenging. This dualism was brought up specifically by one GSI on the Fall 2018 GSI questionnaire as they stated that "it's really hard to cover both green chemistry and the experiment in the lab section. However, I think the questions in the report are still important." One potential solution was to have the course instructor ask the GSIs how they plan to incorporate green chemistry topics into their prelab lecture for the upcoming experiment or have GSIs reflect and/or share how they discussed green chemistry during previous prelab lectures. This both helps normalize the presence of green chemistry in the course and leverages peer feedback to help GSIs learn how best to integrate green chemistry into their lab lectures.

Ultimately, the former approach was adopted for the final summative implementation of GC^2 during the Fall 2019 semester as this was the last semester available for the lead researcher for this project to make major changes to the written laboratory manual. The course instructor planned to implement the latter approach in subsequent semesters once the written student curriculum was finalized.

In addition to stakeholder feedback, GC^2 v1b was also revised upon reflection and incorporation of green chemistry and learning sciences frameworks. Regardless of the exact placement of green chemistry questions in the curriculum, the practice of green chemistry involves constantly weighing tradeoffs and making decisions (Burmeister et al., 2012). The analysis of student learning for the original (2013-2017) green chemistry curriculum showed that students needed more practice applying green chemistry in a diverse range of situations, more exposure to more real green chemistry scenarios and metrics and tradeoffs (Armstrong et al., 2019). Indeed, one of the guiding principles for the curriculum redesign was to expose students to provide them with more opportunities to grapple with the tradeoffs (or comparative analyses) inherent to green chemistry. However, one of the difficulties with introducing green decision making in an introductory class is that evaluating 'greenness' is an inherently complex and multidimensional task. To allow students to begin making these decisions, many green chemistry courses ask students to change a single aspect of an existing synthesis or process to improve greenness (e.g., Guron et al., 2016). The drawback to this approach is that, while it is accessible for novice students, it doesn't accurately represent the complexity of green chemistry decisions and doesn't provide students with the real tools they need to make these decisions.

Thus, Machado et al.'s (2015) holistic framework 'green' reaction evaluation along with the KI framework (Linn, 2006; Linn & Eylon, 2006, 2011) served as a guide for the design of new green chemistry 'decision' questions as well as the revision of existing questions that provided opportunities to engage in evaluation or application of green chemistry principles. Machado et al.'s (2015) holistic framework aimed to bridge the gap between overly simplified single dimension/principle evaluations of reaction greenness and overly complex (for novice learners) lifecycle analyses traditionally used by green chemists to evaluate how green a reaction or process is. Machado and co-authors used the *12 Principles of Green Chemistry* (Anastas & Warner, 1998) to create visual metrics of increasing complexity to help guide students to towards a more sophisticated evaluation of the overall greenness of chemical processes.

While Machado et al.'s visual metrics weren't replicated exactly for the next and final version of GC^2 (GC^2 v2), the idea of using the *12 Principles* as explicit scaffold for making green decisions (and adding increasing complexity to how students evaluate if a process was acceptable for a given principle) was integrated into several questions sets throughout the semester. Starting from the very first experiment in GC^2 v2, students are asked to make green chemistry choices or recommendations (in this case, which reaction would they recommend for inflating a car airbag). To help students make this choice, they are guided through a green metric (atom economy) calculation and then asked to compare this metric (one of the *12 Principles*) for both possible reactions. They are asked to think about what other measures are important to gauge the true efficiency of a reaction and compare the hazard for both reactions. Finally, they are asked to make a recommendation for one airbag reaction considering all their in-lab observation, data collection, and theoretical calculations.

Subsequent question sets now build upon this framing. During a lab module focused on polymers, students are asked to choose between five provided options for reducing plastic waste. They are given outside resources to incorporate into their argument and then asked to explicitly consider and respond to potential counterarguments to their choice. Later, they are asked to consider what it means for a reaction to be green by identifying which of the *12 Principles of Green Chemistry* apply for the biofuels synthesis that they have just completed. To help students incorporate more systems thinking they apply the *12 principles* not just to the biofuels reaction but to the sourcing of materials and eventual biofuel product and byproduct production. In the final experiment of the semester, students are asked to rank extraction methods from best to worst identifying their own criteria to make this choice. They are then asked to explicitly incorporate environmental and health impacts into this choice (if they haven't already done so) and explain their updated ranking. And once again, they're asked to reflect on their choice by considering counterarguments.

Implementation of Final Curriculum: Student Perceptions

Curricular Design for GC^2 v2 in Chem 1AL

As detailed in the previous section, during the Spring 2019 semester, student and instructor input along with theoretical reframing was once again used to refine GC^2, which culminated in the final version of GC^2 used during the Fall 2019 semester (GC^2 v2). This version introduced new green chemistry introductory content, restructured the layout of the postlab question sets, added additional in-lab prompts, revised or replaced existing questions with new questions that more directly connected to the in-lab experiment and data, provided more scaffolding for quantitative and qualitative data analysis and comparison, and provided additional opportunities to distinguish and reflect on how to make green chemistry decisions (see Appendix VI for all new green chemistry questions for the Fall 2019 semester). Knowledge integration (Linn & Eylon, 2011) was once again used as the framework to design these new questions and prompts with the goal of helping students link the chemistry and green chemistry concepts they learned or experience during their in-lab work and gain more experience making green chemistry decisions.

Methods: Implementation of GC^2 v2 in Chem 1AL

Implementation

GC^2 v2 was implemented during the Fall 2019 semester with approximately 1000 students (1040 of whom consented to be a part of this study), 30 GSIs, and the same lab instructor as for the previous two semesters. The overall course structure remained the same as the previous semesters.

Guiding Assessment Questions

The main question used to focus the evaluation process for the final and summative curriculum implementation shifted away from curriculum improvement and towards the degree to which the overall curriculum goals had been achieved. The overarching goal of the General Chemistry Green Curriculum was to introduce students to green chemistry concepts and practices with the hope that they see value in these ideas for their future courses, careers, and research. Thus, these goals would be met if students believed they had learned green chemistry after completing Chem 1AL and if they saw value in green chemistry beyond the course.

Student perceptions of their green chemistry understanding/learning gains was assessed using nearly a dozen fixed response items from the online student surveys administered during the Fall 2019 semester. Additionally, data from two free questions were used to explore if students valued green chemistry once they completed Chem 1AL. These items had been administer starting in the Fall 2016/2017 semesters, which allowed for a limited comparison of GC^2 to the original (2013-2017) green chemistry curriculum.

Data Collection and Analysis

Student survey: Free response. Two free response survey items (Table 3.5) were used to explore student perceptions of green chemistry after completing Chem 1AL. These two items had been administered during the Fall 2016/2017 semesters and thus allowed for a limited comparison between the original (2013-2107) green chemistry curriculum and the updated General Chemistry Green Curriculum (GC^2) used in the subsequent semesters.

These two free responses items did not directly prompt students to discuss green chemistry but from previous analyses (Armstrong et al., 2019) it was known that green chemistry (and related topics such as biofuels, laboratory safety, energy, and sustainability) were common response topics. From previous analysis during from the Fall 2016 and 2017 datasets, three main themes were noted: explicit inclusion of green chemistry, connections to the environment/climate, and direct mentions of the green chemistry focused experiments used in the course (biofuels, ocean acidification). An additional round of coding revealed three more common categories related to energy/catalysis, waste/byproducts, and material lifecycle. From this initial coding, a list of green chemistry related words was developed for each theme along with anticipated variations of each word (e.g., sustainable versus sustainability). The number of times each of these words were mentioned for each student response was counted using Excel's SEARCH function. A response was coded as having "green aligned" content if it returned at least one of the defined green chemistry aligned words. More strict inclusion criteria were used to code for explicit mentions of green chemistry. A response was coded as having explicit green chemistry content if it returned the term "green chemistry" or any variation of "sustainability." The validity of this coding was confirmed against a human coder for 20% of the Fall 2018 responses to the questions "What was the most valuable thing you gained from lab?". The Excel text search returned results within 2% of the human coder. This text analysis was then used for the remaining items over all semesters, which allowed for rapid coding of thousands of student responses.

Table 3.5. Free response posttest survey items

Green Chemistry Survey Item	Response Type	Semesters analyzed
What was the most valuable thing you gained from lab?	Free response	Fall 2016, Fall 2017, Fall 2018, Spring 2019, Fall 2019
Describe a connection that was meaningful to you.	Free response	Fall 2017, Fall 2018, Spring 2019, Fall 2019

Student survey: Fixed Response. Green chemistry understanding was measured using a pretest and posttest survey designed to capture changes in understanding after completing Chem 1AL. A combination of eight Likert and three Guttman items from the online pretest and posttest student surveys were used to measure student self-reported understanding of green chemistry (Table 3.6 and Table 3.7). These items were assigned numerical values for further analysis (e.g., *strongly disagree* was assigned a value of 0, *somewhat disagree* a value of 1, *somewhat agree* a value of 2, and *strongly agree* a value of 3). These items were specifically designed to cover a range of green chemistry competencies from simple definitions or recall of green chemistry principles to evaluating the greenness of reactions and suggesting changes to make a reaction greener. The means and standard deviations for each semester for the pretest and posttest were calculated. Wilcoxon signed rank sum tests were used to compare changes in pretest and posttest scores for each item.

Table 3.6. Self-reported green chemistry understanding survey items. All items used a Likert scale of Strongly Disagree, Somewhat Disagree, Somewhat Agree, and Strongly Agree.

Green chemistry item	Item name	Response type
I know what the term green chemistry means.	LK_GCDef	Likert
I can define green chemistry principles (e.g., atom economy, catalysis, renewable feedstocks).	LK_GCPrin	Likert
I can identify hazards associated with a reaction or experiment.	LK_IdHaz	Likert
I can suggest ways to make a reaction or experiment less hazardous.	LK_RxnHaz	Likert
I understand how to minimize chemical waste.	LK_MinWaste	Likert
I understand what happens to waste after it leaves the laboratory.	LK_DipWaste	Likert
I can identify factors that make a reaction 'green'.	LK_IdRxn	Likert
I can suggest improvements to make a reaction greener.	LK_ImRxn	Likert

Table 3.7. Self-reported green chemistry understanding survey items. All items used unique Guttman scales.

Green chemistry item	Item name	Response type
How well can you define green chemistry?	**GUT_DefGC**	I cannot define green chemistry. I can define green chemistry in broad terms, but I cannot provide explanations or examples. I can define green chemistry and provide **simple** explanations or examples. I can define green chemistry and provide **a few detailed** explanations or examples. I can define green chemistry and provide **many detailed** explanations or examples.
How well can you define green chemistry principles (e.g., waste prevention, energy efficiency, atom economy)?	**GUT_GCPrin**	I cannot define green chemistry principles. I can define **a few** green chemistry principles. I can define **about half** of the green chemistry principles. I can define **most** green chemistry principles. I can define **most** green chemistry principles and provide examples for these terms.
How well can you evaluate the 'greenness' of a chemical reaction?	**GUT_Rxn**	I don't understand how green chemistry can be used to evaluate something. I can identify that evaluation is needed but I might not know what principles to apply to the reaction. I could probably make some broad suggestions. I can identify a few factors or principles to evaluate the greenness of the reaction. I might struggle with identifying all of the needed factors. I can identify the needed factors or principles to evaluate the greenness of the reaction. I can identify the needed factors or principles and make recommendations to improve the greenness of the reaction.

Additionally, previous work during the Fall 2016 semester led to the development of a construct map and a set of items to measure student understanding of green chemistry. This construct map and items were developed using a measurement model approach; the 'four-building blocks' described by Wilson (2005) – construct, item responses, outcome space, and measurement model (Figure 3.6) – helped ensure the content validity of instrument and provides a pathway for instrument design and improvement. The design of the original instrument encompassed one (or one and half) iteration of this outlined process. The construct map and items were designed, item responses were obtained, the outcome space (scoring of items and mapping back to the construct map) was defined, and the Rasch partial credit measurement model was used to evaluate the construct. After going through one cycle of this process the results of the measurement model were used to redesign the construct and redefine the outcome space. The Rasch measurement model was once again used to evaluate and refine the redesigned construct. This produced a final construct map with three main levels of green chemistry understanding: *Intuiting*, *Applying*, and *Analyzing* (Figure 3.7).

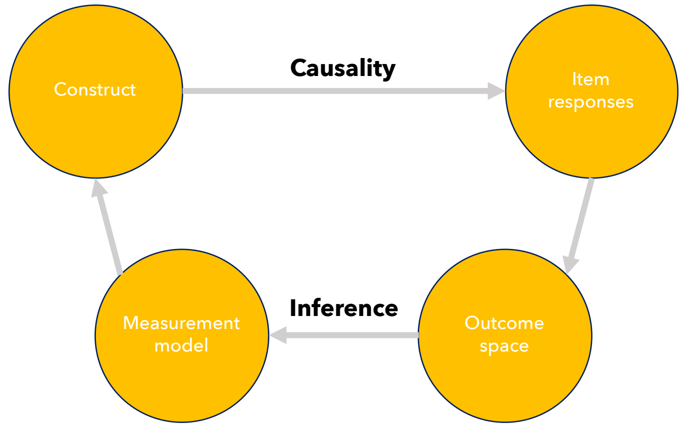


Figure 3.6. Iterative process of designing an instrument (Wilson, 2005)

Level 1: Intuiting

At this lowest level of green chemistry understanding, students have little to no understanding of green chemistry. If they do attempt to define green chemistry or use green-aligned language or terms, they relie on guesses/inferences and/or is supported with colloquial 'green' language and does not incorporate more specific normative knowledge of green chemistry. Often respondents specifically state (or choose the response that indicates) that they don't know what green chemistry or related terms/practices mean or how to apply them.

Level 2: Applying

At this level, students can define and apply green chemistry using normative green chemistry knowledge and practices. At this level, students are familiar and comfortable with green chemistry, use green chemistry vocabulary correctly, and can provide clarifying statements and general applications of green chemistry principles. There can be a mix of specific and colloquial green language (e.g., *eco-friendly*, *sustainability*, *good for the environment*) but specific green chemistry terms or examples are used to clarify/support these more general statements and/or provide clarifying explanations, examples, or applications.

Level 3: Analyzing

At this level, students can both define green chemistry/terms and apply that understanding to novel situations. Students understand that green chemistry should be used to analyze systems and understand the applications of green chemistry (e.g., develop sustainable processes, chemicals, chemistries, products). They can apply general knowledge to real or hypothetical problems or scenarios. Students can analyze/evaluate situations from a green chemistry perspective and can apply green chemistry principles correctly. They understand multiple metrics should be used to make decisions and that green chemistry deals with tradeoffs and optimizations. They also understand the likely contributors to the environmental footprint of a product from a systems thinking perspective.

Direction of increasing green chemistry understanding

Levels	Respondents	Responses to Items
Level 3: Analyzing Understands how to use green chemistry to analyze systems; understand green chemistry applications	**3:** Can **analyze/evaluate** situations from a green chemistry perspective; can **apply** green chemistry principles to new situations; understands the likely contributors to the environmental footprint of a product from a systems thinking perspective; understand multiple metrics should be used to make decisions	Uses green chemistry principles to **evaluate** systems**;** can use **metrics** for decision making analysis; evaluates systems based on performance, efficiency, minimized human health and environmental hazards; can **analyze** processes, chemicals, products; understands multiple metrics/principles should be used
Level 2: Applying Able to define and apply green chemistry	**2:** Familiar and comfortable with green chemistry; **uses green chemistry vocabulary correctly**; can provide clarifying statements and **general applications** of terms	**Use green chemistry vocabulary**; can provide examples of green chemistry and can explain the meaning and general use of green chemistry principles
Level 1: Intuiting Little to know understanding of green chemistry	**1**: Intuit a naïve meaning of green chemistry from name; students define green chemistry using colloquial terms	Responses indicate students have a vague idea about green chemistry; ideas do not align with normative green chemistry terms

Direction of decreasing green chemistry understanding

Figure 3.7. Construct map for green chemistry understanding in the general chemistry classroom

Respondent Characteristics

A sample of 630 students from Chem 1AL was used for this analysis (Table 3.8). The majority of these students were female (67%), were not the first in their family to attend college (72%), were not underrepresented minority (URM) students (86%), and spoke English as a primary language (89%). Students who did not complete all the pretest and posttest items were dropped from the dataset. Those that did not give consent were also dropped from the dataset.

Table 3.8. Sample demographic characteristics (N = 630)

	Number of students	Percentage of students (%)
URM Status		
Non-URM student	540	86
URM student	90	14
Gender		
Female	424	67
Male	206	33
First-generation status		
Not first-generation student	454	72
First-generation student	176	28
Language		
English as a primary language	562	89
English as an additional language	68	11
Total	**630**	

Categorizing Items and Scoring

The construct map shown in Figure 3.7 served as the framework for analyzing and interpreting the student responses for each item. Each item was individually mapped back onto the construct map (Table 3.9) using the previous measurement model results from Fall 2016. This prior analysis had shown that defining and applying green chemistry are not necessarily hierarchical ideas. Instead, a basic level of understanding is needed to apply green chemistry and applying green chemistry in turn informs overall green chemistry understanding. Thus, the construct map (and resulting scoring guide) that emerged from this initial analysis allowed for respondents to simultaneously define and apply green chemistry at various levels, which led to items (theoretically) spanning the full range of the construct (Table 3.9).

Data analysis

A Rasch Partial Credit Model (Masters, 1996; Masters & Wright, 1981; Masters, 1982) was used for this pre-post analysis to calibrate item difficulties and student ability levels (WinSteps 4.8.2 was used for all item response analysis). This model was ideal since it is a polytomous version of the Rasch model that can calibrate ordered polytomous scale items (Likert and Guttman) that score at two or more levels. For this analysis, there were 11 items that had 4-5 levels and 3-4 step parameters (Guttman items had 5 levels and 4 step parameters while Likert items had 4 levels and 3 step parameters). These 11 items had previously been developed using a measurement model (Wilson, 2005) approach and had shown a high degree of validity and reliability with item thresholds that spanned the range of respondent abilities.

Table 3.9. Scoring guide for fixed response items

Item Name	Step Threshold	Construct Level		
		Level 1: Intuiting	Level 2: Applying	Level 3: Analyzing
LK_GCDef	Pr(≥1)	X		
	Pr(≥2)	X	X	
	Pr(≥3)			
GUT_DefGG	Pr(≥1)	X		
	Pr(≥2)	X		
	Pr(≥3)		X	
	Pr(≥4)			X
LK_GCPrin	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
GUT_GCPrin	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)		X	
	Pr(≥4)			X
LK_IdHaz	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
LK_RxnHaz	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
LK_IdRxn	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
LK_ImRxn	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
GUT_Rxn	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X
	Pr(≥4)			X
LK_MinWaste	Pr(≥1)	X		
	Pr(≥2)		X	
	Pr(≥3)			X

However, prior to any interpretations, the fit of the data to the model was once again examined (Table 3.10). The outlier-sensitive fit statistics mean square (outfit mean square) and information-weighted fit statistics mean square (infit mean square) ranged from 0.86-1.31 for the pretest and 0.65-1.44 for the posttest with a mean infit and outfit mean square of near 1 for both tests. While there is no absolute limit for fit indexes, a lower bound of 0.75 (3/4) and an upper bound of 1.33 (4/3) are commonly used (Adams & Khoo, 1996). Most items were within these bounds except for three: LK_IdHaz, LK_IdRxn, and LK_DipWaste. The first two items showed posttest infit and outift mean squares, respectively, below the lower bound indicating that the observed variance was less than expected. In contrast, the third item had both posttest infit and outfit mean square values above the upper bound indicating the observed variance was greater than expected (Wilson, 2005).

Table 3.10. Green chemistry understanding items calibrated at pretest and posttest with mean-square variance–ratio fit statistics (SE = standard error). Cells highlighted in red indicate infit or outfit mean square values outside the lower and upper bounds (Adams & Khoo, 1996).

Item name	Calibration (logit (SE))		Infit Mean Square		Outfit Mean Square	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
LK_GCDef	-1.86 (0.1)	-0.78 (0.09)	1.00	0.94	0.98	0.96
GUT_DefGG	0.36 (0.07)	0.04 (0.07)	1.16	1.15	1.17	1.17
LK_GCPrin	0.01 (0.08)	-0.39 (0.09)	0.86	0.86	0.84	0.84
GUT_GCPrin	1.34 (0.07)	0.73 (0.06)	1.08	1.16	1.04	1.21
LK_IdHaz	-0.88 (0.08)	-0.32 (0.09)	0.95	0.7	0.92	0.83
LK_RxnHaz	-0.14 (0.08)	-0.37 (0.09)	0.89	0.86	0.89	0.85
LK_IdRxn	-0.72 (0.08)	-0.53 (0.1)	0.90	0.71	0.89	0.66
LK_ImRxn	-0.06 (0.08)	-0.08 (0.09)	0.91	0.82	0.93	0.78
GUT_Rxn	1.2 (0.07)	0.52 (0.07)	1.06	1.12	1.05	1.10
LK_MinWaste	-0.19 (0.08)	-0.52 (0.1)	0.91	0.91	0.91	0.88
LK_DipWaste	0.95 (0.07)	1.71 (0.07)	1.24	1.38	1.31	1.44

Differential item functioning. Since the goal of this analysis was a pre-post comparison of student abilities, it was important to evaluate the differential item function (DIF) to ensure item stability for the pre-post comparisons. . shows the DIF for the pretest versus the posttest and Table 3.11 provides the estimated item difficulty differences (absolute values) and statistical significance between the pretest and posttest as both statistical significance and effect size need to be considered for DIF (Wilson, 2005). In terms of Rasch models, Peak and Wilson (2011) propose that a difference in item difficulty of less than 0.426 logits is considered ‘negligible’ while a value over 0.638 logits is considered ‘large’ (values in between are considered ‘intermediate’).

Most items had similar difficulty estimates between the pretest and posttest with several items estimated to be significantly less difficult on the posttest compared to the pretest (items below the identity line). However, item #11 ("I understand what happens to waste after it leaves the laboratory") was significantly more difficult on the posttest compared to the pretest ($t = -8.62$, $p < .001$). Of the items that had statistically significant logit differences two had item differences of 'negligible' DIF, one had an item difference of 'intermediate' DIF, and only one – Item #11 – had a 'large' DIF. Thus, this item was dropped from the dataset for all subsequent pre-posttest analysis.

Table 3.11. Differential item functioning (DIF) for pretest and posttest. Step item difficulties highlighted by Paek and Wilson's (2011) criteria and report of statistically significant DIF based on confidence interval overlap. Cells in red indicate a "large" (>|.638|) difference while cells highlighted in green indicate a "negligible" (<|.426|) difference.

Item name	Estimated item difficulty differences (absolute values)	p-value
LK_GCDef	0.244	0.071
GUT_DefGG	0.048	< 0.001
LK_GCPrin	0.553	0.070
GUT_GCPrin	0.140	0.002
LK_IdHaz	0.212	< 0.001
LK_RxnHaz	0.175	0.149
LK_IdRxn	0.188	0.703
LK_ImRxn	0.427	0.119
GUT_Rxn	0.445	< 0.001
LK_MinWaste	0.348	0.242
LK_DipWaste	0.889	< 0.001

Rasch learning gain calculations. Rasch measures of change must be done with items that function the same in both pretest and posttest conditions. When measuring 'learning gains' one expects (or hopes) that the students will change from time 1 to time 2 but care must be taken to ensure that the test items and rating scales are consistent throughout those two time points. Traditional "raw scores" learning gains typically assume that the test items and rating scales remain constant from pretest to posttest. However, both persons *and* items may change from time 1 to time 2, both must be put on the same "frame of reference" for both time points to ensure that these changes have "unambiguous numerical representation and substantive meaning" (Wright, 1996).

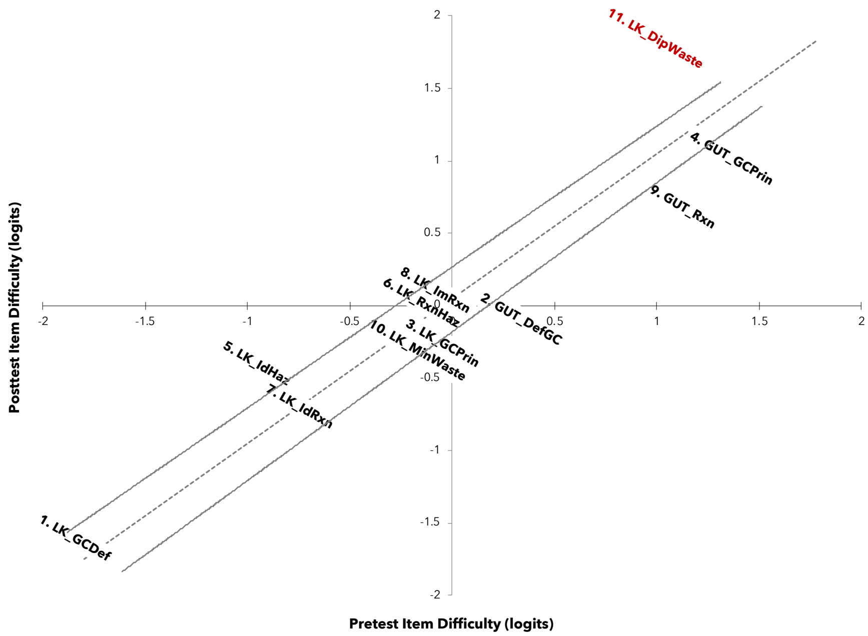


Figure 3.8. Differential item functioning (DIF) between the pretest and posttest. The dashed line represents the identity line while the solid lines represent the 95% upper and lower confidence intervals. The identity line is not a line of best fit by rather indicates *X* = *Y* across the *X*- and *Y*-axes.

The first step in this process, was to analyze the pretest and posttest data separately to eliminate any obvious errors and verify scale stability (see above analysis). However, this analysis also revealed that the items did indeed change with time (i.e., they are time dependent). The lower scale categories were frequently endorsed on the pretest and then rarely used on the posttest; this was an expected shift as students gained knowledge and confidence in their green chemistry abilities, but it still changed the rating scale structure of the items between the two timepoints. Thus, the next step in this process was to obtain a rating scale calibration (step difficulties) that were most consistent with the pretest (time 1) and posttest (time 2,) which were then used as the anchor rating scale calibration for the final pre-post analysis (Table 3.12). This was accomplished by stacking pre and posttest data vertically so that each student appeared twice and each item once.

Table 3.12. Pooled (simultaneous analysis of pre/posttest) rating scale threshold measures

Item Name	Item	Category	Thurstonian threshold measure (logits)
LK_GCDef	1	0	0
	1	1	-3.47
	1	2	-1.25
	1	3	4.72
GUT_DefGG	2	0	0
	2	1	-4.94
	2	2	-1.45
	2	3	1.69
	2	4	4.7
LK_GCPrin	3	0	0
	3	1	-3.25
	3	2	-0.83
	3	3	4.08
GUT_GCPrin	4	0	0
	4	1	-4.74
	4	2	-0.01
	4	3	1.02
	4	4	3.73
LK_IdHaz	5	0	0
	5	1	-3.37
	5	2	-1.17
	5	3	4.54
LK_RxnHaz	6	0	0
	6	1	-3.57
	6	2	-0.87
	6	3	4.44
LK_IdRxn	7	0	0
	7	1	-3.23
	7	2	-1.16
	7	3	4.39
LK_ImRxn	8	0	0
	8	1	-3.61
	8	2	-0.81
	8	3	4.42
GUT_Rxn	9	0	0
	9	1	-4.43
	9	2	-1.29
	9	3	1.83
	9	4	3.89
LK_MinWaste	10	0	0
	10	1	-3.82
	10	2	-0.59
	10	3	4.41

Table 3.13. Pooled item difficulties (simultaneous analysis of pre/posttest) used to estimate student abilities estimated using common rating scale thresholds (Table 3.12)

Item Number	Item Name	Pooled Item Difficulty (logits)	
1	**LK_GCDef**	-1.53	(easiest)
2	**GUT_DefGG**	0.07	
3	**LK_GCPrin**	-0.12	
4	**GUT_GCPrin**	1.25	(hardest)
5	**LK_IdHaz**	-0.27	
6	**LK_RxnHaz**	0.19	
7	**LK_IdRxn**	-0.58	
8	**LK_ImRxn**	0.27	
9	**GUT_Rxn**	0.88	
10	**LK_MinWaste**	-0.17	

Results: Assessment of GC^2 v2 in Chem 1AL

Do Students Believe They Have Learned Green Chemistry After Completing GC^2 v2?

For any course or curriculum it is important to ensure that the designer's goals translate and are readily apparent to the actual users of the curriculum (Meyers & Nulty, 2009), e.g. the students. In general, the overarching goal of the GC^2 was to increase student understanding of green chemistry principles and practices and therefore one way to measure achievement of this goal was to ask students if they felt like they had a better understanding of green chemistry after completing Chem 1AL. To test this alignment, three of the learning outcomes originally used to design GC^2 were identified and mapped to 11 fixed response pretest and posttest green chemistry survey items (Table 3.14).

Table 3.14. Learning outcomes for GC² mapped to 11 fixed response survey items. Item scale is indicated as Likert or Guttman; for additional information on items and scales please see Table 3.6 and Table 3.7

Learning outcome	Survey item
Reaction greenness • understand what it means for a reaction to be green • identify factors that make a reaction green • Suggest improvements to increase reaction greener	1. How well can you evaluate the 'greenness' of a chemical reaction? 2. I can identify factors that make a reaction 'green'. 3. I can suggest improvements to make a reaction greener.
Chemical waste generation • understand that waste should be prevented • identify waste produced from experiments and understand how that waste is disposed • Suggest ways to minimize waste generation	4. I understand what happens to waste after it leaves the laboratory. 5. I understand how to minimize chemical waste.
Chemical hazards • understand what it what it means for chemicals/reactions to be less hazardous • identify/compare hazards of reaction • Suggest ways to make reaction less hazardous	6. I can identify hazards associated with a reaction or experiment. 7. I can suggest ways to make a reaction or experiment less hazardous.
General green chemistry understanding and systems thinking • Understand the purpose of green chemistry • Understand the connections between different (green) chemistry principles • Understand boundaries of chemistry/green chemistry • Understand that chemistry has far reaching effects	8. How well can you define green chemistry? 9. How well can you define green chemistry principles (e.g., waste prevention, energy efficiency, atom economy)? 10. I know what the term green chemistry means. 11. I can define green chemistry principles (e.g., atom economy, catalysis, renewable feedstocks).

Analysis of these survey items showed that students self-reported that, overall, their understanding of green chemistry increased significantly from the beginning to the end of the semester. Students' self-reported ability to define green chemistry and green chemistry principles, identify and reduce hazards and waste, and identify factors that make a reaction green all increased significantly between the beginning and end of the Fall 2019 semester (Figure 3.9 and Figure 3.10), which closely matched the intended learning outcomes for the GC².

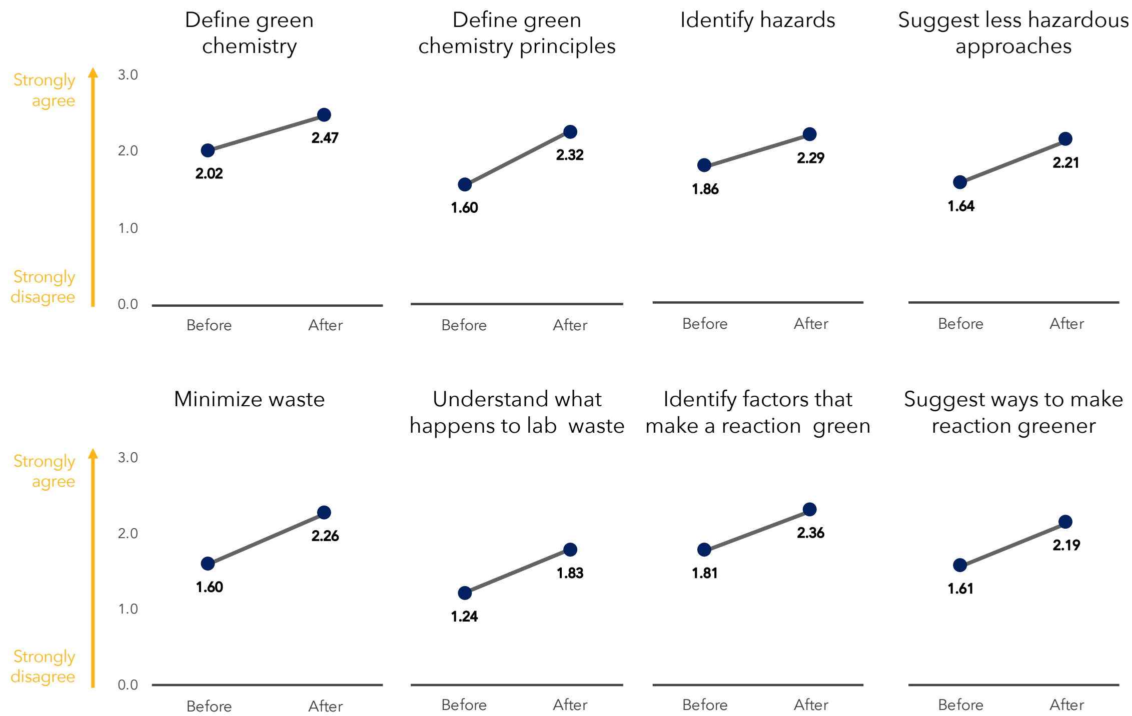


Figure 3.9. Mean pretest and posttest scores for eight green chemistry Likert items on the student survey. Wilcoxon signed-rank tests showed that there were statistically significant changes in student scores for each category before and after completing Chem 1AL ($p < 0.001$, $N = 648$).

For both Likert and Guttman item types, students were most confident in their ability to define green chemistry at the beginning and end of the course though a significant change in self-reported understanding still occurred from the pretest to the posttest (Likert: $z = -14.48$, $p < 0.001$; Guttman: $z = -20.35$, $p < 0.001$). This was reasonable as students were introduced to green chemistry at the beginning of the semester (near the time of the pretest survey administration) and then, it could be argued, all the subsequent course material served to build upon and provide more nuance to that original introduction of green chemistry.

Interestingly, this confidence didn't extend to student's self-reported ability to define green chemistry principles. At the beginning of the course students rated their ability to define the *12 principles* relatively low – below their ability to identify reaction hazards and identify factors that make a reaction green (as measured using Likert items, Figure 3.9) though this trend had mostly disappeared by the end of the semester. Students also rated this competency the lowest for the three Guttman items both before and after they had completed the course.

This trend was not fully anticipated since many of the other items rated higher by the students required a solid foundation within the *12 Principles* (for example, evaluating the greenness of a reaction not only requires a good understanding of the *12* *principles* but also the ability gather, consider, and weigh data related to those factors and consider other green metrics). However, students may have expressed lower confidence in their competency with this item due to the word *define* and the specificity that entails with the *12 Principles* (each of which have distinct definitions). It's not surprisingly that at the beginning of the semester students would not be fully familiar with the *12 principles* and thus would not be able to define them (especially for the Guttman item which had detailed criteria around exactly how many principles students should be able to define for each category level). However, at the end of the semester while students would certainly be more aware of these principles, they may still not be confident in their ability to define all these terms without any external reference.

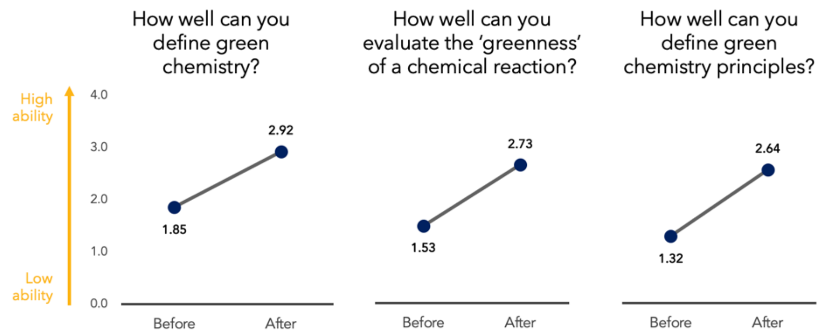


Figure 3.10. Mean pretest and posttest scores for three green chemistry Guttman items on the student survey (see Table 3.7 for full item scales). Wilcoxon signed-rank tests showed that there were statistically significant changes in student scores for each category before and after completing Chem 1AL ($p < 0.001$, $N = 648$).

Item response theory. Item response theory allowed for a detailed, direct comparison between respondent scores and item difficulties, making this a more informative way to understand student self-reported green chemistry ability instead of simply comparing mean pretest and posttest item scores. The Wright map provides a detailed picture of individual student green chemistry ability and item threshold levels (Figure 3.11). A lower (i.e., increasingly negative) threshold value indicates that an item is easier for a respondent to endorse (or that a respondent of a lower ability level is more likely to endorse the item at that particular threshold level). A higher (i.e., increasingly positive) threshold value indicates that the item is harder for a respondent to endorse (or that a respondent of a lower ability level is less likely to endorse the item at that particular threshold level). The Wright map shows that item thresholds extend the full range of respondent pretest abilities, but that many student posttest abilities extend past the highest item thresholds. The horizontal dotted lines on the Wright map indicate qualitative transitions from one construct threshold level to another: Level 1: Intuiting, Level 2: Analyzing, and Level 3: Applying.

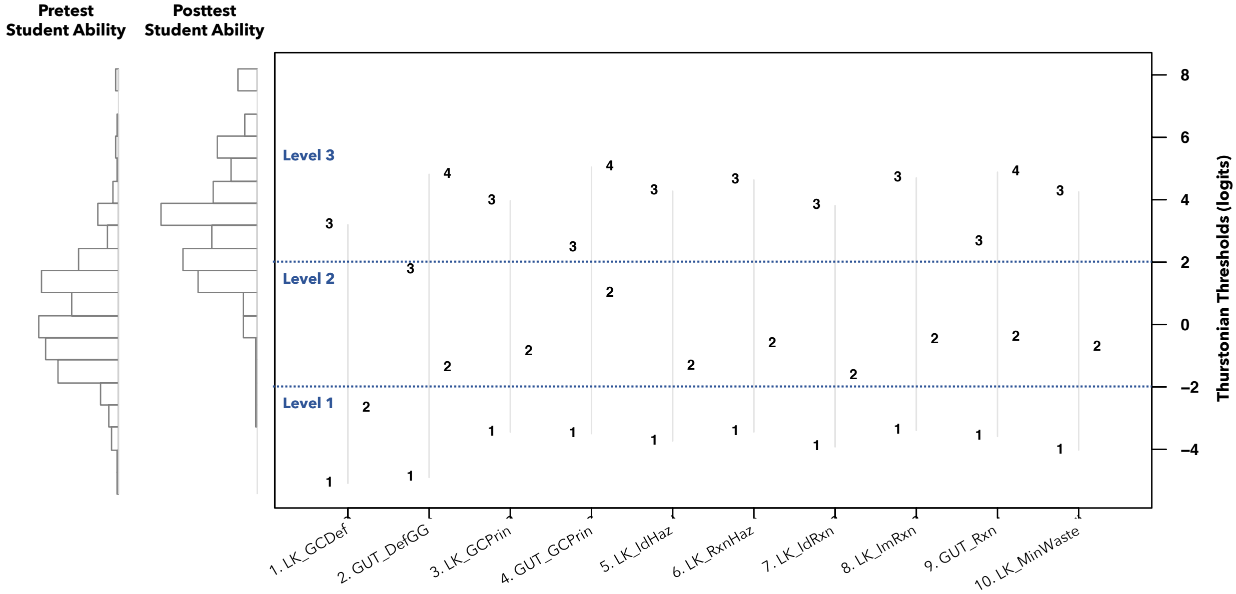


Figure 3.11. Wright map of pretest and posttest student abilities and item thresholds. The horizontal dotted lines on the Wright map indicate qualitative transitions from one construct threshold level to another: Level 1: Intuiting, Level 2: Analyzing, and Level 3: Applying.

The lowest qualitative threshold (Level 1: Intuiting) corresponds to the lowest pretest student abilities (-5 to -2 logits). At this intuiting level, student understanding of green chemistry is either not present or based on naïve or colloquial understanding of greenness. These students only can endorse or agree with the lowest scale choices (e.g., "strongly disagree/somewhat disagree" or "I cannot define green chemistry/ I can define green chemistry in broad terms, but I cannot provide explanations or examples") indicating little to no understanding of green chemistry and/or confidence in their green chemistry abilities. Within the "Intuiting" level there is one higher threshold (LK_GCDef) indicating that these students have an approximately 50% chance of "somewhat agreeing" that they can define green chemistry, which is consistent with this level having a colloquial understanding of green chemistry. On the posttest, virtually no students fall within this bottom "Intuiting" level. Instead, students have decisively shifted to "Level 2: Analyzing" or "Level 3: Applying."

Indeed, even most pretest student abilities fall within this mid-level threshold of "Analyzing" (-2 to 2 logits). At this level, students can define and apply normative green chemistry vocabulary; students have a 50% probability 'somewhat agreeing' that they can, for example, identify reaction hazards or minimize chemical waste or suggest ways to make a reaction greener. On the posttest, a minority of students have abilities that correspond to this middle level, but most students have clearly reached the highest "Level 3: Applying" threshold. At this level, students can apply green chemistry knowledge and practices towards new green chemistry scenarios and applications. Students found it easy to 'strongly agree' that they could, for example, suggest ways to make reaction less hazardous and suggest improvements to make a reaction greener. They could "define most green chemistry principles and provide examples for these terms" and "identify the needed factors or principles and make recommendations to improve the greenness of the reaction."

This shift in student ability from the beginning to end of the semester was also seen through the mean student pretest and posttest abilities. Overall, student ability increased from a mean pretest ability of 0.03 logits to mean posttest ability of 3.16 logits. This showed that, on average, students had moved from the middle construct level of "Analyzing" to the highest (currently defined) construct level of "Applying." In fact, many students on the posttest had estimated abilities that exceeded the highest threshold difficulty indicating that they had a much greater than 50% chance of endorsing the highest threshold (almost no students exhibited this ability level on the pretest). While this was encouraging to see in terms of student posttest abilities it also indicated the need for more items that matched the actual posttest abilities of the students. This, along with the lack of distinction between the highest Guttman item thresholds, indicates the existence and need for at least one additional construct level and corresponding item development to capture more advanced green chemistry understanding.

Do Students See Value in Green Chemistry Outside of the Chem 1AL?

In addition to simply introducing students to green chemistry content, another overarching goal of GC^2 was to for the introduction of green chemistry concepts and practices to serve as a guide, inspiration, or springboard for students' future courses, careers, interests and/or research. The hope was that situating Chem 1AL within the larger framing of green chemistry would enable students to see that chemistry had an impact outside of this one course, as green chemistry brings chemistry into a dialogue with the environment, people, and society.

For the past several years, both before and during the development of GC^2, students were asked "What was the most valuable thing you gained from lab?" on the posttest survey. Before the development of GC^2 (pre-Fall 2018) students reported that green chemistry was the most valuable thing they gained from the course in 3-4% of responses (Figure 3.12). When all green aligned words/phrases were included (e.g., mentions of biofuels, safety, environment, waste) this percentage increased to 7-8%. However, once GC^2 was implemented15% responses indicated that green chemistry was the most valuable thing they gained from the course. If all green aligned terms are included, then 23% of all responses expressed this sentiment. This dramatic increase continued for the subsequent GC^2 implementations culminating in 19% of student responses explicitly stating (and 29% implicitly stating) that green chemistry was the most valuable thing that they gained from Chem 1AL during the Fall 2019 semester (Figure 3.12).

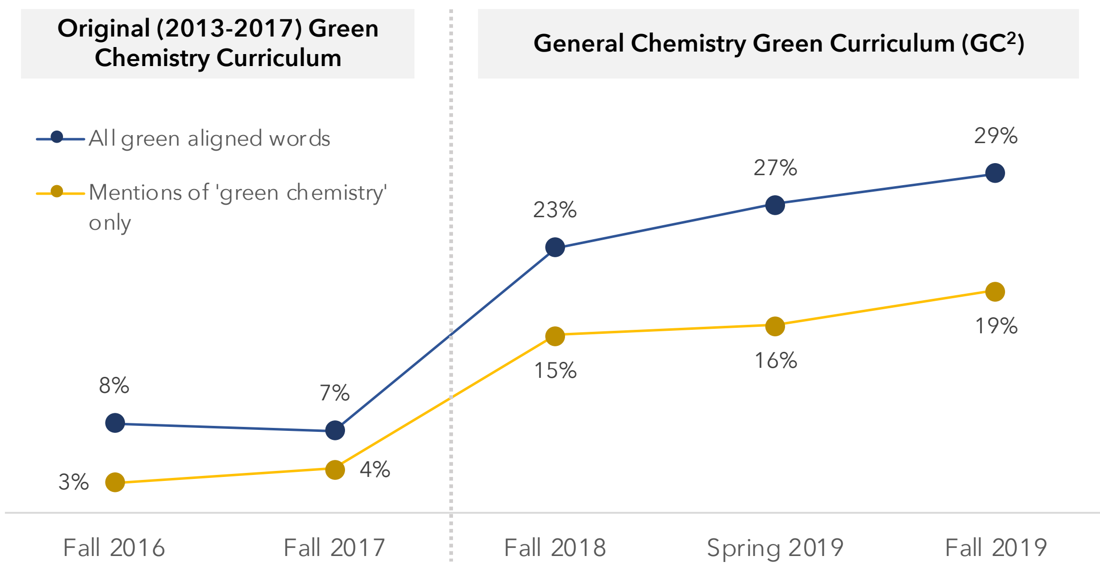


Figure 3.12. Coded Chem 1AL student survey responses to the end of semester survey question "What was the most valuable thing you gained from lab?" for the Fall 2016 – Fall 2019 semesters

Even in semesters prior to the implementation of GC^2, it was always surprising and encouraging that even a fraction of students decided that green chemistry was the most valuable part of the course. Chem 1AL serves as the gateway course for learning laboratory content and techniques and is often the only chance students have to gain any hands-on experience in a laboratory during their first semester on campus. The fact that nearly a quarter of students now say that green chemistry, instead of basic laboratory skills, is the most important part of the course is evidence of the impact that green chemistry has in general as well as the specific impact that the GC^2 curriculum has had on the student experience in Chem 1AL.

Starting in the Fall 2017 semester, students were also asked to "Describe a connection that was meaningful to you" on the posttest survey. Interesting, during Fall 2017, before the development of GC^2, 78% of student responses mentioned green chemistry or other green aligned terms in response to this question. Unlike the previous question about value, which saw a marked increase in green chemistry mentions upon the introduction of GC^2, this item saw a decrease in how many responses identified green chemistry aligned terms as a 'meaningful connection' for Chem 1AL. While the initial level of enthusiasm from the Fall 2017 semester was hard to match even with the introduction of GC^2, green aligned terms were still encouragingly observed in nearly half of all responses for subsequent semesters (Figure 3.13). Additionally, explicit mentions of green chemistry remained consistent between semesters regardless of the curriculum employed.

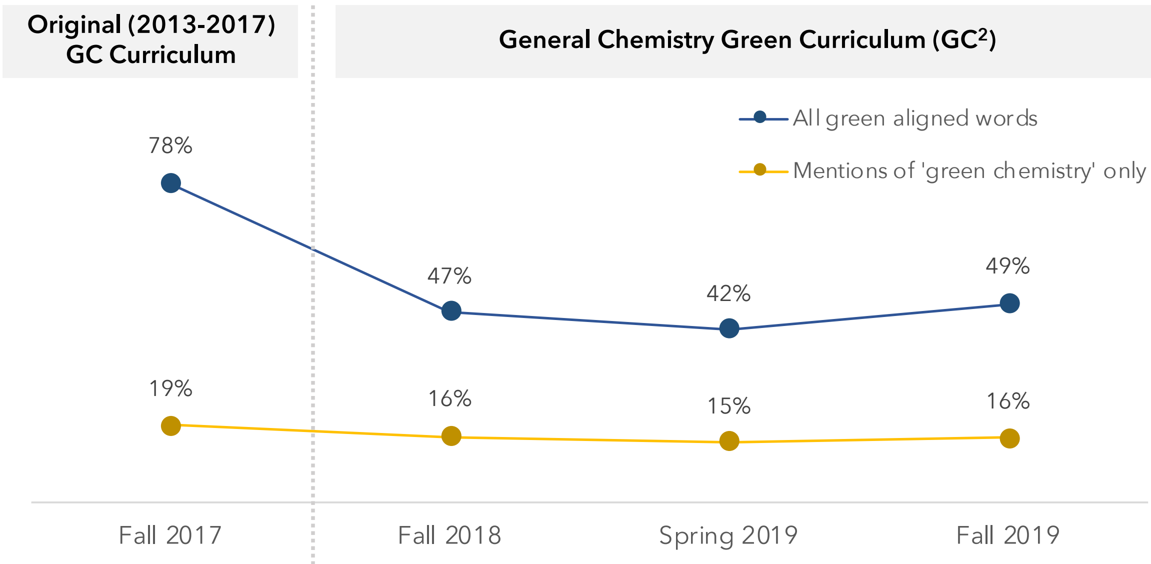


Figure 3.13. Coded Chem 1AL student survey responses to the end of semester survey question "Describe a connection that was meaningful to you." for the Fall 2017 – Fall 2019 semesters

Further exploration of this item showed that one of the reasons for this difference between the Fall 2017 semester and subsequent semesters was due to how often students referenced specific laboratory experiments. During the Fall 2017 semester, nearly 50% of student responses mentioned two of the main green chemistry lab modules: Biofuels and Acids in the Environment. In contrast, during the Fall 2019 only 28% of responses mentioned these modules – a decrease of 21%.

Additionally, to better understand what may have led to the decrease in frequency of green chemistry aligned terms after the Fall 2017 semester, a random sample of the responses that did *not* mention green chemistry were coded for emergent themes for the Fall 2017 (N = 82, 50% of non-green responses) and Fall 2019 (N = 72, 20% of non-green responses) semesters. The most notable difference between the two semesters was the increased prevalence of a meaningful connection being defined by "human connection." There was a 19% increase between the Fall 2017 and Fall 2019 semesters for responses that mentioned that the most meaningful connection made was the literal connection between people within the course (between peers and with GSIs/instructors) and that friendship/relationship building was a vital component of the course and individual advancement (e.g., "Interacting with the [teacher scholar] and peers because it allowed me to not only meet more people, but be more comfortable to ask questions.").

Limitations. In addition to the curricular changes between the Fall 2016/17 semesters (original green chemistry curriculum) and subsequent semesters (GC^2), the posttest survey also changed drastically between semesters. While the two questions explored above remained consistent across semesters the surrounding structure and focus of the survey did not. During the Fall 2016/17 semester the posttest survey only had one explicit green chemistry item; the rest of the survey focused on chemistry content and technique ability and nature of science/experimental design ability. Starting in the Fall 2018 semester, the survey was redesigned to focus on green chemistry ability, attitudes, and behaviors with a reduced focus on chemistry outcomes and the removal of all experimental design items. Additionally, different free response questions preceded and proceeded the two questions analyzed above for the different survey versions. Thus, it's possible that the differences in responses between the Fall 2016/17 and Fall 2018 – Fall 2019 semesters are due, at least in part, to survey changes instead of/in addition to curricular changes.

Conclusions

The implementation and assessment of the original (2013-2107) green chemistry curriculum during the Fall 2016 semester showed room for improvement in both the amount and design of explicit green chemistry content. The original goal of 'greening' the general chemistry laboratory courses was to "integrate sustainability and green chemistry concepts into every aspect of the curriculum." While the principles of green chemistry had certainly been used to develop each new general chemistry teaching experiment this design was not made explicit to the users of the curriculum.

The General Chemistry Green Curriculum (GC^2) aimed to build off the original green chemistry curriculum to realize more fully 'an integrated green chemistry curriculum' for the general chemistry laboratory at UC Berkeley. The original curriculum already had a robust set of teaching experiments – each designed using green chemistry principles; the creation of GC^2 meant that the general chemistry laboratory now both directly contributed to sustainability and equipped students with the basic chemical ideas and practices inherent to green chemistry. The creation of GC^2 highlighted the connections between chemistry and every day decisions, products, and processes, which is theorized to make chemistry more meaningful to students (Burmeister et al., 2013).

The development of GC^2 was an iterative process that spanned three semesters and involved thousands of participants. Over 50 new green chemistry postlab questions, 25 new green chemistry prelab questions, and 47 green chemistry in-lab prompts were developed for the final version of GC^2. This curriculum also contained an enhanced introduction to green chemistry and systems thinking, green chemistry introductory material for each experiment, and instructor notes and solutions for all new green chemistry content and questions. Over the three iterations, the new green chemistry questions were refined to allow students opportunities to reflect on and expand upon in-lab data and observations as well as provide a connection to relevant external societal contexts or issues, provide scaffolding for quantitative and qualitative data analysis and comparison, and allow students to distinguish and reflect on how green chemistry decisions are made. Knowledge integration (Linn, 2006; Linn & Eylon, 2011) was used as the main framework for the development of GC^2 as its core structure (elicit, add, distinguish, reflect) explicitly supports the development of connections between normative scientific ideas, which made it an ideal framework to link green chemistry and chemistry concepts, practices, and contexts within the new curriculum.

Curricular Goals and Outcomes. Ultimately, the goal of this curriculum development process was to 1) utilize stakeholder feedback to iteratively improve GC^2 and 2) ensure that theoretical goals of the curriculum were actually realized during the final implementation GC^2 (Meyers & Nulty, 2009). The main goals of GC^2 were to teach students about green chemistry concepts and practices and provide them with opportunities to use that knowledge to engage in green chemistry decision making – a core green chemistry activity (Andraos & Dicks, 2012). Ultimately, it was hoped that students would leave the course feeling like they had gained green chemistry knowledge and ability and that they had been able to discover how green chemistry was useful and valuable inside and outside of the classroom.

Overall, these goals successfully translated from curriculum designer to student as students reported that their ability to define green chemistry and green chemistry principles, identify and reduce hazards and waste, and identify factors that make a reaction green all increased significantly after completing GC^2. Many students also reported that green chemistry was the most valuable component and most meaningful connection of the course. During student interviews students stated that green chemistry was interesting and relevant. Students thought that green chemistry was "better than just chemistry" as it provided motivation and real-world application and was linked to their personal interests.

The emergence of green chemistry as a valuable course component and meaningful connection was not unexpected as many previous studies have shown the value (cognitive and affective) that green chemistry brings to chemistry education. Green chemistry can provide students with an ethical framework for doing chemistry (Andraos & Dicks, 2012), bring relevance to the chemistry classroom (Bodner, 2016), and provide more meaning to chemical learning (Burmeister et al., 2013). Green chemistry is a new and ever evolving field that still has many more questions than solutions, which allows students to see the process of how scientific knowledge is constructed and modified – that is, scientific knowledge evolves, reflects scientists' perspectives, and provides opportunities for students to construct their own understanding of scientific knowledge (Andraos & Dicks, 2012). Ultimately, green chemistry provides meaning to chemistry classrooms by allowing students to learn about and work toward solving some of the grand challenges of sustainability using chemistry and often aligns with students own personal ethics towards environmental responsibility.

Design Process Lessons

This curriculum project relied on a robust learning sciences framework – knowledge integration – for the initial GC^2 design and subsequent iterations. The application of this framework was vital for the overall structure and success of the curriculum. While this was, at its heart, a green chemistry focused curriculum it was critical that the design of the green chemistry questions and supporting material occurred through an intentional and concerted process. The KI framework helped ensure that the questions were designed to elicit students' prior knowledge, promote discovering and distinguishing between prior knowledge and new ideas, and support reflection on newly constructed knowledge (Linn & Eylon, 2006). As the curriculum iterations progressed, the KI framework helped restructure curricular material to support students in 1) discovering and building connections within and between chemistry and green chemistry concepts, practices, and applications and 2) in learning how to make 'greener' choices by engaging in comparative analysis and critical reflection on a given choice. Ideally, these ideas and applications would extend outside of the classroom with students finding connections and value between their interests/aspirations and the green chemistry they learned through GC^2.

In addition to using the KI framework for curriculum design, utilization-focused evaluation (Patton, 2008) was used as a guide to monitor the implementation of all versions of GC^2 and ultimately assess if the main goals of the curricular redesign had been met. The goal of UFE is to ensure that the evaluation results are used and useful, which means involving intended users (in this case, students and instructors) early and often. This framing shifted the role students played in the curriculum implementation from simply 'learners' to valuable contributors to curriculum development and improvement. Indeed, much of the iterative curricular changes were motivated from student feedback from their experience with GC^2.

GC^2 Curricular Lessons

One of the main themes to emerge from the iterative design and redesign of GC^2 was the idea of 'green chemistry integration' into the curriculum. This theme of integration arose de novo from student survey and interview responses and shifted in focus and prevalence over the three semesters as curricular changes were made. Responses indicated that the green chemistry content and questions in the curriculum should be better connected to specific in-lab experiments and/or to the overall course material. In general, this theme revolved around the desire to see green chemistry in all aspects of the course – not just as extension or application questions at the end of a set of postlab questions. Students wanted to not only think and learn about green chemistry in theory, but also gain hands-on experience with green chemistry laboratory practices and decision making. In later semesters, a number of student responses stated that they wish they'd been able to apply green chemistry principles during their in-lab experiments. For example, students wanted the ability to reduce the amount of plastic waste they produced or to at least identify and explore real-time decision points that could lead to greener experimental procedures.

In many ways, the complexity of green chemistry education mirrors the complexity of green chemistry as field or metadiscipline. Green chemistry is a wide and diverse field that can encompass many different methods and processes (Anastas, 2011; Anastas & Allen, 2016). Ultimately, it's argued that green chemistry is a philosophy for all chemistry; it is not a separate field of chemistry but rather a way of doing or thinking about chemistry that attends to the safety of people and the environment (Anastas & Kirchhoff, 2002; Epicoco et al., 2014; Linthorst, 2009). This idea holistic integration of green chemistry into chemistry parallels the students' desire to have green chemistry fully integrated into their chemistry course. However, how that integration should occur for both green chemistry and green chemistry education is not well defined and can hold different meanings for different people. Ultimately, holistic integration of green chemistry into chemistry education requires immense time and effort for instructors and departments and relies on both 'top-down' and 'bottom-up' implementation for full adoption (Bodner, 2016; Burmeister et al., 2012). These changes entail both adaptations to written curricular materials *and* instructor practices, and hopefully occur not just in isolated courses but in a logical progression through an entire departmental (or inter-departmental) sequence.

Future work

The iterative process used to create the final version of GC^2 provided many curricular insights. Overall, the development of GC^2 focused on enhancing the written laboratory material used for Chem 1AL. This included designing new prelab and postlab questions, instructor solutions and notes, and green chemistry introductory material for each experiment, which was well received by the students overall. However, introducing green chemistry content to a written curriculum is only one dimension of a course. Feedback from instructors and students alike made it clear that more alignment was needed between the green chemistry focus of the written curricular materials and the in-lab practices of instructors. Green chemistry needs to be integrated into all aspects of the course (laboratory manual, prelab and postlab questions, in-lab procedure, instructor discussions) for students to feel like the curriculum is coherent and green chemistry is truly an integral part of chemistry.

Thus, obtaining instructor buy-in for a green chemistry curriculum is a key component to truly integrate green chemistry into the entire course. However, green chemistry has historically been a contentious topic for individual and systematic adoption (Haack & Hutchison, 2016; Howard-Grenville et al., 2017; Iles, 2013; Woodhouse & Breyman, 2005). Indeed, while green chemistry has become much more prevalent (in research and education alike) it is still misunderstood by many chemists; since green chemistry is not part of the standard curriculum in most schools (though this is beginning to change) few chemists have exposure to green chemistry (Matus et al., 2012). This pattern was readily apparent for graduate student instructors for GC^2 (Fall 2018) as over half had never heard of green chemistry before becoming an instructor for Chem 1AL.

Thus, it cannot be assumed that all chemistry educators have a uniform background in green chemistry, which makes it critical that any green chemistry curriculum is designed to support and guide instructors in teaching (and in some cases learning themselves about) green chemistry. While there are examples of integrating green chemistry into instructor preparatory classes most of this work has focused pre-service teachers (Karpudewan et al., 2009, 2012b), whose training is structurally different than that of university instructors and graduate student instructors. Thus, future work should focus on how best to prepare and support university instructors who add green chemistry content and practices to their courses to ultimately achieve a more robust adoption and integration of green chemistry into the undergraduate curriculum.

Chapter 4: What's in a Word? Student Beliefs and Understanding About Green Chemistry

Introduction

What is Green Chemistry?

Green chemistry is a relatively recent addition to chemistry and has been developed and codified over the past 25 years (Anastas, 2011; Anastas & Beach, 2009). Green chemistry was conceptualized to address acute environmental and societal issues within chemistry and the chemical industry. The chemical industry was (and still is) one of the biggest sources of pollution and environmental hazards (Epicoco, et al., 2014; Woodhouse & Breyman, 2005) and, prior to green chemistry, chemicals were often designed without evaluating long-term environmental and health impacts (Iles, 2013; Iles et al., 2017; Martin et al., 2021; Woodhouse & Breyman, 2005). The chemical industry still relies on and promotes largely non-renewable petrochemicals as feedstocks (Epicoco et al., 2014; Woodhouse & Breyman, 2005), is energy-intensive, and responsible for producing, using and transporting many harmful substances (Epicoco et al., 2014). In short, traditional ways of practicing chemistry have not been fully accountable to society (Iles, 2011). Green chemistry aims to provide a framework or philosophy for chemistry that initiates a new relationship between chemistry, the environment, and society at large (Bodner, 2016).

The field of green chemistry is widely considered to have been codified by Paul Anastas and John Warner's *Twelve Principles of Green Chemistry* in 1998 (Anastas and Warner, 1998). Most simply, green chemistry is a process, which as Anastas (2011) states "requires looking across systems and across life cycles to design products and processes that are benign to both people and the environment." The *Twelve Principles of Green Chemistry* are often used as a framework or series of guidelines for what constitutes green chemistry design and development.

12 Principles of Green Chemistry (Anastas & Warner, 1998)

1. Waste Prevention
2. Atom Economy
3. Less Hazardous Synthesis
4. Design Benign Chemicals
5. Benign Solvents and Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis (vs. Stoichiometric)
10. Design for Degradation
11. Real-Time Analysis for Pollution Prevention
12. Inherently Benign Chemistry for Accident Prevention

Green Chemistry Curricula and Courses

With the advent of green chemistry, there has been a corresponding interest and effort in developing educational materials focused on green chemistry and sustainability principles (Andraos & Dicks, 2012; Haack & Hutchison, 2016). The goals for introducing green chemistry into courses and curricula vary depending on the instructor and institution but often fall into several main categories: 1) improving the cost/safety of laboratory spaces or classes, 2) teaching students the basic chemical principles behind sustainability and green chemistry, and/or 3) enhancing student learning or their experience with chemistry through the use of green chemistry practices and contexts.

Laboratory courses are often the first step in integrating green chemistry into a chemistry program. Traditional chemistry instructional experiments often use toxic, carcinogenic, and corrosive substances, no longer accurately represent the type of chemistries used in academic or industrial settings, and are very expensive to operate with high costs for waste disposal and well ventilated laboratory space (Haack & Hutchison, 2016). Using green chemistry principles to conduct science education laboratory work (e.g., creating chemistry teaching experiments that use less hazardous reagents) has the benefit of directly contributing to sustainability by, for example, reducing chemical waste. However, this approach does not explicitly teach students skills to contribute towards sustainable development (Burmeister et al., 2012).

Many chemistry teaching laboratories not only use green chemistry to 'green' their reactions and reagents but also bring green chemistry to the forefront of the student experience. Indeed, there are many examples of green chemistry curricula for elective courses or organic laboratory courses (Andraos & Dicks, 2012; Aurandt & Butler, 2011; Beltman et al., 2015; A. E. Marteel-Parrish, 2014; Morra & Dicks, 2016; Roesky et al., 2009). While less common than their organic chemistry counterpart, there are several comprehensive green chemistry general chemistry lecture (Prescott, 2013) or laboratory (Gron et al., 2013; Henrie, 2017; Klingshirn & Spessard, 2009) curricular designs and a number of green chemistry laboratory experiments for general chemistry courses (e.g. Purcell *et al.*, 2016; Buckley *et al.*, 2013).

Bringing green chemistry ideas and practices into the laboratory curriculum helps highlight chemical principles behind every day processes making chemistry more meaningful to students (Burmeister et al., 2012). Additionally, green chemistry provides students with an ethical framework for conducting chemistry (Andraos &

Dicks, 2012), which often aligns with students own personal ethics towards the environment and can help engage students who previously saw chemistry or chemicals as polluting or dangerous (Haack & Hutchison, 2016). Green chemistry brings relevance to the chemistry classroom (Bodner, 2016) and provides more meaning to chemical learning (Burmeister, Rauch, & Eilks, 2012) by allowing students to learn and do chemistry in the context of some of the grand challenges of sustainability (Haack & Hutchison, 2016).

Green Chemistry Assessment

While green chemistry has gained a robust standing within the chemistry education community over the last two decades the corresponding assessment of these green curricula and courses and resulting student outcomes is in a more nascent stage of development. The development of green chemistry courses and resources is often treated as the end goal with the assessment of student learning taking a secondary position. While the creation of robust green chemistry curricula is needed and appreciated, it is equally important to document the outcomes, both expected and unexpected, from these courses to ensure the goals of the curricula are being met and that they are serving all of the students in the course. This is especially important for a field like green chemistry education that often is the result of a 'bottom-up' rather than a 'top-down' interest and drive (Bodner, 2016). Additionally, assessment not only informs and improves the development of new curricula (e.g., Andraos & Dicks, 2015; Garner et al., 2015; Marteel-Parrish, 2014; Paluri et al., 2015) but also provide evidence for why sustained support and institutional investment is worthwhile for these courses.

Over the past decade, there has been a steady growth in publications focused on assessing green chemistry student learning outcomes. Since most green chemistry courses and curricula are designed for post-secondary students, correspondingly most assessment has occurred at the undergraduate level though there are also some examples of high school (Mandler et al., 2012) and pre-service teacher (Karpudewan et al., 2012b) studies. The focus of this work has ranged from assessing student knowledge (Gron et al., 2013; Guron et al., 2016; Karpudewan et al., 2012a, 2016, 2015b, 2015a; Mandler et al., 2012; Shamuganathan & Karpudewan, 2017); to attitudes, motivation, and values (Guron et al., 2016; Karpudewan et al., 2012a, 2015a, 2015b; Mandler et al., 2012; Shamuganathan & Karpudewan, 2017); to laboratory skills (Gron et al., 2013) in the context of green chemistry courses.

While there is variety in the type of green chemistry topics assessed the method of assessment tends to rely heavily on surveys or questionnaires (Armstrong et al., 2018) that utilize Likert and sometimes free response items (Aubrecht et al., 2015; Gron et al., 2013; Purcell et al., 2016). The choice of assessment method obviously depends on many factors including both time and available resources (both for data collection and analysis). An advantage of Likert style items is their ease of analysis relative to other assessment methods, which can be especially important for an instructor who is developing, implementing, and assessing a new green chemistry curriculum themselves and/or for large enrollment courses (e.g. Purcell et al., 2016). However, this type of question requires respondents to self-assess their own knowledge or skills, allowing the researcher to capture only what students *believe* they know about a given topic. As many have found, self-assessments of knowledge is often not a reliable measure of cognitive learning (Davis et al., 2006; von Blottnitz et al., 2015) and instead provides a measure of affective components (Sitzmann et al., 2010).

In addition to surveys, there are also more and more examples (e.g. Andraos & Dicks, 2015; Galgano et al., 2012; Gron et al., 2013; Marteel-Parrish, 2014) of researchers using student course work (often in addition to survey results) to explore student outcomes. Additionally, interviews and focus groups have also been used to provide a more holistic picture of student understanding (Karpudewan et al., 2015a, 2015b; Mandler et al., 2012; Shamuganathan & Karpudewan, 2017). While interviews and focus groups provide detailed qualitative information, they are time intensive to conduct and analyze and thus can often only be used with a small number of students. Especially for large enrollment courses, alternative modes of assessment, such as short answer and multiple-choice content questions, are needed to assess green chemistry student learning outcomes more fully.

Green Chemistry at UC Berkeley

General Chemistry Green Curriculum (GC^2)

For more than a decade, the UC Berkeley College of Chemistry has invested in greening teaching laboratories and developing a corresponding green chemistry curricula (Armstrong et al., 2019; Buckley et al., 2013; Purcell et al., 2016). Over 30 new green chemistry focused experiments have been developed for general chemistry non-chemistry majors' and chemistry majors' laboratory courses. These experiments cover topics such as biodegradable polymers, extraction and analysis of plant-based antibiotics, ecotoxicity, fuel cells, solar cells, and biodiesel synthesis. Since 2018, a new green chemistry curriculum (General Chemistry Green Curriculum) was designed to accompany these experiments for the non-major's general chemistry laboratory course.

The General Chemistry Green Curriculum (GC^2) was designed to equip students with the chemical ideas, principles, and practices inherent to green chemistry (Chapter 3). This curriculum includes dozens of new green chemistry postlab questions, green chemistry prelab questions, and green chemistry in-lab prompts designed to highlight or connect to specific aspects of the *12 Principles of Green Chemistry*. GC^2 also contains an enhanced introduction to green chemistry and systems thinking, green chemistry introductory material for each experiment, and instructor notes and solutions for all new green chemistry content and questions. The knowledge integration framework (Linn, 2006; Linn & Eylon, 2011) guided the development of GC^2; knowledge integration's core structure (elicit, add, distinguish, reflect) explicitly supports the development of connections between scientific ideas, which made it an ideal framework to link green chemistry and chemistry concepts, practices, and contexts within the new curriculum. The new green chemistry questions were developed to allow students opportunities to reflect on and expand upon in-lab data and observations as well as provide a connection to relevant external societal contexts or issues, provide scaffolding for quantitative and qualitative data analysis and comparison, and opportunities to distinguish and reflect on how green chemistry decisions are made.

Assessing Student Understanding of Green Chemistry

Just as teaching green chemistry is complex and multidimensional so too is evaluating what students understand about green chemistry. GC^2 was developed using a constructivist framework – Knowledge Integration (Linn, 2006; Linn & Eylon, 2011) – and the ensuing assessment of student learning also utilized a constructivist approach. Constructivism is a theory of learning based on the idea that people are not 'blank slates' that simply absorb information from others, but rather actively construct their own understanding of the world through the interplay of their prior knowledge, observations and experiences, and reflection (Bada & Olusegun, 2015; Bodner, 1986; Honebein, 1996; Hyslop-Margison & Strobel, 2007; Phillips, 1995). Constructivism posits that learning occurs when meaningful connections are made between prior knowledge and new knowledge and that these connections are mediated by both cognitive and affective considerations (Bada & Olusegun, 2015; Bodner, 1986; Phillips, 1995). Green chemistry education and assessment inherently aligns with some of the pedagogical goals of constructivist learning environments such as embedding learning in realistic contexts and providing opportunities to evaluate alternative solutions from multiple perspectives (Honebein, 1996).

The development of GC^2 provided an opportunity to investigate demonstrated student understanding of green chemistry with a large enrollment class. This new green chemistry curriculum provided a context to explore both the green chemistry ideas and beliefs students brought into the classroom as well as changes to their understanding of green chemistry after completing the laboratory course. A main goal of this project was to create assessment items that would allow students to demonstrate their understanding of green chemistry and related concepts, apply green chemistry principles to novel scenarios, and make decisions based on green chemistry practices.

Both free and fixed response items were developed to explore the depth and bread of student green chemistry knowledge (Figure 4.1). Two free response items were developed to explore students' holistic understanding of green chemistry and ability to make decisions between two competing processes and justify their choice from a green chemistry perspective. The free response items were intentionally designed to be open-ended to give students the opportunity to demonstrate any and all of their knowledge about green chemistry, which would help surface their prior 'green' knowledge and beliefs at the start of the course and illustrate in what ways normative green chemistry ideas were integrated into their understanding after completing GC^2. Several fixed response items were also developed to probe specific green chemistry concepts or to investigate how students applied green chemistry principles to novel scenarios. While these items were more constrained than the free response design, they did allow for efficient data collection and analysis for a large enrollment course. The fixed response items, while designed to probe targeted green chemistry concepts or principles, also provided a measure of the knowledge and beliefs that students brough into the course and if these understandings shifted after completing GC^2.

Additionally, most of these items were contextualized within real green chemistry scenarios or practices. For example, one free response item, which asked students to make a green chemistry decision, was designed to mimic an authentic practice of green chemistry: comparative analysis. Green chemistry frequently calls for comparative analysis between two or more

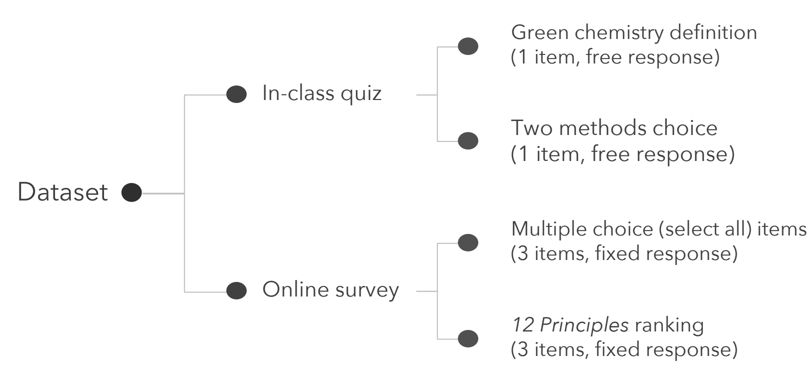


Figure 4.1. Overview of items used to assess student understanding of green chemistry during the Fall 2018 and Fall 2019 semesters. All items were administered at the start (pretest) and end (posttest) of the course.

alternatives where there is a range of appropriate green chemistry solutions (Andraos & Dicks, 2012). Authentic green chemistry questions and research require optimizations and tradeoffs (DeHaan, 2009; Kitchens et al., 2006) and often the appropriate solution(s) is (are) constantly evolving (Andraos & Dicks, 2012). Thus, these assessment questions were designed without a single 'correct' answer in mind but rather as opportunities to allow students to demonstrate their green chemistry knowledge and decision-making abilities and indicate which parts of green chemistry they deemed most relevant or valuable.

Research Questions

This research focuses on exploring the ways in which students understand and use green chemistry, both before and after they complete a green chemistry focused laboratory course:

1. In what ways do students' abilities to ***define and use*** green chemistry change after completing a general chemistry green chemistry (GC^2) laboratory course?

2. In what ways do these changes differ based on a student's ***background*** (gender, first-generations status, underrepresented minority status) and/or ***prior chemistry or green chemistry experience***?

This work contributes to the body of literature around green chemistry assessment by documenting the complexity of students' understanding of green chemistry and how different facets of student knowledge can be observed depending on item design and context. Additionally, this work illustrates areas of student green chemistry learning that are well served by GC^2 as well as areas that could be better supported in the future.

Methods

Research Context

General chemistry at UC Berkeley

This research took place within a general chemistry laboratory course for non-chemistry majors (Chem 1AL) at UC Berkeley for the Fall 2018 and Fall 2019 semesters. Chem 1A/L is divided into a lecture (Chem 1A) and laboratory (Chem 1AL) course with separate instructors. Most students take the two courses simultaneously, but students can complete the courses sequentially as the courses are offered every semester. Chem 1AL includes a 1-hour laboratory lecture (taught by the course instructor), a 3-hour laboratory section (taught by a graduate teaching assistant) each week, and an end of term written lab exam. Chem 1AL has an enrollment of approximately 1200 students each Fall semester.

General Chemistry Green Curriculum (GC^2)

The General Chemistry Green Curriculum (GC^2) was used during the Fall 2018 and Fall 2019 semester for Chem 1AL. GC^2 used a consistent set of general chemistry experiments (Table 3.1) developed between 2008-2013 with an explicit green chemistry curriculum as described in detail in the previous chapter (Chapter 3).

Participants

Participants in this study were general chemistry students in Chem 1AL during the Fall 2018 and Fall 2019 semesters. The research was approved by the university's Institutional Review Board (Protocol ID 2012-09-4666), and all student participants consented to participate. Consent rates were high with more than 90% of students consenting to be part of the study (Table 3.2). Each student was assigned a pseudonym to report any specific examples or findings.

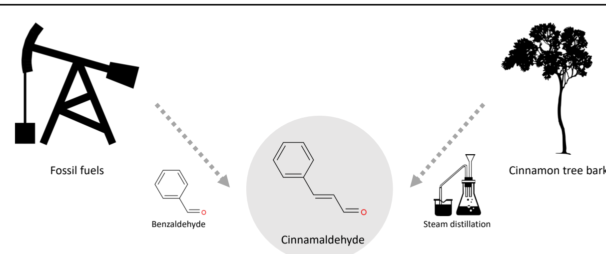
Description of Items

In-class Green Chemistry Quiz

An in-class green chemistry quiz with two free response green chemistry items was used to probe student understanding of green chemistry. The first item on this quiz asked students to define green chemistry in their own words and had been administered for many semesters previous to this research (see Chapter 2 and Armstrong et al., 2019). The second green chemistry item was iteratively developed over the Fall 2018 to Fall 2019 semesters. Initially, this quiz had four items: the first item asked students for a definition of green chemistry, the second and third items asked students to consider what information they would need to determine if a compound was safe for humans and the environment, and the fourth and final question asked students to choose a method for synthesizing a new compound from a green chemistry perspective. These latter three questions were developed to allow students to build and extend upon their definition of green chemistry – allowing them to not only describe green chemistry but to also begin analyzing chemical systems/processes from a green chemistry framework.

However, based on student responses from Fall 2018 it was clear revisions were needed for these three new items. Student responses to the middle two items were vague or repeated information already covered in their definition of green chemistry. Additionally, students were only given 10 minutes to answer all four questions, which potentially led to rushed responses especially for the latter items. Thus, for the Fall 2019 semester the middle two items were removed from the quiz leaving only the two items presented in Table 4.1. Additionally, the scenario used for the second question, titled *Two Methods Choice,* was significantly streamlined to reduce time spent reading and potentially distracting information. Since these questions were potentially memorable, an explicit explanation for re-administering these items was included for the posttest (Appendix IV).

Table 4.1. In-class quiz items administered during the Fall 2018 (green chemistry definition item only) and Fall 2019 (both items) semesters. Students were asked to make it clear if they didn't know how to answer an item by saying "I don't know but my guess is…".

Item Name	Item Prompt
Green chemistry definition	In my own words, green chemistry means:
Two methods choice	The fall season typically brings an increased demand for pumpkin spice flavored… everything! For large scale production it's hard to get consistent flavors using natural spices. It's much easier to use synthesized flavor molecules like eugenol for clove, zingiberene for ginger, and cinnamaldehyde for cinnamon.  There are several different ways of making cinnamaldehyde, two of which are shown above. From a green chemistry perspective, why would one method be preferable to the other? Be as specific as possible.

Student Survey

Online pretest and posttest surveys were used to administer the seven fixed response green chemistry multiple choice and ranking items used for this research (Fall 2019 semester) and collect demographic information from respondents (Fall 2018 and Fall 2019 semesters). Initially, five multiple choice (select all that apply) items and six 'ranking' green chemistry scenario items were piloted during the posttest survey for the Spring 2019 semester. The green chemistry scenarios for the ranking items were taken from past Presidential Green Chemistry Challenge winners (American Chemical Society, 2013; *Examples of Green Chemistry and Sustainable Chemistry*, 2021; US EPA, 2013). Students who completed this survey were randomly assigned half of these items to collect student response data without greatly increasing survey length. Based on student responses and expert feedback, four multiple choice items and three ranking items were selected for the Fall 2019 semester. Think alouds were conducted with two additional lower division students for these selected items to check response process clarity. Ultimately, four multiple choice items and all three ranking items (Table 4.3) were administered during the Fall 2019 semester. After reviewing the resulting student responses from Fall 2019 with additional researchers, one multiple choice item was dropped from the final analysis due to expert confusion over the item prompt and choices. Thus, three multiple choice items and three ranking items were used for the final analysis (Table 4.2).

The surveys used to administer the multiple choice and ranking items also covered additional topics including self-reported understanding of green chemistry and chemistry knowledge, green chemistry and chemistry attitudes, behaviors related to green chemistry principles and practices, and course feedback – as well as the multiple choice and ranking items used in this Chapter. Results from the self-reported green chemistry items were reported in Chapter 3. Appendix IV provides the full surveys used during the Fall 2019 semester.

Table 4.2. Multiple choice (select all that apply) survey items administered during the Fall 2019 semester on the online survey. Students were asked to answer these questions without outside help and to select ‘I don’t know’ instead of guessing if they did not know how to attempt or answer the question. The correct choice for each item can be found in Appendix VIII.

<table>
<tr><th>Item Prompt [Item Name]</th><th>Choices</th></tr>
<tr><td>[Select All #1: Atom Economy] The reaction below can be used to fill an automobile airbag.
<table>
<tr><td></td><td>$2NH_4NO_3(s)$
(ammonium nitrate)</td><td>→</td><td>$4\ H_2O(l)$
(water)</td><td>+</td><td>$2\ N_2(g)$
(nitrogen)</td><td>+</td><td>$O_2(g)$
(oxygen)</td></tr>
<tr><td>M.W.
(g/mol)</td><td>80.04</td><td></td><td>18.02</td><td></td><td>28.01</td><td></td><td>32.00</td></tr>
<tr><td>LD_{50}
(mg/kg in rats)</td><td>2217</td><td></td><td>>90,000</td><td></td><td>none available</td><td></td><td>none available</td></tr>
</table>
The atom economy for this reaction is 55%. This means that: (Select all that are accurate.)</td><td>☐ 45% of the starting material ends up as waste in the form of water
☐ 55% of the starting material ends up as waste in the form of water
☐ 55% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag
☐ 45% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag
☐ The theoretical yield of the reaction is 55%.
☐ The theoretical yield of the reaction is 45%.
☐ I don't know.</td></tr>
<tr><td>[Select All #2: LD_{50}] The reaction below can be used to fill an automobile airbag.
<table>
<tr><td></td><td>$2NH_4NO_3(s)$
(ammonium nitrate)</td><td>→</td><td>$4\ H_2O(l)$
(water)</td><td>+</td><td>$2\ N_2(g)$
(nitrogen)</td><td>+</td><td>$O_2(g)$
(oxygen)</td></tr>
<tr><td>M.W.
(g/mol)</td><td>80.04</td><td></td><td>18.02</td><td></td><td>28.01</td><td></td><td>32.00</td></tr>
<tr><td>LD_{50}
(mg/kg in rats)</td><td>2217</td><td></td><td>>90,000</td><td></td><td>none available</td><td></td><td>none available</td></tr>
</table>
The LD50 for the starting material, ammonium nitrate, is shown above. LD50 tells you:
(Select all statements that are accurate.)</td><td>☐ The amount of a chemical that it takes to cause death in half the members of a test population
☐ The amount of a chemical that it takes to cause mutations in an entire test population
☐ The amount of a chemical that it takes to cause bioaccumulation in half the members of a test population
☐ The amount of a chemical that it takes to cause endocrine disruption in an entire test population
☐ The amount of a chemical that it takes to cause birth defects in half the members of a test population
☐ The amount of a chemical that it takes to cause cancer in an entire test population
☐ I don’t know.</td></tr>
<tr><td>[Select All #3: Natural vs Renewable] Over the last few years, there has been an increased demand for natural and/or renewable resources. Please select all of the following statements that are true.</td><td>☐ Natural products are sustainable.
☐ Renewable products are sustainable.
☐ The terms “natural” and “renewable” are interchangeable.
☐ Natural products are likely to be safe for humans and the environment.
☐ Renewable products are likely to be safe for humans and the environment.
☐ Natural products or processes are always preferable to synthetic ones.
☐ Renewable products or processes are always preferable to synthetic ones.
☐ I don't know.</td></tr>
</table>

Table 4.3. 12 Principles ranking items administered during the Fall 2019 semester on the online survey. For each question, students were asked to choose the top three green chemistry principles that applied to each scenario and to order them from most (1) to least (3) applicable to the scenario. If they did not know the answer they were asked to select 'I don't know.' The online browser and mobile layout of these items is shown in Appendix IV. The correct choice for each item can be found in Appendix VIII.

<table>
<tr><th>Item Prompt [Item Name]</th><th>Choices (same for all questions)</th></tr>
<tr><td>[12 Principles #1] Traditionally, paper has been bleached with chlorine to give it a white appearance. Chlorine and its derivatives (such as chlorine dioxide) are very dangerous for humans and toxic to aquatic organisms. Eliminating the use of chlorine in paper production is an example of which green chemistry principle(s)?</td><td rowspan="3">▢ Prevention
▢ Atom Economy
▢ Less Hazardous Chemical Syntheses
▢ Designing Safer Chemicals
▢ Safer Solvents and Auxiliaries
▢ Design for Energy Efficiency
▢ Use of Renewable Feedstocks
▢ Reduce Derivatives
▢ Catalysis
▢ Design for Degradation
▢ Real-time Analysis for Pollution Prevention
▢ Inherently Safer Chemistry for Accident Prevention
▢ I don't know</td></tr>
<tr><td>[12 Principles #2] BASF (the largest chemical producer in the world) is currently developing plastic bags made partly from cassava starch and calcium carbonate. These bags completely disintegrate into water, CO2, and biomass in industrial and city composting systems. These bags are examples of which green chemistry principle(s)?</td></tr>
<tr><td>[12 Principles #3] Oil-based "alkyd" paints emit high levels of volatile organic compounds (VOCs). As the name suggests, VOCs evaporate from drying paint and can produce many harmful health effects (ranging from eye irritation to liver damage to cancer). Sherwin-Williams won the 2011 Presidential Green Chemistry Challenge Award for the development of low-VOC, water-based paints that are made from recycled plastic bottles and soybean oil. This new paint formulation is an example of which green chemistry principle(s)?</td></tr>
</table>

Administration of Items

In-Class Green Chemistry Quiz

Students completed an in-class green chemistry assignment at the *beginning* and *end* of the Fall 2018 and 2019 semesters (Table 4.1). Students were given 10 minutes to complete this written assignment during the first and last laboratory sections of the semester. Standardized instructions were given to each graduate teaching assistant for the administration of the quiz in their laboratory section (Appendix IV). Students were advised that this assignment would be graded based only on effort and that if they did not know how to answer a question, they should state "I don't know but my best guess is…." Students were also asked to not discuss this quiz with other students in the course so students in later laboratory sections wouldn't try to prepare for this quiz. Nearly every student enrolled in the course completed these quizzes;

additionally, the in-class administration allowed for student responses to be collected without access to search engines or other outside resources.

Student Survey

Students completed the multiple choice (select all that apply) (Table 4.2) and *12 Principles* ranking items (Table 4.3) at the *beginning* and *end* of the Fall 2019 semesters through an online Qualtrics survey. The link to the survey was distributed through a personalized bCourses announcement through the course site. The course instructor was also asked to announce the survey during their lectures if possible. Two reminder announcements were posted for each survey – one several days before the due date and one the day the survey was due. The respondents had between 7 – 10 days to complete the survey.

The pretest survey was administered during the first two weeks of the semester and the posttest survey was administered during the last two weeks of the semester. All respondents received course bonus points for completing the online survey. If students did not want to complete the survey but still wanted to receive the course bonus points, they could instead write a one-page essay on a recent green chemistry innovation.

Analysis of Items

All item results were considered significant at the 95% level. Respondents who did not consent to participate in the research study were dropped from the dataset. Respondents who did not complete both quizzes (pretest and posttest) or did not provide demographic information were also dropped from the dataset leading 636 respondents for the Fall 2018 semester and 615 respondents for the Fall 2019 semester. All analyses were completed using StataSE 14.2 and Python 3.9.

In-Class Green Chemistry Quiz

Green chemistry definition item. Responses to the *Green Chemistry Definition* item (Table 4.1) were analyzed using a rubric developed for a previous study for this same item (Chapter 2, Armstrong et al., 2019). During the Fall 2016 semester, this green chemistry definition item was administered to students through an in-class pretest and posttest quiz. Qualitative coding of those responses led to the development of a coding scheme that included categories for minimizing hazards, minimizing waste, energy, material lifecycle, research and development, green chemistry philosophy, and buzzwords (words or phrases that students used that were not connected to actual green chemistry content). The inclusion and exclusion criteria for each category were revised and clarified through additional coding by the two lead researchers for the Fall 2016 dataset. This process was repeated until no more changes to the codebook were produced. This finalized coding scheme (shown in Appendix VII) was then used to code the Fall 2018 and Fall 2019 responses to this item. The same researcher who had co-developed the coding scheme and coded the previous Fall 2016 set of responses also coded these Fall 2018 and Fall 2019 responses. Any responses that were ambiguous to this individual researcher were flagged and discussed with the second researcher who had also developed the original rubric for this item.

A total item score was assigned to each response by summing the individual coding categories as seen in Chapter 2 and Armstrong et al. (2019). A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 point plus 1 point for each specific green chemistry category present in the response. Thus, a response that only mentioned "green buzzwords" received a score of 1 while a response that discussed reducing chemical hazards and laboratory waste would receive a score of 3. Additionally, two more summative scores were calculated for 1) the total number of green chemistry components mentioned (minimizing hazards, minimizing waste, material lifecycle, energy/catalysis) and 2) the number of holistic categories mentioned (green chemistry philosophy, *12 Principles*, multiple reaction components, research and innovation). McNemar's test for paired dichotomous data was used to compare the pretest and posttest proportions for each coding category. A paired two-sample t-test was used to compare the mean pretest and posttest total item scores. Wilcoxon signed-rank tests were used to compare the median pretest and posttest ranks for the *holistic* and *component* scores.

Two methods choice item. A randomized sample of thirty student responses to the *Two Methods Choice* question (Table 4.1) were qualitatively coded and four emergent themes arose: renewability, minimizing hazards, energy, and waste. The *minimizing hazards* theme was split into two categories: harmful byproducts and hazardous reactants. This coding scheme was applied to 20% of the total student responses and discussed with additional researchers. The themes were additionally divided into "supported" and "unsupported" categories to document responses that simply stated or mentioned certain green chemistry principles and those that explained, justified, and/or applied the principle. If an incorrect assumption or statement was made, the response was still coded into their appropriate "unsupported" category to capture what green chemistry principles the student prioritized in their responses (Table 4.4).

Table 4.4. Examples of supported and unsupported responses for several common rubric categories

Category	Unsupported Response	Supported Response
Renewability	*"The best way would be via cinnamon tree barks as it is a renewable method."*	*"Cinnamon trees can be planted making them less scarce than fossil fuels which cannot be regenerated."*
Harmful byproducts	*"I would choose the method based on….whether it produces toxic byproducts"*	*"Look at the toxicity of the byproducts….check CO_2 emissions for each method."*
Less waste/waste disposal	*"I'd see if there are a lot of waste or byproducts by each method."*	*"I think the best method to use for making cinnamaldehyde would be the method that creates less trash and pollution to begin with this is important because it is easier to create less trash in the first place, then clean it up after."*

After coding through the initial 20% responses, two new themes emerged: *Sustainable Systems* and *Amount of Material*. *Sustainable Systems* was distinct from but aligned with the *12 principles* of green chemistry. These responses demonstrated a holistic and systems thinking approach to green chemistry, focusing on topics beyond the immediate laboratory or about the extent and magnitude of choices made in the laboratory. This broad category encompassed topics such as life cycle analysis, ethical considerations with respect to environmental issues, habitat/ecosystem impact, human health and safety, and practices utilized in extraction/production of raw materials.

The category *Amount of Material* was added because many students would make statements about the amount of material involved in either of the two methods without tying the physical amount to other categories, such as hazards, waste, renewability, yield, or any of the other categories. For example, the statement *"Steam distillation minimizes the use of external chemicals"* would be coded into this category because the statement paints the use of external chemicals in a negative light but doesn't tie the use of extra materials to green chemistry principles like hazards or waste. This category captures many students that understand that the amount of material used or produced (as byproducts) is important when considering green chemistry but did not articulate why it is important. Finally, categories such as *yield* and *atom economy* were added as many students included these topics in their responses but did so without explanation or evidence to support their claims. A final category was also added to capture the responses that implied or assumed that benzaldehyde (an intermediary for one method) was a toxic or harmful substance.

Using this new coding scheme, two researchers independently coded an additional set of student responses and discussed their results to achieve 100% agreement. The inclusion and exclusion criteria were revised based on these results. This process was repeated until no additional changes to the codebook were produced. The remaining student responses were divided and independently coded by a researcher. Any unexpected responses were discussed by both researchers until consensus was reached. If consensus could not be reached a third researcher was brought in to break ties.

A total item score was assigned to each response by summing the individual coding categories. A blank or off-topic/incorrect response received a score of 0. All other responses received a score of 1 point plus 1 point for each unsupported green chemistry category and plus 2 points for each supported green chemistry category present in the response. Additionally, breadth and depth scores were created to capture 1) the number of green chemistry components mentioned (total breadth score) and 2) the number of times a response provided a justification for including a green chemistry component (total depth score). The breadth score was simply the sum of all green chemistry components (*renewability, hazardous byproducts, hazardous reactants, reducing waste, economics, yield, atom economy, amount of material*) present in a response regardless of it they were supported or unsupported. The depth category was a sum of *only* the supported coding categories (*supported renewability, supported hazardous byproducts, supported hazardous reactants, supported reducing waste, supported economics, supported sustainable systems)* present in a response. This summative score was designed to capture if students provided a justification for including a particular normative green chemistry component. McNemar's test for paired dichotomous data was used to compare the pretest and posttest proportions for each coding category. A paired two-sample t-test was used to compare the mean pretest and posttest total item scores. Wilcoxon signed-rank tests were used to compare the median pretest and posttest ranks for the *breadth* and *depth* scores.

Student Survey

Multiple choice (select all that apply) items. Of the 615 respondents that completed both in-class quizzes and answered demographic questions 537 also completed all the pretest and posttest multiple choice (select all that apply) items. Respondents that completed the survey multiple times were dropped from the dataset for a final total of 508 respondents.

These *select all* green chemistry items (Table 4.2) were analyzed for correct, incomplete correct, partially correct, incorrect, and "I don't know" (IDK) responses (Table 4.5). These categories were used to visualize shifts in student response patterns from the pretest to the posttest. Students were also assigned a numeric score that considered the balance of correct, incorrect, and IDK choices selected (Appendix VIII shows the incorrect and correct choices for each item). Formula scoring (Ravesloot et al., 2015) was used to calculate the total score for each item; formula scores were created by centering IDK choices at score of zero and then subtracting one point for each wrong choice and adding one point for each correct choice to create the total score.

Table 4.5. Categorization rubric for 'select all' multiple choice items

Category	Definition
Full correct	Respondent selects **all** correct choices and **no** incorrect choices
Incomplete correct	Respondent selects **only** correct choices but **not all** of the correct choices; no incorrect choices are selected
Partially correct	Respondent selects a **mixture of correct and incorrect** choices; the number of correct choices selected is greater than the number of incorrect choices selected
Incorrect	Respondent selects **more incorrect** choices than correct choices or selects **only incorrect** choices
I don't know	Respondent selects the "I don't know" choice

The inclusion of an IDK option can impact construct validity and reliability (Cecilio-Fernandes et al., 2017; Muijtjens et al., 1999; Ravesloot et al., 2015) as IDK options may not only measure knowledge level but also risk-taking tendency, which is influenced by gender and personality traits (Budescu & Bar-Hillel, 1993; Byrnes et al., 1999; Kelly & Dennick, 2009; Ravesloot et al., 2015). However, including an IDK option is thought to reduce random error by minimizing guessing, which leads to higher internal consistency and thus reliability (Burton, 2004). An IDK option was included on these survey items because the threat to construct validity was hypothesized to be reduced due to the context of these items. There was no penalty nor benefit to the student for getting an item correct or incorrect; they received bonus points for simply completing the survey. They were also explicitly instructed to choose the IDK option instead of trying to guess an answer, which hopefully reduced differences due to gender and personality. Additionally, it was thought the IDK option would stop students from trying to use outside resources to find the 'correct' answer for these online survey items as the IDK option made it explicit that they were not expected to be knowledgeable about all these items (especially for the pretest survey).

The means and standard deviations for the pretest and posttest were calculated and Wilcoxon signed-rank tests were used to compare the median pretest and posttest ranks for each item.

***12 Principles* ranking items.** Of the 615 respondents that completed both in-class quizzes and answered demographic questions 546 of them also completed all the pretest and posttest *12 Principles* ranking items. To maintain consistency in the dataset, students who did not rank at least three principles were removed from the data set. Students who ranked more than three principles were kept in the data set, but any rankings beyond their top three were ignored from the dataset. Respondents that completed the survey multiple times were dropped from the dataset for a final total of 522 respondents.

To visualize shifts in the overall popularity of the principles from the pretest to the posttest, each principle was given a weighted frequency based on both the frequency at which it was ranked in the top three and its order within the top three. The order the principle was ranked was used to give it a value or "weight." Ranking a principle in the top position (#1) resulted in the highest "weight" of 3 while ranking a principle in the lowest position (#3) resulted in a "weight" of 1. The weighted frequency for each principle was then calculated based on these weighted values, for however many times the principle had been ranked within the top three for the entire respondent population.

Additionally, each individual response was assigned a number right and a modified formula score. The number right score was simply a count of the number of correct principles ranked in the top three for each student response (Appendix VIII shows the relevant principles for each item). The modified formula score (Figure 4.2) was constructed by first centering IDK choices at a score of zero. Incorrect principles ranked within the top three resulted in the subtraction of one point while correct principles ranked within the top three resulted in the addition of one point to the modified formula score for each item. Additionally, correct principles were further subdivided into implicitly and explicitly correct categories for the modified formula score. Explicitly correct principles were identified as the most relevant principles that clearly applied to the given green chemistry scenario. Implicitly correct principles were tangentially related to the given scenario and/or would only apply if certain preconditions or assumptions were met. Thus, if an explicitely correct principles was ranked within the top three it would result in the addition of two points to the total score, while implicitely correct principles would results in the addition of only one point. Additionally, if an explicitly correct principle was ranked in the top position, it would receive an additional 'bonus' point. For example, if an item had one explicitly correct principle, then if that one principle was ranked first (position #1) it would result in an additional 'bonus' point; if an item had two explicitly correct principles, then if either of those two principles were ranked first *or* second it would result in an additional 'bonus' point, etc.

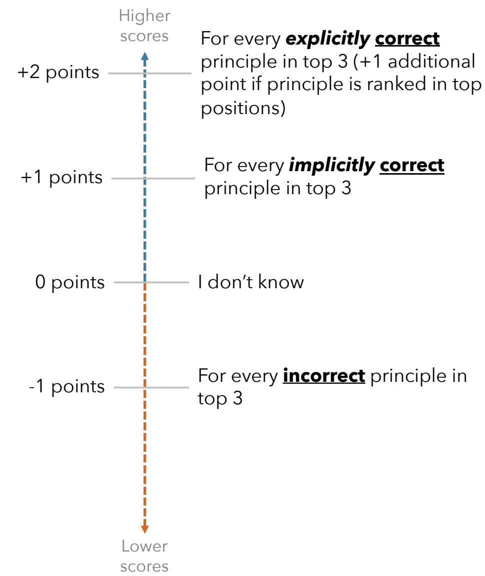


Figure 4.2. Modified formula scoring for *12 Principles* ranking items. Explicitly correct principles clearly applied to the given scenario. Implicitely correct principles were less relevant to the given scenario or would apply only if certain preconditions or assumptions were met.

The means and standard deviations for the pretest and posttest were calculated. Wilcoxon signed-rank tests were used to compare the median pretest and posttest ranks for each item.

Overall Data Analysis

Initial Green Chemistry Performance

The two free response items were further analyzed to see if there were differences in student performance gains based on initial green chemistry performance. These two items were chosen for this more detailed analysis since their open-ended design provided a more comprehensive picture of the (many) ways in which 1) students defined green chemistry and 2) made green chemistry decisions. Students could apply almost any green chemistry knowledge to these two items giving a more robust measure of the breadth and depth of their green chemistry ideas, values, and practices.

Students were divided into groups based on their initial performance on each of the two free response items (*Green Chemistry Definition* and *Two Methods Choice*). For each item, students were categorized as having "low initial green chemistry performance" if they had a total item score of 1 or lower and as having "high initial green chemistry performance" if they had a total item score of 2 or higher for that item. A total item score of 0 indicated a blank or off-topic/irrelevant response while a score of 1 indicated a correct but non-specific definition/answer for both of these items. A score of 2 or above indicated that the response included at least one green chemistry component. For each item, independent sample t-tests were used to compare the mean posttest total item scores of the low and high initial green chemistry performance groups to see if there were significant gaps in performance between these two initial performance groups after completing Chem 1AL.

Regression Analysis

Linear regression was used to investigate the association between student performance on the two in-class quiz items (*Green Chemistry Definition* and *Two Methods Choice*) and several explanatory variables (gender, first-generation college status, underrepresented minority (URM) status, prior green chemistry experience, or prior chemistry experience). These explanatory variables were generated from student responses to several items on the pretest survey and details on each explanatory and response variable can be found in Appendix IX.

For the *Green Chemistry Definition* item student responses across Fall 2018 and Fall 2019 were combined since the average pretest and posttest scores for each rubric category were very close or followed similar pre/post gain patterns across both semesters. This gave a total set of 1203 complete student responses for this item. For the *Two Methods Choice* item students responses from Fall 2019 were used for a set of 593 complete student responses. For both items, respondents with missing values for any variable were dropped from the dataset.

Regression models were created to explore two different response variables for each item: student pretest total item scores and student 'gain' scores (change in total item score from pretest to posttest). The pretest score response variable was used to investigate the green chemistry understanding that students brought into the course and how that might differ based on background and prior chemistry/green chemistry experience. The 'gain' scores response variable was used to investigate the ways students' knowledge about green chemistry changed after completing Chem 1AL. This resulted in the four regression models outlined in Table 4.6 below.

Regression diagnostics were then performed to validate the use of the multiple linear regression model (Appendix IX). No collinearity was found between the predictors (the variance inflation factor (VIF) was less than 1.1 for all variables with a mean VIF of 1.04). However, the studentized deleted residuals did not appear to be normally distributed for any of the models and the spread of the residuals was not constant suggesting some heteroscedasticity. Thus, multiple linear regression with robust standard errors was used to create all final regression models.

Table 4.6. Regression models for two in-class green chemistry quiz items

Green Chemistry Definition	
Model 1 (Pretest)	**Model 2 (Gains)**
Total pretest score was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience.	**Gain score (posttest total score – pretest total score)** was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience.

Two Methods Choice	
Model 1 (Pretest)	**Model 2 (Gains)**
Total pretest score was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience.	**Gain score (posttest total score – pretest total score)** was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience.

Results: Item analysis

Course Demographics. Chem 1AL is the first semester general chemistry laboratory course at UC Berkeley and is typically taken by incoming non-chemistry majors. Students in Chem 1AL have diverse backgrounds and prior chemistry experience. The students in this study encompassed a wide range of intended majors including, but not limited to, life sciences, bioengineering, nutrition science, public health, environmental science, and civil engineering. The majority (73% for Fall 2018 and 68% for Fall 2019) of students had at least one parent with a four-year degree and nearly 50% have a parent with a graduate degree. Nearly every student had taken at least one semester of chemistry prior to their entry into the university with, on average, having completed three prior semesters of chemistry. About half of the students had completed two semesters and ~40% had completed four or more semesters of chemistry before entering Chem 1AL. More than half of the students had taken honors chemistry (60%) and/or AP chemistry (48%). The course had more female (65%) than male (35%) students, which is typical. Most students were of Asian descent (~57%) with White (~26%), Latinx (~12%) and African American (~1%) students comprising the remainder of the class. Detailed demographic data are presented in Appendix II.

Green Chemistry Definition

An open-ended *Green Chemistry Definition* item (Table 4.1) was used to explore how students conceptualized green chemistry as a discipline and/or as a framework for practicing chemistry. The open-ended structure of this question gave students the opportunity to demonstrate any and all of their knowledge about green chemistry and did not necessitate prior chemistry knowledge. This was important since students entered Chem 1AL with a wide range of prior chemistry experience and may or may not have ever heard of green chemistry prior to this course.

Full Class Analysis

Student responses to this item were first analyzed for correctness, guessing, only mentioning "buzzwords", and mentioning terms related to the environment for both the Fall 2018 and Fall 2019 semesters (Figure 4.3). "Buzzwords" were defined as colloquial 'green-aligned' terms students may have heard in their daily life, such as "sustainability" or "efficiency", and mentions of the environment often took the form of "environmental friendliness", "eco-friendly" or "less harm to the environment." Additionally, students were encouraged in the question text to make it clear if they were guessing about what green chemistry meant, which provided a measure for their confidence in understanding green chemistry.

Similar trends were seen across both semesters with, on average, a decrease in guessing, incorrect responses, and buzzword only responses by the end of the semester. Mentions of environmentally aligned terms did not change appreciably between the pre and posttest for either semester with approximately 78% of responses containing these phrases. An exact McNemar's test determined that there was not a statistically significant difference in the proportion of students who were coded into this category pre- and post-course ($N_{Fall19} = 615$, $p_{Fall19} = 0.551$; $N_{Fall18} = 636$, $p_{Fall18} = 0.387$). This stasis was expected since there is nothing inherently wrong with mentioning the environment when defining green chemistry. In fact, many popular definitions of green chemistry contain references to the environment including one such definition by the "father of green chemistry" Paul Anastas (2011): "*Green chemistry requires looking across systems and across life cycles to design products and processes that are* ***benign*** *to both* ***people*** *and the* ***environment****.*" What is important and interesting is how students connect and integrate these environmental terms with other normative green chemistry ideas and practices.

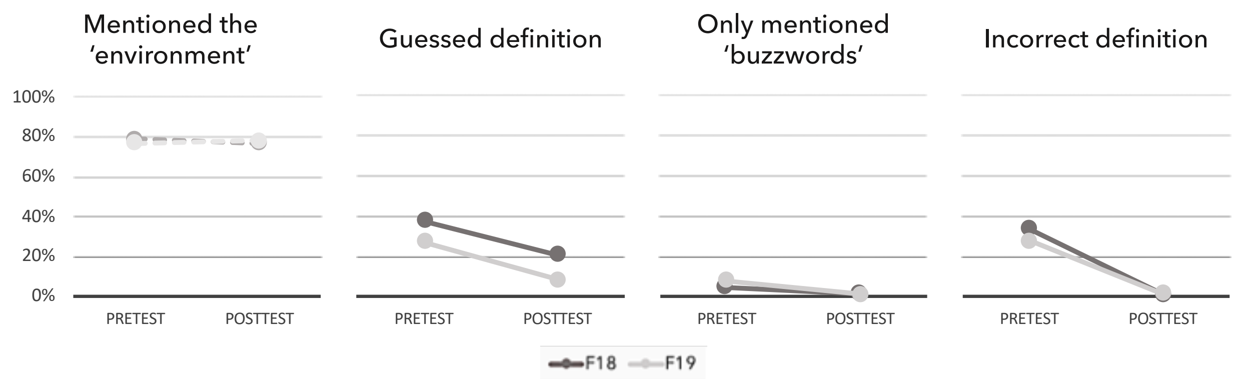


Figure 4.3. Percentage of pretest and posttest response categories for the question "In your own words, define green chemistry" for the Fall 2018 and Fall 2019 semesters. Exact McNemar's tests showed there were significant differences in the proportion of students coded into each category pre and posttest except *mentions of the environment* (N_{F19} = 615, N_{F18} = 636). A solid line (–) represents a statistically significant difference in proportion and a dashed line (---) represents a non-significant difference in proportion from pretest to posttest.

Students not only made gains in confidence and correctness, but also showed an increased level of sophistication as they were able to identify and describe more components of green chemistry (e.g., reducing waste, minimizing hazards, material lifecycle considerations, energy use/catalysis) after completing Chem 1AL (Figure 4.4). Mei's paired pretest and posttest responses provided a relevant example of a student who began the semester with a very naïve understanding of green chemistry but then was able to connect her core environmental knowledge with many normative components of green chemistry by the end of the semester. At the start of the semester, Mei defined green chemistry using colloquial environmental language along with the idea that natural resources are superior to synthetic or, as Mei says "artificial", processes:

> *[Green chemistry is] [c]hemistry that takes into consideration the environmental impacts of any products or process included in experiments. Green Chemistry aims to create an understanding of the importance of the world's natural resources in a field that is normally seen as dealing with 'artificial' substances/processes.*

After completing the course, Mei's view of green chemistry still included the core idea that green chemistry should 'create a healthier world' but specifically linked normative green chemistry ideas to this framing giving it clear specificity and scope. Mei took a holistic view of green chemistry arguing that it applies in both industrial and research setting and ties waste prevention, renewable resources, energy efficiency, and reducing chemical hazards to the idea of true sustainability:

Ensuring that our chemical processes, whether industrial, experimental, or otherwise are part of a sustainable cycle. This means reducing and eliminating waste, using renewable sources and limiting the production of harmful byproducts. These are only a few green chemistry concepts that aim to create a healthier world that will last for generations to come. Energy efficiency also plays a role in green chemistry.

This shift towards specificity was seen globally as well as, in contrast to students' pre-course responses of which approximately 40% were incorrect or only mentioned buzzwords, student's post-course responses mentioned at least one specific component of green chemistry 82% of the time. Minimizing hazards and waste were the top two considerations with material lifecycle considerations and energy use/catalysis coming in third and fourth respectively. Using exact McNemar's tests showed that there was a statistically significant difference in the proportion of students who were coded into each category pre- and post-course ($N_{Fall19} = 615$, $p_{Fall19} < 0.001$; $N_{Fall18} = 636$, $p_{Fall18} < 0.001$).

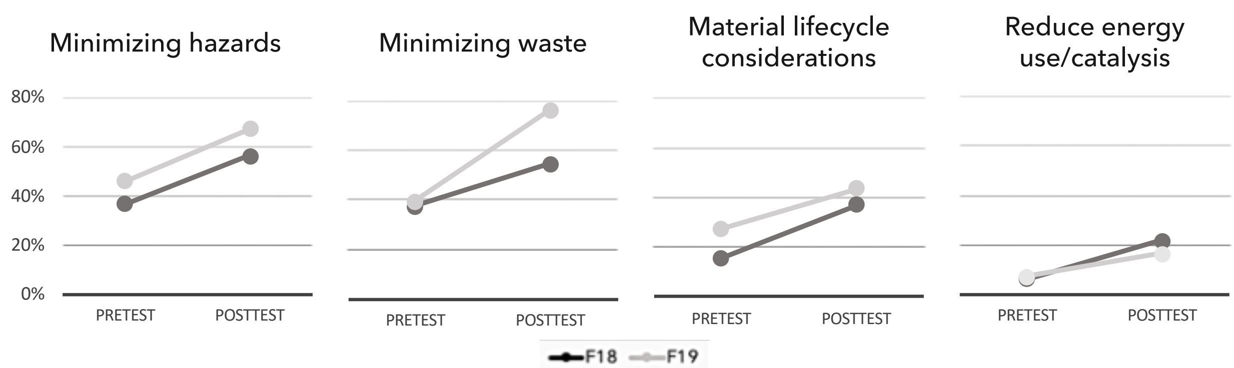


Figure 4.4. Percentage of pretest and posttest response categories for the question "In your own words, define green chemistry" for the Fall 2018 and Fall 2019 semesters. Exact McNemar's tests showed there were significant differences in the proportion of students coded into each category pre and posttest ($N_{F19} = 615$, $p < 0.001$; $N_{F18} = 636$, $p < 0.001$). A solid line (–) represents a statistically significant difference in proportion from pretest to posttest.

Students not only talked about common principles of green chemistry but also demonstrated an increased holistic or systems thinking (Constable et al., 2019; Dicks et al., 2019; Flynn et al., 2019; Hutchison, 2019) understanding of green chemistry (Figure 4.5).

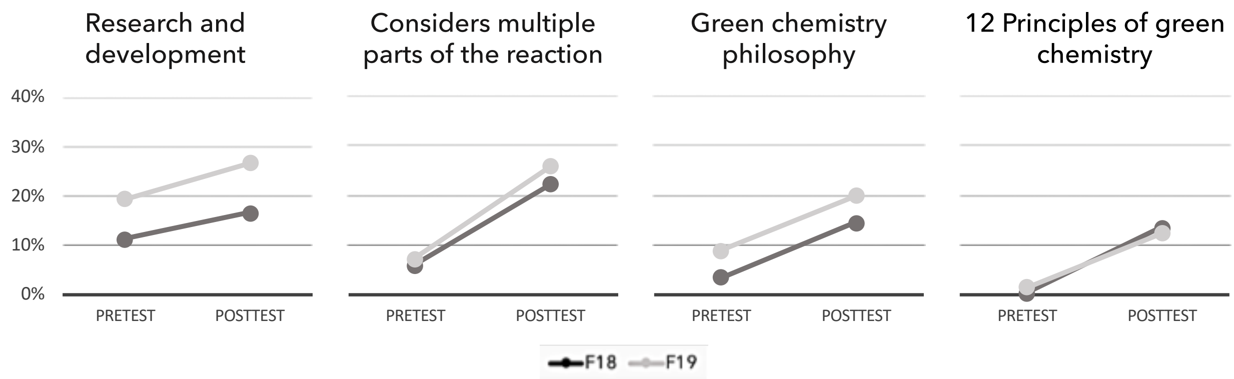


Figure 4.5. Percentage of pretest and posttest response categories for the question "In your own words, define green chemistry" for the Fall 2018 and Fall 2019 semesters. Exact McNemar's tests showed there were significant differences in the proportion of students coded into each category pre and posttest (N_{F19} = 615, $p < 0.001$, N_{F18} = 636, $p < 0.005$). A solid line (–) represents a statistically significant difference in proportion from pretest to posttest.

Kristen included many of these holistic components in her definition of green chemistry at the end of the Fall 2019 semester. She first made explicit the many dimensions that green chemistry must speak to (the environment, human health, economics) and that these decisions occur along the entire lifecycle of a chemical process. She also brought specific green chemistry principles that target both the reaction process and resulting byproducts and recognized that every decision made within chemistry should be done with care and attention to the entire system it impacts:

> *Green chemistry means acknowledging the environmental, human, and economic consequences of any decisions made before, during, or after conducting chemistry. It means striving to create the most efficient reactions and mitigating byproducts, striving for renewable, reusable compounds to be used in experimental, industrial, and everyday practice, limiting toxicity to human health, and many other concepts, all united by this prospect of being cognizant of the effects of our decision in chemistry.*

Overall, at the start of the course, very few students understood that green chemistry strives to create new technologies, methods, and other innovations (*research and development*) but by the end of the course 17% (Fall 2018) and 27% (Fall 2019) of students were able make this connection. Similarly, at the start of the course less than 8% of student responses acknowledged that green chemistry targets all aspects of a chemical process (reactants, reaction, products/byproducts), but by the end of the semester 22% (Fall 2018) and 26% (Fall 2019) of student responses considered multiple components of the reaction. Additionally, after completing Chem 1AL, 14%

(Fall 2018) and 20% (Fall 2019) of students discussed how green chemistry is a philosophy for all chemistry – not just a niche topic – demonstrating a more nuanced understanding of green chemistry as a metadiscipline (Epicoco et al., 2014; Linthorst, 2009; Woodhouse & Breyman, 2005). Finally, at the beginning of the course, less than 1% of students explicitly mentioned the *12 Principles of Green Chemistry* (Anastas & Warner, 1998) in their definition, yet 62% of responses did implicitly mention one of these principles (defined by the presence of one or more of the categories in Figure 4.4). After completing the course, 14% (Fall 2018) and 12% (Fall 2019) of responses did explicitly mention this framework in their definition of green chemistry and 82% of responses implicitly mentioned one or more of these principles.

Overall Scores

Definitions of green chemistry can vary widely depending on, among other factors, the speaker's own positionality and familiarity with green chemistry and the intended audience's familiarity with green chemistry. No one definition was expected to include all the coding categories defined for this item as the coding scheme was developed to capture the breadth of categories that could be included in a definition. Nevertheless, it was still instructive to calculate summative categories for 1) the total number of green chemistry components mentioned (Figure 4.4), 2) the number of holistic categories mentioned (Figure 4.5), and 3) a total item score. A total item score was assigned to each student's responses by summing the individual coding categories. A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 plus 1 point for each specific or holistic green chemistry category present in the response.

The mean pretest total item score was 2.11 (Fall 2018) and 2.42 (Fall 2019) points indicating that, on average, students included one specific or holistic green chemistry category in their definition (Figure 4.6). By the end of the semester the mean total item score had increased significantly to 3.21 (Fall 2018) and 3.74 (Fall 2019). A paired-samples t-test was used to compare the mean student pretest and posttest total item scores for both semesters, which showed that there was a significant difference in mean total item scores between the pretest and posttest (Fall 2018: $t = 15.53$, $d.f.=635$, $p < 0.001$; Fall 2019: $t = 17.70$, $d.f. = 614$, $p < 0.001$). The difference in means between the pretest and posttest was estimated as 1.10 with a 95% confidence interval from 0.96 to 1.23 and 1.32 with a 95% confidence interval from 1.78 to 1.47 for Fall 2018 and Fall 2019 respectively. This shows that students were able to integrate, on average, over two (and nearly three for Fall 2019) specific or holistic green chemistry categories into their definition.

Similar results were seen for the holistic and component scores over both semesters. Posttest component and holistic scores were higher than pretest scores for both semesters. A Wilcoxon signed-rank test indicated that the median *component* posttest ranks were statistically significantly higher than the median pretest ranks for both semesters (Fall 2018: $Z = -12.08$, $p < 0.001$; Fall 2019: $Z = -13.88$, $p < 0.001$). Similarly, the median *holistic* posttest ranks were statistically significantly higher than the median pretest ranks for both semesters (Fall 2018: $Z = -9.93$, $p < 0.001$; Fall 2019: $Z = -9.60$, $p < 0.001$).

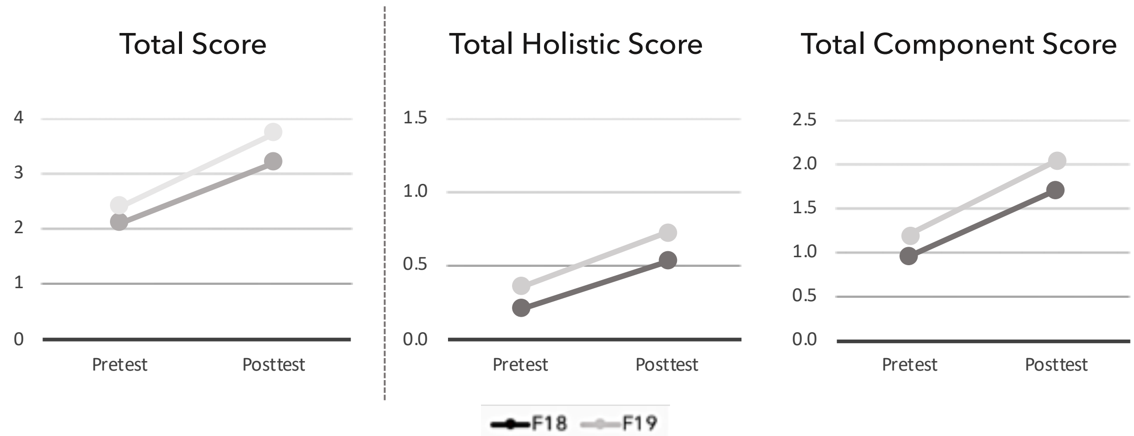


Figure 4.6. Total pretest and posttest summary scores for the question "In your own words, define green chemistry" for the Fall 2018 and Fall 2019 semesters. Paired t-tests (f the total score) and Wilcoxon signed-ranks test (total holistic and total component score) showed there were significant differences in the posttest and pretest scores for each category. A solid line (–) represents a statistically significant difference in pretest to posttest score.

What these scores indicate is that most pretest definitions used green-aligned terms or phrases but with minimal demonstrated understanding of those words/phrases. Students tended to integrate only one specific components of green chemistry into their definition and did not demonstrate a sophisticated understanding of systems thinking. In contrast, posttest definitions still had many green-aligned terms (e.g., buzzwords) but with the additional integration of green chemistry principles, examples, and explanations. Students also showed an increased holistic green chemistry perspective with detailed *12 Principles* callouts. Overall, students mostly believe that green chemistry is aligned with reducing hazards and waste and often bring in the idea of waste prevention instead of remediation. They see green chemistry as a way for doing chemistry and some students recognize the complex, innovative, and interconnected nature of green chemistry.

Two Methods Choice

The *Two Methods Choice* item was developed and piloted over the Fall 2018 and Spring 2019 semesters and administered in its final form on the in-class quiz during the Fall 2019 semester. This item was designed with a similar intent to the *Green Chemistry Definition* item as it was a broad scenario that would let students showcase any and all knowledge they held about green chemistry. This was especially important since this item was administered near the beginning of the semester when students could not be assumed to have prior green chemistry knowledge. However, in contrast to the previous definition item, *Two Methods Choice* was scenario-based and asked students to choose the 'greener' of two methods for making a common food-based product and to justify their choice (Table 4.1). While any green chemistry principle could have been used to support their choice, this question did naturally focus on the ideas of renewability and energy usage, which had only been infrequently mentioned when students defined green chemistry (Figure 4.4). This item did not simply ask for students to define a term but rather make a green chemistry decision and rationalize that decision.

Full Class Analysis

The *Two Methods Choice* item provided information on how students made a 'green' choice and the diverse reasoning that accompanied such a choice (Table 4.1). There was no one 'right' answer or subsequent justification for this question (as is so often the case with green chemistry decisions) and instead it was an opportunity for students to showcase the way in which they'd approach making a choice based on green chemistry principles. However, most students agreed that the method that used cinnamon tree bark as a starting material was the greener method with 92% of students choosing this method on the pretest and 95% choosing this method on the posttest. Only 6% of students chose the method that used fossil fuels as a precursor on the pretest and that percentage dropped to 3% on the posttest. The remaining 2% of students did not indicate which method they believed was greener.

Like the *Green Chemistry Definition* item, hazards and waste were popular considerations for choosing a greener method for making cinnamaldehyde (Figure 4.7). Nearly half of the responses mentioned concerns regarding hazardous byproducts on both the pretest (46%) and posttest (51%), hazardous reactants (9% on the pretest, 16% on the posttest), and/or waste (11% on the pretest, 21% on the posttest). Exact McNemar's tests showed that there was a statistically significant difference in the proportion of students who were coded into the reducing waste and hazardous reactants categories pre- and post-course ($N = 615$, $p < 0.001$).

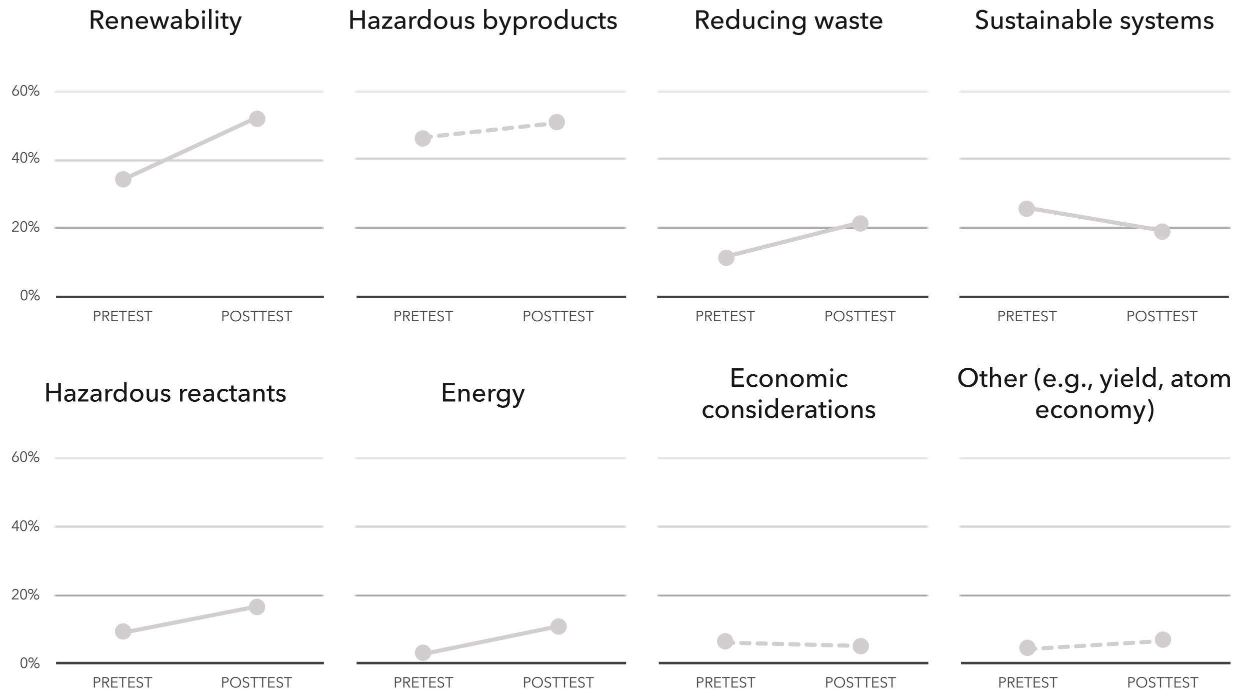


Figure 4.7. Percentage of pretest and posttest response categories for the Two Methods Choice question for the Fall 2019 semester. Exact McNemar's tests showed there were significant differences in the proportion of students coded into each category pre and posttest except for *hazardous byproducts*, *economic considerations*, and *other* (N = 615). A solid line (–) represents a statistically significant difference in proportion and a dashed line (---) represents a non-significant difference in proportion from pretest to posttest.

This item also surfaced different ideas from the previous *Green Chemistry Definition* item as renewability considerations became the most prominent posttest category and showed the most growth from pretest to posttest. Most of these responses focused on how cinnamaldehyde (the desired product) derived from cinnamon tree bark was potentially a renewable feedstock especially in comparison to the fossil fuel precursor method. Gregory expressed this reasoning in his explanation for choosing the cinnamon tree bark method making an explicit comparison along renewability lines between tree bark and fossil fuels. He also explicitly tied the idea of renewability to timescales stating that the timescale for fossil fuel regeneration was not feasible option:

> *Making pumpkin spice from cinnamon tree bark is preferable from making it from fossil fuels because trees are a renewable resource, while fossil fuels are a limited resource. We can always grow more cinnamon for more production of pumpkin spice, but we'd need to wait billions of years for more fossil fuels to be created.*

Overall, students recognized that renewability concerns were one of the most relevant green chemistry dimensions for justifying either method choice in this particular context since one method used fossil fuel precursors while the other uses a tree bark extraction. At the beginning of the semester 34% of students mentioned renewability considerations in their response, which increased to 52% of students by the end of the semester for an 18% increase.

While most categories increased or stayed constant from pretest to posttest, one category – *sustainable systems* – decreased significantly from pretest to posttest ($N = 615$, $p = 0.003$). *Sustainable systems* was a category that emerged from the initial coding of student responses. The original coding scheme for *Two Methods Choice* was based on the *12 Principles of Green Chemistry* using a similar categorization method as the *Green Chemistry Definition* coding scheme. However, it was quickly observed that many responses focused on specific aspects of sustainability or environmentalism that fell outside the traditional *12 Principles* language. Concerns about the environment had been a common but vague theme when students defined green chemistry. In contrast, in the *Two Methods Choice* responses, environmental concerns were much more detailed and contextualized within the actual scenario. For example, a response might focus on the potential harm that removing tree bark from a tree might cause – "*is the tree still able to survive and thrive*" after this process? Other examples of included land use and potential deforestation for the tree bark method. For example, Stephanie said that she would *"look at how each method produces the substance in terms of the amount of land…required to produce the molecule (i.e., if it diverts land from agriculture, requires deforestation to clear land for production…)"*.

The decrease seen for this category from pre to post-course wasn't completely unexpected since it was hypothesized that posttest responses would shift away from environmental ideas towards more normative green chemistry terms and principles as students would have just completed a course focused on those formalized ideas and practices. Indeed, the number of **supported** *sustainable systems* responses (i.e., those that provided a justification this idea) remained constant from pre to post-course at 4% while the number of **unsupported** *sustainable systems* responses decreased from 21% to 15%. Additionally, students who had initially included *sustainable systems* ideas in their pretest response but no longer included it in their posttest response tended to make larger gains in the number of normative green chemistry categories included in their posttest response compared to students who either never had included sustainable systems in their pretest response or still included it in their posttest response (Table 4.7).

Table 4.7. Change in number of normative green chemistry components from pretest to posttest for response groups that did or did not include a sustainable systems component. All groups had a median of 1 normative green chemistry component for the pretest.

***Sustainable Systems* present in response?**		**N**	**Change in # of normative green chemistry components from pretest to posttest**[a]	
Pretest	*Posttest*		*Median*	*Mean (st. dev.)*
No	No	385	0	0.48 (1.15)
No	Yes	72	0	0.22 (1.12)
Yes	**No**	**113**	**1**	**0.78 (1.40)**
Yes	Yes	45	0	0.36 (1.05)

[a] Normative components include renewability, hazardous byproducts and reactants, reducing waste, economics, and the 'other' coding categories

As with the *Green Chemistry Definition* item, students were asked to make it clear if they guessed on their response to this item (Figure 4.8). At the beginning of the semester, 27% of students said that their response to this question was a guess; by the end of the semester guessing had dropped to only 3% responses. Responses were coded for incorrectness which remained near 1% for both pretest and posttest responses. An additional category was added to capture students' assumptions around an intermediary (benzaldehyde) for the fossil fuel method. These responses asserted that benzaldehyde was unsafe or less safe compared to the alternative tree bark method's processes or materials without presenting any evidence or explanation for why that might be true (e.g., *"We would rather perform natural processes such as steam distillation rather than artificial synthesis with benzaldehyde."*). This category was not very common nor did it change significantly from pretest to the posttest but it did illustrate a potential, more universal issue, with how novice students (and the population in general) negatively perceive "chemical" sounding names especially in relation to food (Dickson-Spillmann et al., 2011; Moscato & Machin, 2018; Román et al., 2017).

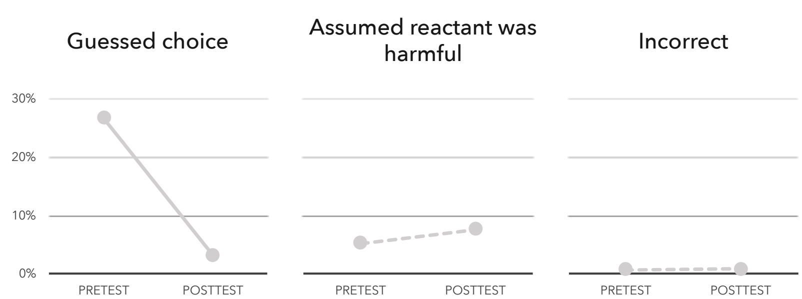


Figure 4.8. Percentage of pretest and posttest response categories for the Two Methods Choice question for the Fall 2019 semester. Exact McNemar's tests showed there was a significant difference in the proportion of students who said they *guessed* on their choice and justification from the pretest to the posttest (p <0.001, N = 615). A solid line (–) represents a statistically significant difference in proportion and a dashed line (---) represents a non-significant difference in proportion from pretest to posttest.

Overall Scores

Summative pretest and posttest scores were calculated for the *Two Methods Choice* question. While there was no one 'right' answer for this question the way students made their choice and subsequently supported it did vary in specificity and comprehensiveness. Three summative scores were calculated for this item: 1) the total number of green chemistry components mentioned (total breadth score), 2) the total number of times a response justified or supported a green chemistry component (total depth score), and 3) a total item score. For the total item score, a blank or off-topic/irrelevant response received a total item score of 0 while all other responses received a score of 1 point plus 1 point for each unsupported green chemistry component present in the response and plus 2 points for each supported green chemistry component present in the response.

The mean pre-course total item score was 3.09 points indicating that, on average, students included two normative green chemistry components in their response or one supported green chemistry component (Figure 4.9). By the end of the semester the mean total item score had increased significantly to 3.44. A paired-samples t-test was used to compare the mean student pre- and post-course total item scores, which showed that there was a significant difference in mean total item scores ($t = 4.22$, d.f. $= 614$, $p < 0.001$). The difference in means between the pre- and post-course scores was estimated as 0.35 with a 95% confidence interval from 0.19 to 0.51.

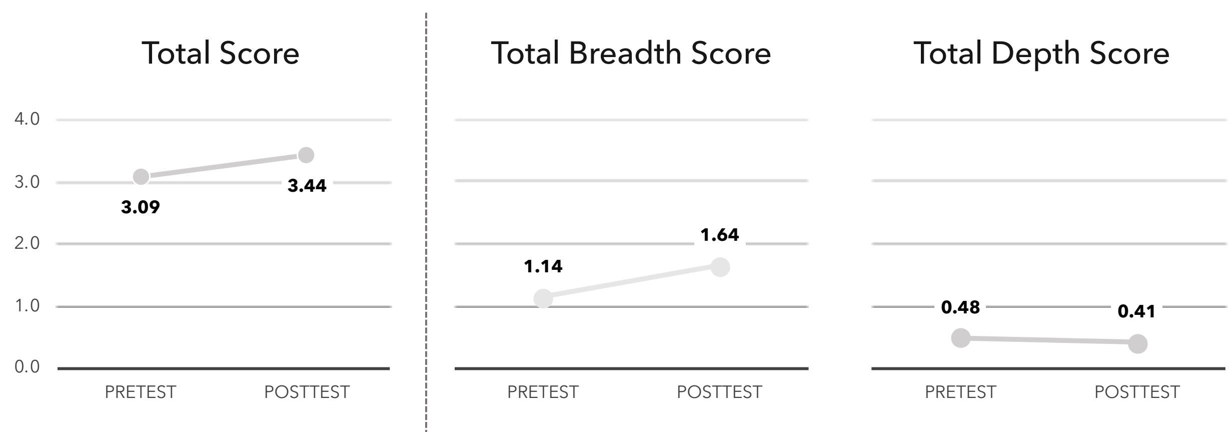


Figure 4.9. Total pretest and posttest summary scores for the Two Methods Choice for the Fall 2019 semester. Paired t-tests (for the total score) and Wilcoxon signed-ranks test (total holistic and total component score) showed there were significant differences in the posttest and pretest scores for each category. A solid line (–) represents a statistically significant difference in pretest to posttest score.

Similar results were seen for the breadth scores but not for the depth scores. On average, the post-course breadth score was higher than pre-course scores, but the depth score was, on average, lower on after the course. A Wilcoxon signed-rank test indicated that the median *breadth* post-course ranks were statistically significantly higher than the median pre-course ranks for both semesters ($Z = 9.13$, $p < 0.001$). However, the median *depth* post-course ranks were statistically significantly lower than the median pre-course ranks ($Z = -2.31$, $p = 0.02$).

Together, these scores indicated that the gains seen for the total post-course score come from an increase in the *breadth* of student responses but not in the *depth* of their justification for using certain green chemistry components to rationalize their method choice. While 89% of the post-course responses mentioned at least one specific green chemistry component (and 32% mentioned two, and 19% mentioned three or more components) only 34% of responses provide any justification for including one or more of those components. Most students tended to list the factors they consider important for making a green chemistry choice but didn't necessarily stop to provide evidence for the inclusion of those factors. For example, Brooke's response below mentions many green chemistry principles – often by name (reducing harmful byproducts, energy efficiency, renewable feedstocks, waste prevention, inherently safer chemistry) – but does not explain how or why these are important to know and/or simply asserts that these principles are better for her chosen method:

Steam distillation:

- *Doesn't produce greenhouse gases as a result of fossilization*
- *More energy efficient → requires less energy (i.e., heat, power) to obtain chemical*
- *Renewable feedstock - chemical compound obtained from cinnamon tree bark (nature) rather than drilling down to find it.*
- *Waste prevention - may not produce as much byproduct as fossil fuels would*
- *Inherent safe chemical process - the extraction process on cinnamon tree bark is safer than fossils.*

Interestingly, it appears that a shift occurred from pretest to posttest whereby responses began to favor *breadth* of response over *depth* of response. Ideally, these two ideas wouldn't be in competition but, since students only had limited time to complete this in-class quiz, there may have been tradeoff made in how they approached this item on the pretest versus the posttest. On the pretest, students may only have known a limited number of applicable ideas for making a green chemistry decision, thus giving them more time and space to explain their choices. Indeed, only 30% of students applied more than one green chemistry component for their pre-course response choice. On the posttest however, students would have had a much wider range of green chemistry principles and practices to draw from to support their method choice; 50% of students now used two or more green chemistry components to support their method choice and 20% used three or more. Thus, the inclusion of an increasing number of normative green chemistry ideas may have come at the expense of having time/space to fully justify the inclusion of these components.

Select All Green Chemistry Concepts

The three *select all* multiple-choice items were designed to probe specific green chemistry ideas that had been observed while coding the *Green Chemistry Definition* item during the Fall 2018 semester. These three items targeted concepts of 1) atom economy, which is a specific green chemistry metric that provides a measure for how efficient a reaction is at the molecular level, 2) *lethal dose, 50%* or LD_{50}, a widely used measure for the acute toxicity of a compound, and 3) natural versus renewable processes. Many student responses to the *Green Chemistry Definition* item had focused on 'hazards/toxicity', 'efficiency', and/or 'renewability' without clearly defining what those terms meant in the context of green chemistry. Additionally, student response (both to the *Green Chemistry Definition* item and to in-class prelab and postlab items) had occasionally appeared to conflate renewability with natural products/process. Thus, these three fixed response survey items were developed to probe what students knew about these specific concepts related to the broader themes already observed in student responses.

The *select all* items illustrated differences in student confidence in their prior knowledge and how that knowledge did or did not shift towards more normative understanding after completing the GC^2 laboratory course (Figure 4.10). Students were largely successful with the first item, which focused on atom economy, even before experiencing most of the green curriculum. Most students, both pre- and post-course, were either completely correct or incompletely correct (selected one of the two correct choices with no incorrect choices) on this item. The positive performance on the pretest (including the low frequency of students saying they didn't know how to respond to this item) was not surprising since atom economy is the first green chemistry principle introduced to students during the course. While the pretest survey was administered during the first week of the course students would still have attended their first lab lecture and started preparing for their first experiment during this time. Indeed, on the in-class quiz that was administered during the first week of the course, several students mentioned having heard of green chemistry (or related terms) during their first lab lecture or from reading the introduction to their lab manual.

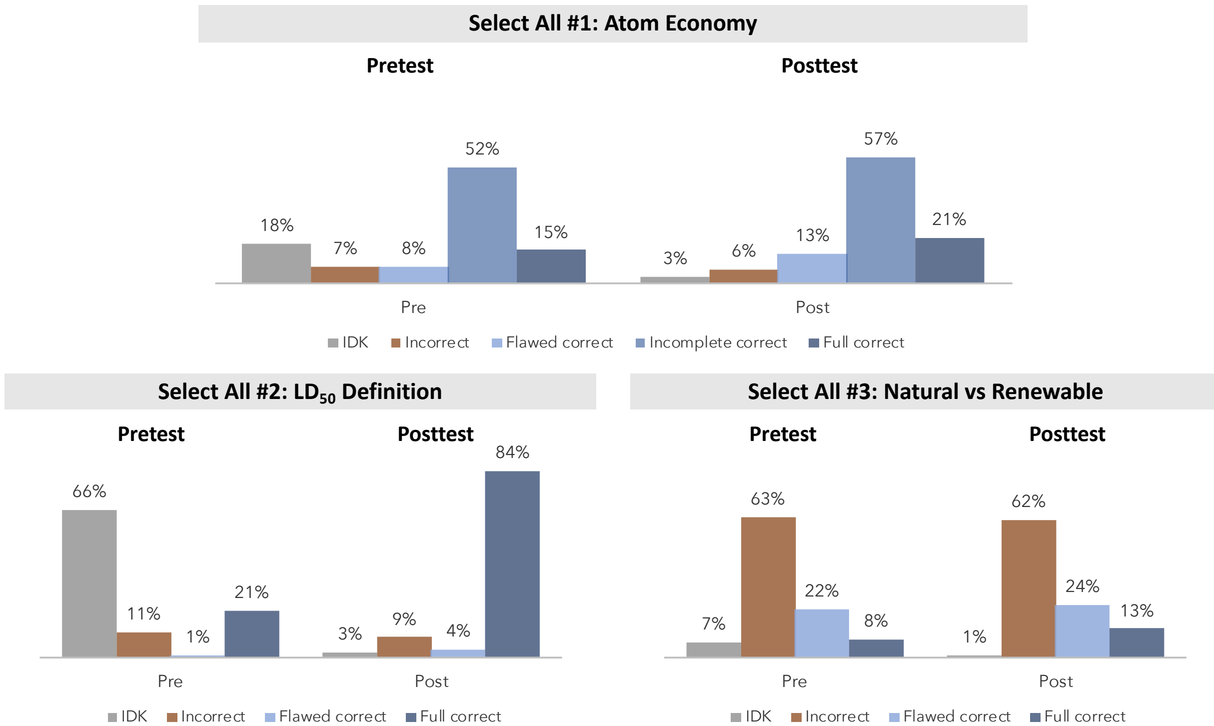


Figure 4.10. Frequency distributions for all 'Select All' multiple choice items. Full item prompts can be found in Table 4.2.

However, even with that direct introduction close to the pretest administration, there was still a slight increase in correctness for the *Atom Economy* item on the posttest ($z = 4.97$, d.f. = 507, $p < 0.001$), which the formula score for this item illustrates (Table 4.8). The formula score considered all the options a student selected with each incorrect choice resulting in the subtraction of one point and each correct choice resulting in the addition of one point to the overall formula item score ('I don't know' responses received a score of zero). Overall, there was still room for growth around the concept of atom economy in moving towards a fully correct answer since most students, even on the posttest, only select one of the two correct descriptions of atom economy.

Table 4.8. Descriptive statistics (formula scores) and Wilcoxon rank sum tests for each *select all* item

Variable	N	Pretest				Posttest				p-value (z-value)
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	
Select All #1	508	0.77	0.82	-2.00	2.00	0.99	0.79	-3.00	2.00	p < 0.001 (4.97)
Select All #2	508	0.06	0.68	-4.00	1.00	0.72	0.71	-4.00	1.00	p < 0.001 (14.97)
Select All #3	508	-1.09	1.27	-4.00	1.00	-1.00	1.32	-4.00	1.00	p = 0.17 (1.36)

In contrast to the atom economy *select all* item, students did not know how to answer the second *select all* item at the start of the semester. This item asked students to choose the correct definition for LD_{50}, which is a specific measure of acute toxicity. It was not expected that many students would have heard of this measure prior to the course, and it was not introduced until midway through the course. Correspondingly, the vast majority (65%) of students said they did not know what this term meant on the pretest and then the vast majority (over 80%) answered this question correctly on the posttest ($z = 14.97$, d.f. = 507, $p < 0.001$) after presumably learning about this concept through the course curriculum.

Students were the most confident on the third and final *select all* item with only 7% saying they did not know how to answer it on the pretest. Yet, students were also the most incorrect on this item as evidence by the, on average, negative formula scores for both the pretest and posttest (Table 4.8). Unlike the first *Atom Economy* item that focused on a concept students were introduced to during the first week of the course, renewability (and especially the comparison to 'naturalness') was not introduced until after the pre-course survey had been completed. And, unlike the LD_{50} item that focused on a concept students learned about through the course and subsequently correctly answered on the posttest, this third item had no appreciable shift in correctness from the pretest to the posttest ($z = 1.36$, d.f = 507, $p = 0.17$) indicating that the course curriculum was not able to appreciably shift student understanding or belief around natural and renewable processes.

12 Principles Ranking

As with the *select all* items, the *12 Principles Ranking* items were developed to supplement the in-class quiz free response items. These ranking items were designed to allow students to demonstrate their ability to apply the *12 Principles of Green Chemistry* to novel scenarios. Students read a short scenario that described the development of greener alternatives for traditional processes or products (Table 4.3) and were then asked to select the top three green chemistry principles they believed applied to the scenario and rank them from most applicable to least applicable.

The first two *12 Principles Ranking* items had three applicable principles with two of the three being equally the most relevant. Most students were able to correctly identify either one or two of the most relevant principles on the pretest for both items (Figure 4.11). In contrast, the third and final ranking item showed a vastly different distribution with most students identifying three correct principles for both the pretest and posttest (Figure 4.11). However, this wasn't surprising since this third item scenario mapped to two explicit principles and four implicit principles giving a total of six ‘correct’ principles. For all these items there was a moderate but significant shift in the average number of correct principles placed in the top three from pretest to posttest (Appendix X).

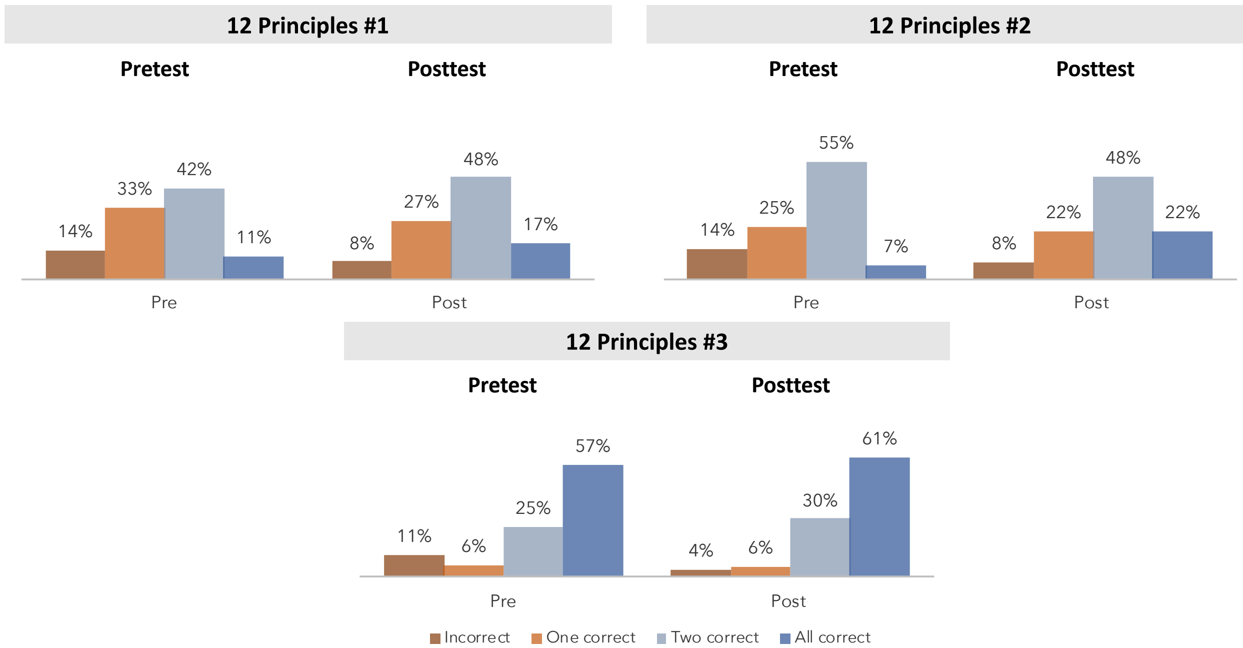


Figure 4.11. Frequency distributions for all ‘12 Principles Ranking’ items. Full item text can be found in Table 4.3.

Figure 4.12 shows how the overall ranking of each principle shifted from pretest to posttest for *12 Principles* item #1 (items #2 and #3 can be found in Appendix X). The first ranking item focused on the reduction and elimination of hazardous chemicals (i.e., the elimination of chlorine in paper production). Even on the pretest students had collectively placed the most relevant principles in their top three choices (*less hazardous chemicals/synthesis, inherently safer chemistry for accident prevention*, and *designing safer chemicals*). The overall order of these three principles did shift from pretest to posttest with *inherently safer chemistry* becoming the second most ranked principle. This aligned correctly with the expected ranking of these principles. *Less hazardous chemical synthesis* and *inherently safer chemistry* were the most relevant principles as this scenario involved the removal of a problematic class of chemicals rather than the design of alternative chemicals.

A similar trend was observed for the second ranking item, with the pretest responses collectively identifying the two most relevant green chemistry principles for the scenario and then the posttest responses brought in the third implicitly connected green chemistry principle. This second scenario’s focus was on *design for* *degradation* (the design of plastic bags that biodegrade under normal conditions) with an additional focus on *waste prevention* (the reduction of plastic waste). Students identified these two principles on the posttest and solidified a top ranking for *design for degradation* on the posttest. Additionally, students identified the *use of renewable feedstocks* as a potential third applicable principle since it is possible that some of the material used to make these plastic bags may be a renewable feedstock though further information would be needed to explicitly link this principle to this scenario.

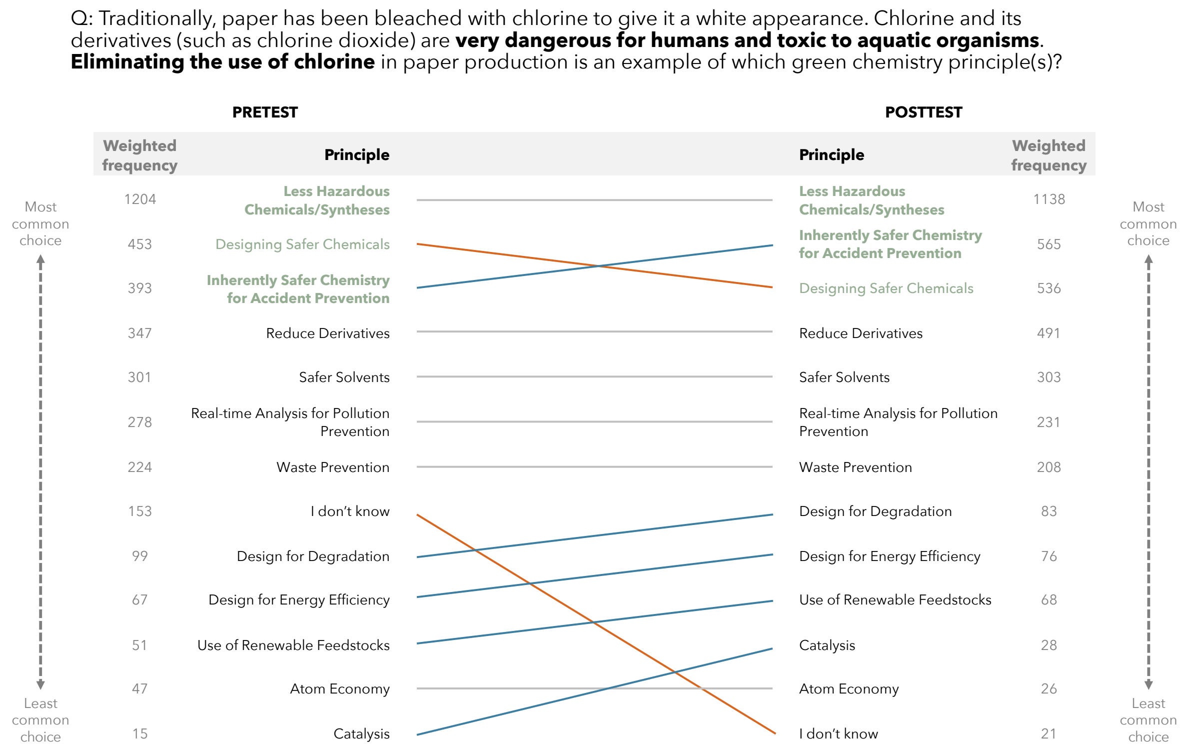


Figure 4.12. Weighted frequencies for 12 Principle Ranking item #1. The weighted frequency for each principle was based on ranking; the top position (#1) resulted in the highest "weight" of 3 while the lowest position (#3) resulted in a "weight" of 1.

Finally, the last ranking item presented students with a very different range and number of potentially relevant green chemistry principles. While the previous two scenarios only had two truly relevant green chemistry principles with a third tangentially relevant principle to round out the top three, this final scenario had six relevant principles. While this certainly increased the odds of a student randomly guessing three relevant principles (though guessing should have been reduced from the inclusion of an "I don't know option") this large number of relevant principles also provided a snapshot into how students used and prioritized multiple applicable green chemistry principles. This scenario focused on the development of less hazardous paints (made from recycled plastic bottles and soybean oil) that use water as a solvent. As with the prior two items, students once again collectively ranked the most relevant six principles in the top six spots even on the pretest with a focus on *less hazardous chemicals*, *designing safer chemicals*, and *inherently safer chemistry for accident prevention*. This order did shift slightly for the posttest with the largest change coming from the addition of *renewable feedstocks* in the top three. While students had most likely heard of renewability prior to the course (as evidenced from the *select all* item discussed in the previous section), *renewable feedstocks* is a very specific green chemistry principle that was covered several times through the course curriculum. Its rise in popularity on the posttest suggested that students did indeed become more familiar with this specific green chemistry principle and were able to apply it correctly to a novel scenario.

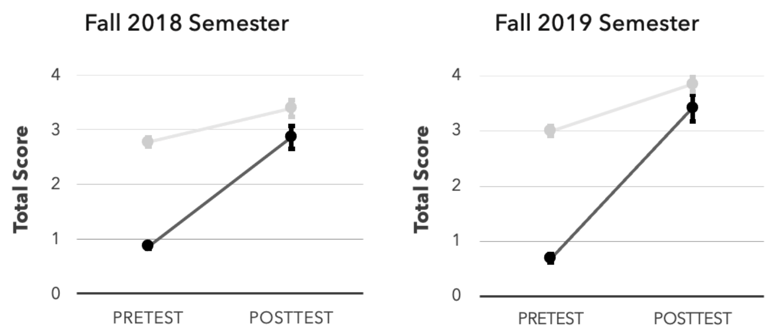


Figure 4.13. Pretest and posttest total definition score for low and high initial green chemistry performance students. The gap in ability to define green chemistry between low (N_{F18} = 220, N_{F19} = 155) and high (N_{F18} = 416, N_{F19} = 460) prior knowledge students was significantly reduced after completing Chem 1AL. A solid line (–) represents a significant change from pretest to posttest.

Results: Closing the Gap?

Initial Green Chemistry Performance

Chem 1AL is a large enrollment course that serves a diverse range of students with different backgrounds, experiences, preparation, and future major/career plans. Similarly, students enter the general chemistry laboratory with widely varying levels of prior green chemistry knowledge; only 30% of students say they have heard of green chemistry before Chem 1AL (often from environmental or sustainability focused chemistry courses or mass media). Thus, it was expected that student performance would vary on the green chemistry pretest items. However, it was hoped that completing the GC^2 laboratory course would help bridge the gap between students who did and did not have prior knowledge of green chemistry.

To begin to explore this question, students were sorted into two groups based on their pretest responses to the *Green Chemistry Definition* item. Students were categorized as demonstrating low initial green chemistry performance if they answered this question incorrectly (total item score of 0) or with a superficial response (total item score of 1) on the pretest. After completing GC^2, low initial performance students were able to define green chemistry at close to the same level as high initial performance students though there was still a gap in performance between these two groups (Figure 4.13). For the Fall 2019 semester, the difference in means between the high and low prior knowledge groups was estimated as 2.31 with a 95% confidence interval from 2.14 to 2.48 ($p < 0.001$, $t = 26.92$, d.f. = 613). However, by the end of the semester this difference in means was estimated as only 0.43 with a 95% confidence interval from 0.15 to 0.71 ($p = 0.003$, $t = 3.02$, d.f. = 613). Similar trends were seen for the Fall 2018 semester; while the gap between groups was greatly reduced by the posttest it was not eliminated.

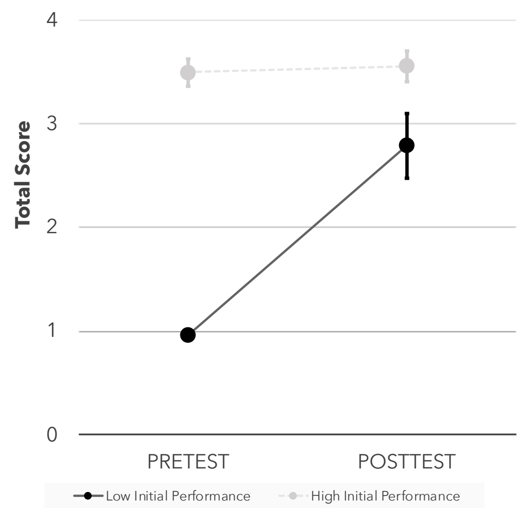


Figure 4.14. Pretest and posttest total *Two Methods Choice* score for low and high initial green chemistry performance students. The gap in ability between low (N= 100) and high (N = 515) prior knowledge students was reduced but not eliminated after completing Chem 1AL. A solid line (–) represents a significant change and a dashed line (•••) represents a non-significant change from pretest to posttest.

This result was a change from previous semesters where the gap between students with low and high green chemistry prior knowledge was closed by the end of the course (Chapter 2, Armstrong et al., 2018). However, in prior semesters, the high initial performance group did not make significant gains from pretest to posttest. Thus, the low initial performance group simply needed to 'catch up' to where the high initial performance group had started. However, for the semester that implemented GC^2, *both* low and high initial performance groups made significant gains in score from the pretest to posttest. Combining data from both the Fall 2018 and Fall 2019 semesters, the low initial performance group had an estimated 2.26-point increase from the mean pretest to posttest scores ($p < 0.001$, $t = 36.18$, d.f. = 635) and the high initial performance group had an estimated 0.68-point increase from the mean pretest to posttest scores ($p < 0.001$, $t = 13.35$, d.f. = 1119).

A similar analysis was carried out for the *Two Methods Choice* item administered on the in-class quiz during the Fall 2019 semester (Table 4.1). This question asked students to choose between two different methods for making a natural product from a green chemistry perspective. After completing GC^2, low initial performance students moved closer to the high initial performance group although there was still a significant gap in performance between these two groups (Figure 4.14). For the Fall 2019 semester, the difference in means between the high and low prior knowledge groups was estimated as 2.54 with a 95% confidence interval from 2.24 to 2.84 ($p < 0.001$, $t = 16.64$, d.f. = 613). However, by the end of the semester this difference in means was estimated as only 0.77 with a 95% confidence interval from 0.40 to 1.14 ($p < 0.001$, $t = 4.13$, d.f. = 613). Unlike the previous definition item, for which both low and high initial green chemistry performance groups made significant gains from pretest to posttest, only the low initial performance group made significant gains on this 'choice' item. The low initial performance group had an estimated 1.83-point increase from the mean pretest to posttest scores ($p < 0.001$, $t = 12.06$, d.f. = 99).

Chi-square goodness-of-fit tests were used to investigate if there was any difference in the demographic composition of the high and low green chemistry performance groups for each item. For *Two Methods Choice*, there was a statistically significant difference in the number of URM versus non-URM students who were in the low initial performance group ($\chi^2(1) = 9.40$, $p = 0.002$); 28% of URM students (N = 87) were in this group versus only 14% of non-URM students (N = 506). There was no statistically significant difference for first-generation status ($\chi^2(1) = 2.87$, $p = 0.09$) or gender ($\chi^2(1) = 0.09$, $p = 0.77$).

Similar trends were observed for the *Green Chemistry Definition* item. Once again, there was a statistically significant difference in the number of URM versus non-URM students who were in the low initial performance group for the combined Fall 2018 and 2019 semester dataset ($\chi^2(1) = 8.60$, $p = 0.003$); 39% of URM students (N = 185) were in this low initial performance group versus only 28% of non-URM students (N = 1018). There was no statistically significant difference for first-generation status ($\chi^2(1) = 0.87$, $p = 0.35$) or gender ($\chi^2(1) = 2.31$, $p = 0.13$).

Impact of Student Backgrounds and Prior Experience

Linear regression was used to investigate the association more fully between student performance on the two free response items (*Green Chemistry Definition* and *Two Methods Choice*) and several important demographic and prior experience explanatory variables (gender, first-generation college status, URM status, prior green chemistry experience, or prior chemistry experience). For all the models shown in Table 4.6, multiple linear regression was performed to create each regression model.

Green Chemistry Definition

The total pretest score for the *Green Chemistry Definition* item was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience. The results of this linear regression model are shown in Table 4.9.

Table 4.9. Estimated regression coefficients (robust standard errors), 95% confidence intervals, and p-values for the effect of being female and other selected variables on the pretest total score for the green chemistry definition item for the combined Fall 2018 and Fall 2019 populations (N = 1203, F = 6.85, R^2 = 0.03).

Variable	Est. Coeff. (Standard Error)	95% Confidence Interval		p-value
Female student	0.14 (0.08)	-0.01	0.29	0.06
First-generation college student	-0.04 (0.09)	-0.21	0.13	0.68
URM student	-0.38 (0.1)	-0.58	-0.18	< 0.001
No prior green chemistry experience	-0.11 (0.08)	-0.27	0.05	0.18
No prior college credit bearing chemistry experience	-0.21 (0.08)	-0.36	-0.06	0.01
Intercept	2.39 (0.09)	2.21	2.57	< 0.001

Controlling for the other variables in the model, the differences in pretest score on the *Green Chemistry Definition* item for female (t = 1.88, d.f. = 1197, p = 0.06) and URM (t = -3.77, d.f. = 1197, p < 0.001) students were approaching significance and significant, respectively. Female students were estimated to score on average 0.14 points higher than male students and URM students were estimated to score on average 0.38 points lower than non-URM students for their pretest score for defining green chemistry. Additionally, students without prior college credit bearing chemistry experience (i.e., no previous AP/IB courses) showed significant differences (t = -2.76, d.f. = 1197, p = 0.01) in pretest score for this item compared to students who had this prior chemistry experience, after controlling for all other variables in the model. Students without this chemistry experience were estimated to score on average 0.21 points lower than students who had taken these more advanced courses.

It's important to note that this model explains only 3% of the variance in pretest scores (R^2 = 0.03), which is also reflected in the wide confidence intervals. This low R^2 value limits the precision of the model though the low p-values still indicate that there is a true association between those significant explanatory variables and the response variable.

The "gain" score (posttest total score – pretest total score) for this item was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience. The results of this second linear regression model are shown in Table 4.10.

Table 4.10. Estimated regression coefficients (robust standard errors), 95% confidence intervals, and p-values for the effect of being female and other selected variables on changes from pretest to posttest total score for the green chemistry definition item for the combined Fall 2018 and Fall 2019 populations ($N = 1203$, $F = 1.24$, $R^2 = 0.01$).

Variable	Est. Coeff. (Standard Error)	95% Confidence Interval		p-value
Female student	0.16 (0.11)	-0.06	0.38	0.15
First-generation college student	0.11 (0.13)	-0.14	0.36	0.38
URM student	0.05 (0.14)	-0.23	0.33	0.75
No prior green chemistry experience	-0.06 (0.12)	-0.29	0.17	0.61
No prior college credit bearing chemistry experience	0.19 (0.11)	-0.02	0.41	0.08
Intercept	1.03 (0.14)	0.76	1.30	< 0.001

This model showed that none of the explanatory variables were significant predictors of the gains that students made from the pretest to posttest though students without prior college credit bearing chemistry experience showed near significant differences ($t = 1.76$, d.f. = 1197, $p = 0.08$), after controlling for all other variables in the model. Students without this prior advanced chemistry experience were estimated to gain on average 0.19 points compared to students who entered the course with this prior experience.

Once again, however this model has a low R^2 value explaining only 1% of the variance in pretest scores ($R^2 = 0.01$).

Two Methods Choice

The total pretest score for the *Two Methods Choice* item was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience. The results of this linear regression model are shown in Table 4.11.

Table 4.11. Estimated regression coefficients (robust standard errors), 95% confidence intervals, and p-values for the effect of being female and other selected variables on the pretest total score for the Two Methods Choice item for Fall 2019 (N = 593, F = 1.88, $R^2 = 0.02$).

Variable	Est. Coeff. (Standard Error)	95% Confidence Interval		p-value
Female student	-0.01 (0.14)	-0.38	0.18	0.50
First-generation college student	-0.06 (0.16)	-0.37	0.25	0.70
URM student	-0.54 (0.2)	-0.94	-0.15	0.01
No prior green chemistry experience	0.02 (0.16)	-0.30	0.34	0.92
No prior college credit bearing chemistry experience	0.09 (0.15)	-0.21	0.40	0.55
Intercept	3.20 (0.16)	2.88	3.52	< 0.001

Controlling for the other variables in the model, the difference in pretest score on the *Two Methods Choice* item for URM students ($t = -3.77$, d.f. = 1197, $p < 0.001$) was significant at the 5% level. URM students were estimated to score on average 0.54 points lower than non-URM students for their pretest score on this item. No other explanatory variables were significant or approaching significance for this model with the estimated coefficients indicating only small differences in pretest score between groups (e.g., male and female students). However, once again, the R^2 value is very low for this model ($R^2 = 0.01$) and is reflected in wide confidence intervals. Thus, there may be greater differences in pretest for each of these dichotomous explanatory variables than the estimated mean coefficients indicate.

As with the previous item, the "gain" score (posttest total score – pretest total score) for *Two Method Choice* was regressed on categorical variables for gender, first-generation college status, URM status, prior green chemistry experience, and prior college credit bearing chemistry experience. The results of this second linear regression model are shown in Table 4.12.

None of the explanatory variables were significant predictors for the gains that students made from the pretest to posttest on this item. URM students made the largest estimated gains of 0.30 points from pretest to posttest, after controlling for all other variables in the model, though this result was not significant ($t = 1.33$, d.f. = 1197, $p = 0.18$). Once again, this model has a very low R^2 value explaining less than 1% of the variance in pretest scores ($R^2 = 0.004$).

Table 4.12. Estimated regression coefficients (robust standard errors), 95% confidence intervals, and p-values for the effect of being female and other selected variables on changes from pretest to posttest total score for the Two Methods Choice item for Fall 2019 ($N = 593$, $F = 0.60$, $R^2 = 0.004$).

Variable	Est. Coeff. (Standard Error)	95% Confidence Interval		p-value
Female student	-0.004 (0.18)	-0.36	0.35	0.98
First-generation college student	-0.21 (0.18)	-0.57	0.15	0.26
URM student	0.30 (0.22)	-0.14	0.73	0.18
No prior green chemistry experience	-0.10 (0.19)	-0.47	0.26	0.59
No prior college credit bearing chemistry experience	-0.001 (0.18)	-0.36	0.36	1.00
Intercept	0.43 (0.21)	0.03	0.84	0.04

Discussion

Students Gain Knowledge about Green Chemistry

This research focused on documenting the ways in which students' abilities to ***define and use*** green chemistry changed after completing the general chemistry green chemistry (GC²) laboratory course. The development and implementation of GC² provided a useful setting to better understand what green chemistry knowledge and beliefs students hold prior to direct green chemistry instruction and how they develop and integrate new normative green chemistry ideas and practices after receiving said instruction.

On average, students demonstrated increased green chemistry understanding after completing the GC² laboratory course. At the start of the semester, students defined green chemistry using colloquial ‘green’ terms (such as sustainability, eco-friendliness, efficiency) and included incorrect statements or assumptions; these definitions, on average, only mentioned one specific components of green chemistry and did not demonstrate a sophisticated understanding of systems thinking. After completing GC², students built upon their starting definitions and gained confidence in their understanding of green chemistry. Post-course definitions still had many green-aligned terms but integrated normative green chemistry principles, examples, and explanations and began to include explanations of how chemical reactions and processes operate as and within complex interconnected systems. Students' definitions of green chemistry showed what they personally valued and what they believed the larger field of chemistry valued about green chemistry.

Students' ability to make a choice between two generalized processes from a green chemistry perspective also changed in meaningful ways after completing the GC^2 laboratory course. Most students (nearly 90%) were able to correctly identify one or more of the main factors for deciding between the two methods presented in the question. As with their definition of green chemistry, students were able to include more normative green chemistry ideas in their justification for choosing one method over the other after completing the course. Students moved away from less formalized 'green' and environmental language and towards more normative green chemistry ideas as seen in the decrease of mentions *Sustainable Systems* on the posttest. However, student responses decreased in *depth* at the end of the course. While more students included additional normative green chemistry ideas and practices post-course, they were no longer explaining the importance of or value in using these components to make a green chemistry decision at the same rate seen pre-course. Students were providing more criteria for making a green decision, but not justifying how or why that criteria applied to the given problem. There were several potential explanations for this shift. First, it's possible that students had enough familiarity to know these green terms applied to the scenario but not enough robust understanding (either of the terms themselves or in the norms for justifying a decision) to fully explain the specific connections or usefulness that these criteria had for the scenario. Second, by the posttest students may have assumed that there was a shared understanding of what these terms and principles meant within the class and thus they did not think it was necessary to define or explicitly explain they were important or relevant anymore. Finally, students only had 10 minutes to complete both this item and the *Green Chemistry Definition* item for both the pre- and post-course quiz. However, students, on average, included more components of green chemistry in their post-course response, which may have led to a decrease in time/energy for students to fully explain their increased number of green chemistry ideas and principles.

Student Prior Knowledge of Green Chemistry

In alignment with constructivist theory, all the green chemistry items showed that students had prior "green" ideas and beliefs and in some cases sophisticated green chemistry knowledge, which was reinforced and built upon during this course. At first glance, it may appear that student understanding of green chemistry was naïve or superficial at the start of the semester. This is certainly true in some cases (and regardless, in most cases, there was still room for substantial growth), but probing specific terms using fixed response items allowed students to demonstrate latent knowledge at both the beginning and end of the course. Very few responses to the free response quiz questions mentioned the concept of atom economy at the start of the course and yet 67% of students could partially or fully define this idea when directly asked. Similarly, students were able to correctly apply multiple green chemistry principles to novel green scenario even at the beginning of the semester. While these fixed response questions didn't require students to recall the *12 Principles* on their own (a selection list was provided) it still showed that students had an emerging understanding of how these principles were relevant to different scenarios.

Additionally, responses to the in-class quiz items showed many instances of unique prior knowledge or beliefs from students that were adjacent to but distinct from the standard *12 Principles of Green Chemistry*. Most notably, many initial responses to the *Two Methods Choice* item focused on specific aspects of sustainability or environmentalism that were contextualized within the scenario for their choice of method (e.g., a response in this category might focus on the potential harm that removing tree bark from a tree might cause, land use, and/or potential deforestation that might occur from one of the method choices). While these concerns do fall within the realm of determining if a feedstock is renewable, students did not explicitly connect *Sustainable Systems* to a normative green chemistry principle or language. However, even without this more formalized understanding students still demonstrated that they brought significant nascent knowledge about important green chemistry or green chemistry aligned considerations into the classroom.

Green Chemistry Is More Than the *12 principles*

The *12 Principles of Green Chemistry* were used as a guiding framework for curriculum design and development and for exploring student understanding of green chemistry, as these principles are widely considered to be the central organizing structure of green chemistry *(Anastas, 2011; Anastas & Warner, 1998; Haack & Hutchison, 2016; Linthorst, 2009; Woodhouse & Breyman, 2005)*. These principles act as a guideline for understanding the parameters around making a process greener. While they do not cover every single way a process could become more green, and a process does not need all 12 to be considered "green" (Linthorst, 2009), they are a common baseline for comparing systems and making judgements especially within chemistry education (Machado, 2015).

Thus, these principles were central for developing the green chemistry free and fixed response items used for this research and categorizing the diversity of student responses to said items, as they aligned with many of the key concepts that students should take away from GC^2 laboratory course. However, student responses, while aligned with the *12 Principles,* also showed that students conceptualized green chemistry as more than the *12 Principles*. Students brought up more holistic themes that showcased their ideas outside of the *12 principles* (ethics, values, tradeoffs, philosophy, environmentalism). A significant minority of students saw green chemistry as a new philosophy for conducting chemistry; green chemistry was not simply as a list of principles to check off but rather a way of doing chemistry that considered the short- and long-term impacts that a chemical reaction or process could have across multiple dimensions. Students believed that green chemistry valued and prioritized human and environmental outcomes and often used those outcomes to explain or justify the importance of many of the formalized principles of green chemistry.

However, students' ideas around environmentalism were mainly focused on a general or abstract idea of the "environment" and not tied to any specific outcomes or other dimensions (e.g., worker health and safety, environmental justice) indicating that instructional guidance around extensions or applications of the *12 Principles* is needed. Indeed, many educators believe that green chemistry curricula need to extend beyond the *12 Principles of Green Chemistry* to include societal factors (Burmeister et al., 2012) with courses grounding these societal impacts within a local geographic area or introducing students to green chemistry through case studies (Karpudewan et al., 2015a). Others advocate for the application of green chemistry (or related ideas) to social justice problems and the development of humanistic approaches to chemistry (Burmeister et al., 2012; Sjostrom, Eilks, & Zuin, 2016; Sjostrom & Talanquer, 2014).

Are Green Chemistry Gains Equivalent Across Student Demographics?

This research also focused on understanding if and how student understanding of green chemistry differed based on a student's **background** (gender, first-generations status, underrepresented minority status) and/or **prior chemistry or green chemistry experience**. The impact of prior chemistry experience (Riegle-Crumb et al., 2012), ethnicity (Ambady et al., 2001; Matsui et al., 2003; Tate & Linn, 2005), gender (Cheung, 2007; Cousins, 2007; Cousins & Mills, 2015; Good et al., 2012; Harding & Parker, 1995; Simon et al., 2016), and/or parents' education level has been a prominent topic of discussion in STEM fields for several decades. It was hypothesized that since green chemistry was less likely to have been introduced to students prior to GC^2 (compared to traditional chemistry topics) students would enter the class with more equal (i.e., low) green chemistry ability and correspondingly complete GC^2 having made equal gains in understanding. However, it was immediately clear that students entered the course with widely varying levels of prior green chemistry knowledge as seen through all the pretest items. However, it was hoped that the completion of GC^2 would help bridge the gap between students who did and did not have prior experience with green chemistry.

Since it was clear that students did enter the course with varying levels of green chemistry understanding it was important to ensure that the general chemistry green curriculum did not maintain or enhance those differences. Students were divided into low and high initial performance groups based on their pretest score for the *Green Chemistry Definition* and *Two Methods Choice* items. After completing the GC^2 laboratory course, low initial performance students made significant gains on both items and were able to define green chemistry and make a green chemistry decision at close to the same level as high initial performance students though there was still a gap in performance between these two groups. While it appeared that completing the GC^2 laboratory course did help lessen the initial performance gap between students it was not able to completely erase it. Additionally, it appeared that URM students were overrepresented in the low initial performance group. Thus, linear regression was used to investigate the association more fully between student performance on these two free response items and several important demographic and prior experience explanatory variables (gender, first-generation college status, URM status, prior green chemistry experience, or prior chemistry experience).

As expected, significant differences for certain explanatory variables were seen for students' abilities to define green chemistry and make a green chemistry decision at the beginning of the course. For both items, URM students were estimated to have lower pretest scores (by an estimated 0.5-points) than non-URM students after controlling for first-generation status, gender, and prior chemistry and green chemistry experience; this estimated difference was statistically significant. Additionally, students who did not have prior college credit bearing chemistry experience were estimated to have lower pretest scores (by 0.2-points) for the *Green Chemistry Definition* item than their counterparts, after controlling for all other variables in the model. For the same item, female students also had significant estimated differences, but they were estimated to score 0.2-points higher on the *Green Chemistry Definition* item than male students. Together, this indicated that there were significant differences in how students performed on these pretest items depending on their background and chemistry experience levels.

However, the change in student scores from the pretest to the posttest for both items did not reproduce these differences. None of the explanatory variables that had previously showed significant differences in performance were significant for these final 'gain' models. The largest estimated gain for the *Green Chemistry Definition* item was for students who had not had prior college credit bearing chemistry experience, after controlling for all other variables in the model. These students were estimated to make a nearly 0.2-point gain over their more "experienced" counterparts though this gain was not significant. The largest estimated gain for the *Two Methods Choice* item was for URM students who were estimated to make a nearly 0.3-point gain non-URM student though, once again, this gain was not significant.

Together this indicated that that green chemistry was not immune to the performance differences traditionally seen in chemistry outcomes as evidenced by the pre-course score analysis. Differences in student understanding by demographics and prior experience can and do exist within green chemistry as green chemistry and the methods used to assess it are not removed from the culture that students live and learn in. However, this analysis does provide evidence that these gaps are not necessarily perpetuated or enhanced through green chemistry curricula or in teaching green chemistry content and practices. No differences across select demographic factors were seen for the gains students made over the semester, which indicated that the GC^2 laboratory course was equally serving most students for these green chemistry learning outcomes.

Student Acceptance of Green Chemistry Ideas

While the previous sections have illustrated what students understand about green chemistry after completing GC^2, not every individual green chemistry concept was received equally by the students. Some green chemistry concepts were easier for students to learn, depending on their prior knowledge and beliefs. Students entered the course with established ideas around certain green chemistry aligned topics and, while the curriculum had an impact on student understanding of certain principles, that impact was not even across all topics.

This was most obvious for student performance on two of the *select all* items: LD_{50} Definition question and Natural vs. Renewable. The *LD_{50} Definition* item asked students to correctly identify the definition for LD_{50} (a widely used measure for the acute toxicity of a compound) while the *Natural vs Renewable* item asked student to differentiate between these two often conflated terms. Students did not have much prior knowledge about LD_{50} as most students (66%) said they did not know how to answer this item on the pretest. In contrast, only 7% of these same students said they did not know how to answer the *Natural vs Renewable* item with 85% of them confidently selecting incorrect or partially incorrect answers on the pretest. When these same students answered these items after completing the GC^2 laboratory course, 84% of students correctly answered the *LD_{50} Definition* item. The same could not be said for the *Natural vs. Renewable* item as students became more confident (only 1% select "I don't know") and yet nearly the same percentage of students answered this item incorrectly or partially incorrectly post-course.

Student's reliance on prior awareness of 'naturalness' and its relationship to greenness was also seen in initial definitions of green chemistry. Melissa's initial definition of green chemistry showed that, to her, green chemistry was aligned with environmental concerns and natural products or processes:

> *I don't know but my best guess is using natural compounds to make chemicals and other compounds that are useful to us. "Green" usually has the connotation of environmentally friendly or natural, so that is why I assumed it has to do with natural compounds.*

Eric's initial definition of green chemistry showed a similar tendency towards conflating green chemistry with environmental harm and naturalness while also conflating the idea of renewability and naturalness:

> *I don't know, but my best guess is that green chemistry heavily emphasizes procedures and method which try to minimize harmful effects on the environment…They want the chemistry to be natural so biofuel as opposed to regular diesel fuel…*

For a concept like natural or renewable products, students entered the class with many ideas about this topic as evidenced by most students who felt confident providing a (non-normative) answer to the Natural vs. Renewable *select all* item as well as using naturalness to define green chemistry at the beginning of the semester. The course curriculum was unable to make a meaningful impact on the complicated differences between these natural and renewable products and processes as students remained attached in their previous ideas around these two topics even after completing the course. However, it appeared that students were able to easily integrate a low prior knowledge concept like LD_{50} into their existing conceptions of chemical safety or toxicity. Most students hadn't heard of this idea prior to the course so there was very little prior understanding or beliefs to shift or align with this new metric.

It was expected that students would be less successful on the *Natural vs. Renewable* item as understanding the differences between natural and renewable products is much more complex than learning a definition for LD_{50}. However, it was unexpected that so many students would be so confident in their answers – especially before any direct instruction on green chemistry. This provides evidence for the strength of their prior beliefs and how those everyday beliefs can make the integration of new normative ideas difficult. Instructors teaching green chemistry should be aware that learning green chemistry terms and ideas will differ depending on how much prior exposure students have to those terms and ideas. A concept like LD_{50} or atom economy that has not become commonly seen or used outside of green chemistry communities will be much easier to introduce to students than concepts like natural products or renewability. More targeted teaching of these high prior knowledge topics and more explicit surfacing of this prior knowledge (Linn, 2006; Linn & Eylon, 2011) is needed to aid in the learning of new, and often contradictory, information around these complex ideas that have made their way into everyday conversations and meaning.

Limitations

This research was conducted at UC Berkeley during the Fall 2018 and Fall 2019 semesters. Berkeley (both the city and the university) has the perception of being liberal and aligned with green policies, which potentially could lead to a liberal/green skewed incoming student population for Chem 1AL (or subsequently influence student beliefs/attitudes/knowledge around green topics). Additionally, the knowledge that students brought into the class was necessarily influenced by events that occurred in their communities, states, and countries. The discourse around topics such as green chemistry (and the related topics of sustainability, climate change, renewable energy, etc.) is constantly changing and can vary by news source and political administration. What students knew and believed during Fall 2018 and Fall 2019 might be very different than what students believe and know several years later. Similarly, it's impossible to isolate the effect that the general chemistry green curriculum (GC^2) had on the changes seen for student understanding of green chemistry without using a randomized or pseudo-randomized study design. During the semester students were completing the GC^2 laboratory course, they may have also learned about green chemistry or related ideas from other sources (e.g., they may have been taking other courses or been part of clubs that touched on green chemistry topics or ideas, reading or exploring the topics on their own, or just hearing about related ideas from friends, family, or media).

The items used for this analysis did allow for the exploration of both the green chemistry ideas and beliefs students brought into the classroom as well as changes in their understanding of green chemistry after completing a green chemistry focused laboratory course, but more work is needed to explore how students engage in core green chemistry practices (especially for us with more advanced student populations like organic chemistry or upper division students). Currently, the developed items serve only as a measure of 'pen and paper' green chemistry understanding or application of green chemistry principles to vague theoretical choices. Green chemistry decision making does not occur in a vacuum but rather involves the optimization of many disparate pieces of information, metrics, and data. The final chapter of this dissertation explores how students engage in this authentic green chemistry practices by documenting the ways in which students make green chemistry decisions when given actual metrics and data.

Conclusions

The development of the general chemistry green curriculum (GC^2) provided an opportunity to explore demonstrated student understanding of green chemistry within the context of a large enrollment non-chemistry major general chemistry laboratory course. The goal of this work was to document the green chemistry ideas and beliefs students brought into the classroom as well as changes in their understanding of green chemistry after completing this green chemistry focused laboratory course. The green chemistry items developed for this work allowed students to demonstrate their understanding of green chemistry and related concepts, apply green chemistry principles to novel scenarios, and make green chemistry decisions. The design and use of both free and fixed responses items allowed for data to be collected from the majority of student in the course while also allowing for meaningful and timely analysis for the hundreds (and in some cases thousands) of responses to each item by a small team of researchers.

Students' ability to define green chemistry, make decisions from a green chemistry perspective, identify and define green chemistry concepts, and apply green chemistry principles to novel scenarios all showed meaningful changes from the beginning to the end of the course. While students came into the course with varying awareness and experience with green chemistry, students, on average, were able to make good gains in understanding green chemistry regardless of their prior experience with chemistry or green chemistry. Additionally, no significant differences were observed across gender, URM status, or first-generation status for the gains students made in green chemistry understanding from the beginning to end of the semester. This provided evidence that, while students may have entered the course with different levels of green chemistry understanding, the GC^2 laboratory course was able to equally support students in their learning of green chemistry.

However, one of the underlying themes for both the design of items and interpretation of results was the many ways that students' prior knowledge mediated their integration of new ideas into their existing mental schema. The green chemistry curriculum effectively introduced new concepts to students, such as LD_{50} and atom economy, but was not able to shift existing beliefs about natural and renewable products. As posited by constructivist learning theory, students were not a 'blank slate' but came into the course with knowledge around green-aligned ideas and practices. From this research, it's clear that more work needs to be done to actively surface student prior knowledge within GC^2 to allow both instructors and students to explicitly register what knowledge students hold and how new ideas taught in the course support or contradict that prior understanding. The course structure needs to allow for repeated and targeted lessons that provide both normative ideas and opportunities to compare those new ideas to prior beliefs (Linn, 2006).

Additionally, these results indicate that a more nuanced understanding of both student knowledge and beliefs around specific green chemistry ideas is needed to effectively teach and assess green chemistry. Terms like "natural" or "renewable" have such varied and, in some cases, interconnected everyday meanings for both societies and individuals (e.g., the idea of conserving natural resources versus the safety and use of natural products versus determining if those natural products come from renewable sources at the necessary scale). These terms are frequently tied to choices individuals must make as consumers in part due to the proliferation of eco-labels (Brécard, 2017; *Ecolabel Index | Who's Deciding What's Green?*, 2021) and greenwashing (Delmas & Burbano, 2011). Additional research is needed to determine the ways in which both cognitive and affective components contribute to learning and integrating new knowledge especially for concepts that had or will have a direct connection to students' immediate choices and ethics.

Finally, it is important to continue developing green chemistry curricula and assessment for courses outside of organic chemistry, i.e., for general chemistry and high school students. General chemistry and high school classes are critical points of entry and intervention for developing normative green chemistry understanding (especially for important but complex topics like natural and renewable products) since most secondary and post-secondary students will never take organic chemistry. At Berkeley, many non-chemistry majors will only take one semester of general chemistry meaning that Chem 1AL is the one opportunity for their green beliefs to be challenged or changed through formalized green chemistry instruction. If green chemistry is truly a framework for chemistry, and not just an add on, then it should be present in all chemistry education to allow the greatest number of students the opportunity to hear and learn about it concepts and practices.

Chapter 5: Assessing the Complexity of Student Green Chemistry Decision Making

Introduction

Principles and Practices of Green Chemistry

As discussed in the previous chapter, green chemistry has been largely codified by Anastas and Warner's (1998) *Twelve Principles of Green Chemistry*. However, these principles, while often used and referenced in green chemistry, are intended to serve as *guidelines* for doing chemistry instead of an exhaustive framework for all of green chemistry (Linthorst, 2009). Green chemistry is a wide and diverse field that can encompass many different methods, processes, disciplines, and practices (Anastas, 2011; Anastas & Allen, 2016). Ultimately, green chemistry is a philosophy for all chemistry – it is not a separate field of chemistry but rather a way of doing chemistry that attends to the entire system that chemistry operates within – including the impact of chemistry on human health and the environment.

The critical need and growing global desire to address climate change as well as many other environmental and humanitarian crises, makes it increasingly critical to equip student with the specific tools necessary to support and promote equitable global sustainability (Kitchens et al., 2006). Introducing general chemistry students to concrete green chemistry knowledge, skills, and practices gives them a more focused approach to sustainability or environmental consciousness, which is especially important for topics that often feel overwhelmingly broad or difficult to address in a meaningful way.

One of the core features of green chemistry is decision making, which requires the ability to identify, understand, and evaluate multiple competing system components such as functionality, life cycle impacts, chemical hazards and risks (*ACS Green Chemistry Institute*, 2020). Green chemistry is a new paradigm for doing chemistry that necessitates that decisions are made by considering all factors (or as many factors as possible) present in a system. This includes the often-stated considerations of 'human health and environmental impact', which in and of itself includes a wealth of variables. Central to green chemistry is the idea that there is almost never one 'right' or 'best' answer for a given problem or decision point; instead, one strives to make the greener decision based on available information (Kitchens et al., 2006). Green chemistry requires thoughtful comparisons, optimizations, and tradeoffs between variables. Making a green chemistry decision is not a static choice but rather the acknowledgement of the information available at the time and a commitment to finding or producing additional data or metrics for better future decision making.

Green chemistry brings both knowledge (of chemistry, green chemistry and engineering principles, and lifecycle and systems thinking components) and practices (chemical design strategies, life cycle impacts, hazard and risk assessment) into the chemistry classroom with the goal of ultimately identifying problems and designing sustainable solutions using multiple criteria to make design decisions (*ACS Green Chemistry Institute*, 2020). Introducing green chemistry to classrooms allows students to engage in these core premises of comparative analysis and the recognition that choices are complex, multi-dimensional, and liable to change with additional information. Green chemistry enhances student thinking and reasoning abilities (Andraos & Dicks, 2012) as authentic green chemistry contexts often motivate the collection, analysis, and critical evaluation of multiple variables and data sources. Green chemistry often calls for a comparative analysis between two or more options in, for example, the context of synthesis in organic chemistry or, as is the case in Berkeley's general chemistry lab curriculum, evaluating biodiesel versus diesel as a fuel source. This comparative analysis leads to deeper analysis and richer discussion (Andraos & Dicks, 2012).

Frameworks for Assessing Student Green Chemistry Decisions

Making a 'green' decision is highly complex and, as discussed above, rarely as simple as finding the one 'best' choice. It involved the careful consideration of many factors (at both a local and global scale) and often requires a specific and coherent justification since there is no single methodology for carrying out green processes or chemistries. Thus, for students to engage in this practice they must engage in both normative green chemistry knowledge as well as connect that information together in coherent ways to create strong justifications for their green decisions.

There have been many different approaches to teaching and analyzing student reasoning within the context of chemistry, science, and sustainability (Table 5.1). Morin et al. (2014) focused on student socioscientific sustainability reasoning (S^3R) and argued that there are four practices for decision making in the context of socioscientific issues (SSIs): 1) recognizing the complexity of SSIs, 2) examining issues from multiple perspectives, 3) understanding that SSIs are subject to ongoing change and examination, and 4) recognizing biases in information. They developed a six-dimensional framework for analyzing student socioscientific sustainability reasoning that focused on problematization (viewing multiple dimensions of the situation from different perspectives), interactions (considering the entire system over different scales), knowledges (utilizing different types of knowledge), uncertainties and risks, values (understanding that ethics and morals are involved in the issue), governance (recognizing the relationships between different interest). This reasoning framework was developed for collective student reasoning (Morin et al., 2013) on long-term group projects (Morin et al., 2014) with recent work focusing on how student interactions can foster S^3R (Morin et al., 2017).

Table 5.1. Different frameworks for defining and assessing student reasoning in science

Framework	Approach to student reasoning
Morin et al. (2014)	Describes socioscientific sustainability reasoning (S^3R) in the context of socially acute questions using a six-dimensional framework (problematization, interactions, knowledge, uncertainties and risks, values, governance)
Sevian & Talanquer (2014)	Describes the modes of reasoning to assess the complexity of student thinking (descriptive, relational, linear casual, multicomponent); chemical thinking is conceptualized as conceptual sophistication *and* modes of reasoning
Linn & Eylon (2006)	Knowledge integration assesses the integration of student ideas and knowledge through scientifically valid link(s) between relevant or normative ideas

In contrast to S^3R, which focused specifically on SSIs, Sevian & Talanquer (2014) focused more broadly on chemical thinking. Chemical thinking includes both content knowledge and modes of reasoning and thus can be used to capture the knowledge, reasoning, and practices inherent to chemistry (and green chemistry). They argued that to fully assess the complexity of student thinking one needs to focus on four modes of reasoning: descriptive, relational, linear causal, and multicomponent. These four modes of reasoning sequentially moved from descriptive (least complex) to multicomponent (most complex). Students who engage in descriptive reasoning use their own experiences and everyday life to explain and justify phenomena, often relying on superficial recognition and similarities. Students who use relational reasoning begin to recognize system properties and correlations while those who display linear causal reasoning invoke cause-effect relationships between a portion of the variables in the system. Those who engage in the highest level of multicomponent reasoning saw "complex phenomena as the result of the dynamic interplay of more than one factor and the direct and indirect interactions of several components." While these modes of reasoning were designed to probe the ways students understand and think about chemical phenomena – not how they make chemical decisions – it parallels the increasing complex reasoning (including multicomponent reasoning) needed to make fully justified green chemistry decisions from a systems-thinking perspective (Constable et al., 2019).

Sevian & Talanquer (2014) posited that content and modes of reasoning together formed chemical thinking. Another approach, Knowledge Integration (KI) provides an explicit framework for assessing the normative ideas and links between those ideas in student thinking (Gerard et al., 2016; Linn & Eylon, 2006, 2011). Knowledge integration is a framework used both for constructivist curriculum development and pedagogy and assessing student learning (Linn & Eylon, 2011). KI curricula elicit ideas from students to help teacher's assess prior knowledge and to allow students to explore and distinguish their prior knowledge from the new ideas; new ideas are then added often from pivotal cases. Then, and most importantly, KI curriculum and instruction helps students distinguish between ideas (through activities such as data representation, argumentation, critique, and debate) so students can see the differences between their old and new ideas. Without this critical step students will not integrate the new knowledge into their prior understandings. Finally, students are given opportunities to reflect on all their ideas (new and old) as well as the connections these ideas have to additional outside topics.

To assess knowledge integration, students are typically asked to select a choice and defend that choice using evidence (Linn & Eylon, 2011). The scientific concepts/ideas that students bring to this choice as well as the connections or interactions these ideas have form the basis for assessing student reasoning from a knowledge integration perspective. KI rubrics have five levels from 0 (no answer), 1 (isolated ideas with no or incorrect links), 2 (incomplete connections between ideas), 3 (full connection or interaction between two ideas), 4 (full connection or interaction between more than two ideas), and 5 (full links along with comparison of contexts and application of appropriate ideas to each context). While knowledge integration wasn't designed with green chemistry in mind its structure allows it to be applicable in any scientific context. Green chemistry is an inherently interdisciplinary discipline that requires being able to identify, analyze, and evaluate many ideas and connections within and between fields. Knowledge integration's focus on the connections or interactions between concepts/ideas makes it a promising potential framework to assess green chemistry decision making.

Research Questions

This work built on that of the previous chapter, which explored the green chemistry ideas and beliefs students brought into the classroom as well as changes in their understanding of green chemistry after completing a green chemistry focused laboratory course. However, this previous analysis examined only one portion of student green chemistry ability. It mainly focused on green chemistry definitions and concepts. When students were asked to select an alternative and justify that selection it was in the context of vague theoretical choices. Authentic green chemistry decision making involves the optimization of many disparate pieces of information, metrics, and data making it is important to extend this analysis to include a measure of how students make green chemistry decisions when given actual metrics and data.

Thus, a comprehensive summative item was developed to give students the opportunity to demonstrate their ability in the core green chemistry practice green chemistry decision making through comparative analysis. This item asked students to make a choice when given multiple traditional and green metrics and justify their decision using this data. Responses to this item were collected from two courses during the same semester – the non-chemistry majors general chemistry laboratory course (Chem 1AL) and the non-chemistry majors second semester organic chemistry laboratory course (Chem 3BL) – which provided the unique opportunity to explore green chemistry decision making within and between two student populations with different levels of green chemistry and chemistry experience.

The research questions for this investigation focused on student green chemistry reasoning and how the ability to make green chemistry decisions changed after taking additional chemistry courses:

1. **RQ1:** How do general chemistry students **reason** about green chemistry choices? In what ways do students use **data** to **support** their choices?
2. **RQ2:** How do organic chemistry students **reason** about green chemistry choices? How does this reasoning **compare** to students who have only completed general chemistry?

Methods

Research Context

General Chemistry at UC Berkeley

This research took place within a general chemistry laboratory course for non-chemistry majors (Chem 1AL) and second semester organic chemistry laboratory course for non-chemistry majors (Chem 3BL) at UC Berkeley during the Fall 2019 semester. Both courses are divided into a lecture (Chem 1A/3A) and laboratory

(Chem 1AL/3BL) course with separate instructors. Most students take the laboratory and lecture courses simultaneously, but students can complete the courses sequentially as both are offered every semester. Both laboratory courses include a 1-hour lecture (taught by the course instructor), a 3-hour in-lab section (taught by a graduate teaching assistant) each week and an end of term written lab exam. Chem 1AL has an enrollment of approximately 1200 students and Chem 3BL has an enrollment of approximately 500 students each Fall semester. Chem 1A/L is typically taken during a student's first semester at Berkeley and is a prerequisite for the organic chemistry series. Students typically take Chem 3B/L two semesters after completing Chem 1A/L.

General Chemistry Green Curriculum (GC^2)

The General Chemistry Green Curriculum (GC^2) was used during Fall 2019 semester for Chem 1AL. GC^2 used a consistent set of general chemistry experiments (Table 3.1) developed between 2008-2013 with an explicit green chemistry curriculum as described in detail in Chapter 3.

While no explicit green chemistry curriculum was used for Chem 3BL during the Fall 2019 semester, all these students would have been introduced to green chemistry when they took Chem 1AL. More than half of these students were introduced to green chemistry through early versions GC^2 as they took Chem 1AL during the Fall 2018 (GC^2 v1a) or Spring 2019 (GC^2 1b) semesters. The remaining Chem 3BL students took Chem 1AL prior to the implementation of GC^2; this version of Chem 1AL still was a green focused laboratory just with less explicit green chemistry content (see Chapters 2 and 3 for a detailed discussion of each curricular version).

Participants

Participants in this study were general chemistry students in Chem 1AL during the Fall 2019 semesters. The research was approved by the university's Institutional Review Board (Protocol ID 2012-09-4666) and all students included in this study consented to participate. Consent rates were high with nearly 100% of Chem 1AL students and 56% of Chem 3BL consenting to be part of the study. Ultimately, 60% and 50% of the total Chem 1AL and Chem 3BL student population, respectively, were included in this study as these students consented, completed the exam for their course, and provided demographic information (Table 5.2). Each student was assigned a pseudonym to report any specific examples or findings.

Table 5.2. Number of general chemistry and organic chemistry laboratory students involved in study during the Fall 2019 semester

Course	Number of students in course	Number who consented, completed exam and demographic questions	% of total student population included in study
Chem 1AL	1031	614	60%
Chem 3BL	486	244	50%

Chem 3BL students were further subdivided based on when they had previously completed Chem 1AL. Of the 244 Chem 3BL students in this study, 132 had completed Chem 1AL after the implementation of the GC^2 while 98 had completed Chem 1AL before this implementation; 14 students did not provide information on when they had taken Chem 1AL or had not completed general chemistry at Berkeley and were subsequently dropped for any subgroup analysis.

Item Design

During the Fall 2016 semester, a green chemistry exam question had been administered for Chem 1AL (Chapter 2, Armstrong et al., 2019). This question asked students to consider why the reaction presented in the question prompt was exciting from a green chemistry perspective. This item assessed students' use of higher-order thinking strategies and allowed students to demonstrate their green chemistry understanding through the exploration of a novel real-world problem. The success of this question, as well as the development and analysis of the *Two Methods Choice* item (Chapter 4), led to the design of a new Chem 1AL exam question for the Spring 2019 semester. This question presented students with three potential methods for synthesizing a particular amide and a data table with real experimental data for each method. This data included the percent yield, atom economy, number of byproducts, reaction temperature, purification method, and cost for each method. Students were asked to choose one method and explain the pros and cons for their method choice. They were finally asked to state what addition piece of information they would want to help make their decision.

This exam question was designed as an extension of the *Two Methods Choice* item; students were once again asked to decide between competing options but this time with real data and metrics to justify their decision. However, in contrast to the *Two Methods Choice* item, this exam question was not framed as a "green" question; instead, students were simply prompted to choose whichever method they thought was best for synthesizing the desired product. Unfortunately, the design of this question did not match the intended goal of the item. Ideally, this question would have presented students with an opportunity to demonstrate their ability with one of the core practices of green chemistry: comparative analysis. However, since this question only asked students to explain the pros and cons of their chosen method, very little analysis or evidence of knowledge integration occurred; students simply listed the good and bad dimensions of their method. Very few responses justified their use of data, engaged in comparative analysis, or even linked together different pieces of information.

Thus, this question was redesigned for the Fall 2019 semester through an iterative, collaborative process with the course instructors for Chem 1AL and Chem 3BL. The original intent of a 'green chemistry decision' question (to give students an opportunity to engage in green chemistry decision making using data and metrics) was retained but otherwise was completely updated. This item was redesigned using a KI framework with the goal of using a KI rubric for assessment; thus, it was necessary to present students with true alternatives that would motivate a choice and full justification of that choice (Linn & Eylon, 2011). For this version, students were presented with two methods for making the same product – *para*-cymene – used in plastic recycling. Once again, a data table was provided that gave students information like the previous question (e.g., percent yield, atom economy, number of byproducts) but also included toxicity and persistence information (Figure 5.1). Additionally, each method was equally matched in terms of 'pros' and 'cons' so there was no obvious method choice. However, one method (Method 1) was designed intentionally to be a more traditional choice (higher yield, faster reaction time, lower cost) while the other method (Method 2) was intended to be the greener choice (higher atom economy, lower number of byproducts, lower acute toxicity).

Exam Question Prompt: Green Chemistry Decision

As you have learned this semester, there are often many different ways to achieve the same chemical goal. Examine the data below detailing two different methods for making p-cymene for use in plastic recycling.

	METHOD 1	**METHOD 2**
% yield of *p*-cymene	91%	83%
atom economy	40%	80%
# of byproducts	4	1
reaction time	3 hours	24 hours
purification method	Recrystallization	Extraction
persistence of **reactants**	Very low	Low
Acute toxicity of **reactants**	High	Low
cost to make 1kg of *p*-cymene	$2,250	$2,710

Which method would you choose for making *p*-cymene?
(Hint: There is no one correct answer! You will be graded based on your explanation and not which method you choose.)

○ **METHOD 1** ○ **METHOD 2**

Why did you choose this method over the other method? Please be as specific as possible with your reasoning (for example, instead of stating that particular measure is 'good' explain what 'good' means to you in this context and how it influenced which method you chose).

Figure 5.1. Green chemistry exam item (Green Chemistry Decision) for Chem 1AL and Chem 3BL

While the overall structure of this question retained a similar layout to the previous iteration, the actual question prompts were redesigned. In order to help students engage in comparative analysis, the question prompted them to choose a method but then explain why they chose this method over the other possible method – encouraging students to engage in comparison and tradeoff analysis. Specific instructions were included to help students understand the depth of response desired for this question and to help students move away from simply asserting that criteria are 'good'. The full exam question layout is shown in Appendix IV.

Item Administration

Chem1AL and Chem 3BL students completed this "green chemistry decision" exam question on their Chem 1AL or Chem 3BL laboratory exams, respectively, during the Fall 2019 semester. The Chem 1AL and 3BL exams were closed book and administered in-class at the end of the semester. Students were given 90 minutes to complete 35 free response and multiple-choice questions for Chem 1AL and 26 free response and multiple-choice questions for 3BL (including the question used for the current analysis). The green chemistry item was the last item on both exams. The green chemistry question was worth 5% of their overall Chem 1AL exam grade and 7% of their overall Chem 3BL exam grade. Nearly all students enrolled in the Chem 1AL and 3BL completed these exams.

Item Analysis

A modified knowledge integration coding scheme was used as the basis for all initial coding for both exam items used in this research (Linn & Eylon, 2006, 2011). Knowledge integration rubrics range in score from 1 (off-task) to 5 (multiple links) and provide information on the type and number of links students make between normative scientific ideas (Gerard et al., 2016). For this research, rubrics were designed to capture both the links between different piece of information/data and the identity of information/data that was used in the response (Figure 5.2). Categories were developed to document the type and frequency of information used and to describe the level at which students justified the data they used to make their decisions. Additionally, inspired by Sevian & Talanquer (2014) and Morin et al. (2014) categories for how students weighed multiple factors (tradeoffs) and valued and prioritized information were developed to provide a snapshot of how students evaluated and valued multiple variables within a green chemistry framework.

A randomized sample of 20 student responses to the green chemistry exam item (Green Chemistry Decision) was independently read by two researchers to explore the ways in which students used the provided data (percent yield, atom economy, number of byproducts, reaction time, purification method, persistence and acute toxicity of reactants, cost) to justify their choice of method. The responses were coded for the type of information and the way it was used to support the choice of method. Originally, it was envisioned that students would use the provided information (measures) either as a "pro" (information supports that their choice of method is superior) or "con" (acknowledgement that the other method is superior

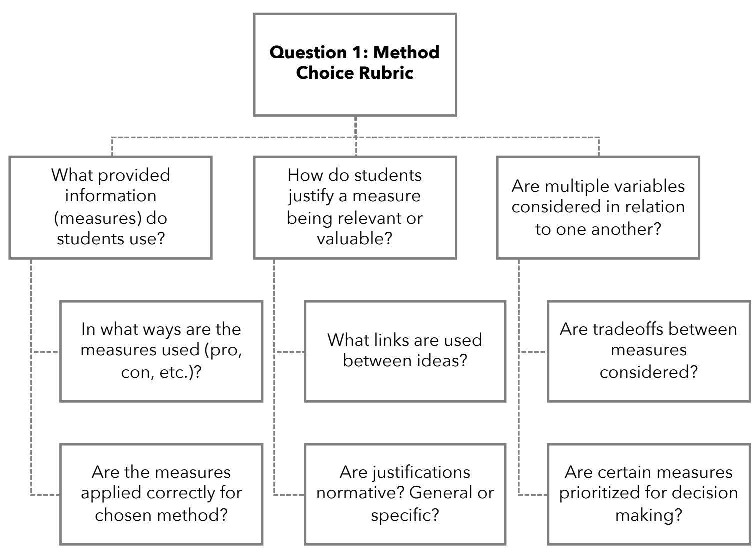


Figure 5.2. Coding scheme for Question 1: Green Chemistry Decision

along this metric) for their choice of method. However, more sophisticated response patterns were quickly observed by both researchers, so an additional 20 responses were included to further elucidate these patterns.

Instead of acknowledging that the provided information was simply a detriment to their chosen method ("con"), students instead argued that the measure was within an acceptable range; they acknowledged that the metric was 'better' for the other method, but it was still sufficient for their chosen method (e.g., yield for Method 2). Additionally, some responses equated information saying that the differences between the methods for a particular measure was small enough that it was essentially equivalent between the two method (e.g., yield, cost) and thus, not a factor in their decision.

These 40 responses were also analyzed for the ways in which students justified the inclusion of the provided information to support their choice of method (i.e., they did not simply assert that the information was 'good' or 'bad' but rather explained why that was true for their choice of method). Four 'support' levels, paralleling a modified KI rubric (Gerard et al., 2016), were developed from reading and discussing the first 20 randomized student responses. The coding of an additional 20 responses helped develop the inclusion and exclusion criteria for each support level (Table 5.3).

Through this process, two additional categories were added which focused on the way students compared or prioritized the provided information. Responses discussed tradeoffs between measures (i.e., recognition that the chosen method does have deficits, but this is outweighed by the benefits of the method) and explicitly prioritizing certain measures over others (i.e., not all measures are equal; some are more important/relevant to this decision than others). A category was also added for mentions of green chemistry. As this question was not framed as a green chemistry item it was important to capture the frequency that students explicitly brought green chemistry considerations into their response.

Using this new coding scheme, the two researchers independently coded an additional set of 30 student responses and discussed their results to achieve 100% agreement. The inclusion and exclusion criteria were revised based on these results. This process was repeated until no additional changes to the codebook were produced and interrater reliability had reached an acceptable threshold for each coding category (Cohen's Kappa of 0.80 or higher). The remaining student responses were divided in half and coded separately. Unexpected or complex responses for flagged by researchers and discussed by both until consensus was reached. The full rubric used for this item can be found in Appendix VII.

Table 5.3. Coding scheme – modified from knowledge integration rubrics (Gerard et al., 2016) – for level of support/justification observed for the Green Chemistry Decision item

Support Score	Description	Examples
0	Asserts that a measure or information is good or bad; often compares information between two methods but provides no justification for why, for example, having higher atom economy, is important	*"Method 2 has higher atom economy compared to method 1."* *"The toxicity of reactants in #2 is low, while the tox of #1 is high."*
1	Attempts to justify use of information but incorrectly links measure and justification (often by confusing % yield with atom economy)	*"Method 2 has a high % yield which means that few byproducts are produced which means reduced waste."*
2	Correctly links information and justification; justification is vague (colloquial green language) or tautological	*"Better atom economy means the reaction is more efficient."* *"[Method 2] is better for the environment since its persistence of reactants is low and it's safer in lab since it's not too toxic."*
3	Correctly links information and justification; justification uses specific green chemistry language and/or show holistic understanding of reaction process/lifecycle (e.g., sourcing, reaction conditions, disposal)	*"Atom economy of method 2 is greater than method 1 which means that less wasteful byproducts are formed."* *"The reactants maybe more toxic than method 2 but the persistence is very low meaning it wouldn't last long in the environment."*

A total score (**Green Chemistry Decision Total Score**) was assigned to each response by summing the number of correct measures used for the chosen method (0.5 points per correct measure) along with the support score (0-3 points) and mentions of tradeoffs (1 point) and prioritization of measures (1 point). Points were subtracted from the total score if a response incorrectly applied a measure (0.5 points per incorrect measurer) or if a portion of the response was off topic/incorrect (1 point).

Statistical Analysis

Chi-square tests were used to test categorical outcome variables by course (Chem 3BL, Chem 1AL) or by choice of method (Method 1, Method 2). Wilcoxon signed ranks tests were used to test ordinal outcome variables by course (Chem 3BL, Chem 1AL) or by choice of method (Method 1, Method 2). Independent sample t-tests were used to test interval outcome variables by course (Chem 3BL, Chem 1AL) or by choice of method (Method 1, Method 2). All item results were considered significant at the 95% level.

Respondents who did not consent to participate in the research study were dropped from the dataset. Respondents who did not complete the exam or did not provide demographic information were also dropped leading to a dataset of 614 Chem 1AL students and 244 Chem 3BL students. All analyses were completed using StataSE 14.2.

Regression Analysis

Linear regression was used to investigate the association between student performance on this exam item and course (Chem 1AL versus Chem 3BL) and choice of method (method 1 versus method 2). A regression model was created by regressing the **Green Chemistry Decision Total Score** onto the categorical variables of **Course** and **Choice of Method** and the continuous variable of the **Total Lab Exam Score**. **Total Lab Exam Score** was the score students received on their summative exam for Chem 1AL and Chem 3BL. This was the same exam that the Green Chemistry Decision item was administered on. To make the **Total Lab Exam Score** comparable for both courses the raw percentage grade (0-100%) was standardized using z-scores. The construction of the **Green Chemistry Decision Total Score** was described in detail in the previous section and further details of the response and explanatory variables can be found in Appendix IX.

Regression diagnostics were performed to validate the use of the multiple linear regression model (Appendix IX). No collinearity was found between the predictors (the variance inflation factor (VIF) was less than 1.1 for all variables with a mean VIF of 1.06). The continuous predictor for **Total Lab Exam Score** appeared to be linearly related to lab ability score after controlling for the other variables as the addition of a squared term for **Total Lab Exam Score** to the regression model was not significant ($t = -0.57$, d.f. = 853, $p = 0.57$). However, the studentized deleted residuals, while normally distributed, did appear to have some potential outliers and the spread of the residuals were not constant suggesting some heteroscedasticity. Thus, multiple linear regression with robust standard errors was used to create all final regression model.

Results and Discussion

Green chemistry is a broad term that encompasses many different concepts, practices, values, and beliefs, and many different desired uses and outcomes. However, one of the core practices of green chemistry is comparative analysis – evaluating multiple factors to decide between two or more options. Previous work in this dissertation (Chapter 4) explored the ways in which students could define and use green chemistry terms and principles and investigated how they approached hypothetical decision making within an explicit green chemistry framework. The current comprehensive item extends this work by allowing students to make and justify decisions using data and metrics. While this item and the resulting decision was not presented as a 'green' choice it did include information that could be used to make and justify a choice from a green chemistry perspective. Thus, this item not only showcased students' ability to make chemical decision but also gave insight into their prioritization of green chemistry.

In What Ways Do Students Use Data to Choose Between Two Methods?

The comprehensive Green Chemistry Decision item used for this analysis asked students to choose between two methods for making *p*-cymene and explain why they chose that method over the other method (Figure 5.1). They were provided with a data table that contained eight different measures: percent yield of the desired product, atom economy, number of byproducts, reaction time, purification method, persistence of reactants, acute toxicity of reactants, and cost to make 1kg of the desired product. The two methods were evenly matched in terms of measure 'pros' and 'cons' though method 1 was designed to be the more 'traditional' method choice (higher percent yield and lower reaction time and cost) while method 2 was the 'greener' method choice (high atom economy/lower number of byproducts, lower acute toxicity of reactants).

What Method Did Students Choose?

Overwhelmingly, students chose method 2 (the 'greener' method) over method 1 (the 'traditional' method) to make *p*-cymene though differences were seen between the general chemistry and organic chemistry students (Table 5.4). Nearly all (96%) of Chem 1AL students chose method 2 while significantly fewer Chem 3BL students (80%) chose this method, $\chi^2(1, N = 844) = 62.62$, $p < .001$. Additionally, there were differences in which Chem 3BL students choose method 1 versus method 2. Nearly 90% of Chem 3BL students who had previously taken Chem 1AL with the new GC^2 curriculum (i.e., Fall 2108 or Spring 2019 semesters) chose method 2, while significantly fewer (71%) Chem 3BL students who had taken Chem 1AL without this updated green chemistry curriculum (i.e., prior to Fall 2018) chose method 2, $\chi^2(1, N = 230) = 9.84$, $p = .002$.

Table 5.4. Number of responses that choose method 1 (traditional) versus method 2 (green) by course and by when students took Chem 1AL (before or after the implementation of GC^2). Percentages show proportion of responses that choose each method by column group (e.g., 4% of current Chem 1AL students chose method 1 while 96% chose method 2).

Method	1AL Students	3BL Students (All)	3BL Students	
			Took 1AL with GC^2	Took 1AL before GC^2
Method 1 (traditional)	22 (4%)	49 (20%)	16 (12%)	28 (29%)
Method 2 (green)	592 (96%)	195 (80%)	116 (88%)	70 (71%)
Total	**614**	**244**	**132**	**98**

Regardless of chemistry experience (general chemistry versus organic chemistry) or green chemistry instruction (Chem 1AL with or without GC^2) most students chose the 'greener' method choice (method 2). However, the proportion of students who chose this method did different by course and by what green chemistry curriculum was used when they took Chem 1AL (or how long it had been since they completed general chemistry). Students who had just completed an explicit green chemistry course (Chem 1AL with GC^2) were more likely to make a decision from a green chemistry perspective when presented with a choice between two appropriate but disparate methods. Chem 3BL students, who were at least two semesters removed from Chem 1AL, still choose the 'green' method at much higher rates than the 'traditional' method but could not match the current Chem 1AL students. However, it should be noted that the layout for these exam questions was not identical between Chem 1AL and Chem 3BL. The Chem 1AL exam utilized section headers and labeled the page with the current Green Chemistry Decision item as a "Green Chemistry" section. Thus, even though the question prompt was designed to not mention green chemistry students most likely assumed that this question was asking them to approach this decision from a green chemistry framework. Thus, the higher proportion of Chem 1AL students who chose method 2 may be explained by this differential question framing.

However, all Chem 3BL students saw the exact same item prompt (that did not mention green chemistry) and there was still a difference in the proportion of students who chose the ‘greener’ method based on prior Chem 1AL experience. Chem 3BL students who had previously taken Chem 1AL with the explicit green chemistry curriculum (GC²) were significantly more likely to choose method 2 compared to Chem 3BL students who had taken Chem 1AL before GC² was implemented. This indicated that the GC² curriculum may indeed have a real impact on student chemical decision-making leading students to prioritize green chemistry aligned outcomes when choosing between potential methods.

What Provided Information Did Students Use?

Student responses clearly showed differential use of provided information (measures) based on which method was chosen. Students were provided with a table that contained eight ‘measures’ with data (percent yield of the desired product, atom economy, number of byproducts, reaction time, purification method, persistence of reactants, acute toxicity of reactants, and cost to make 1kg of the desired product) for each method (Figure 5.1).

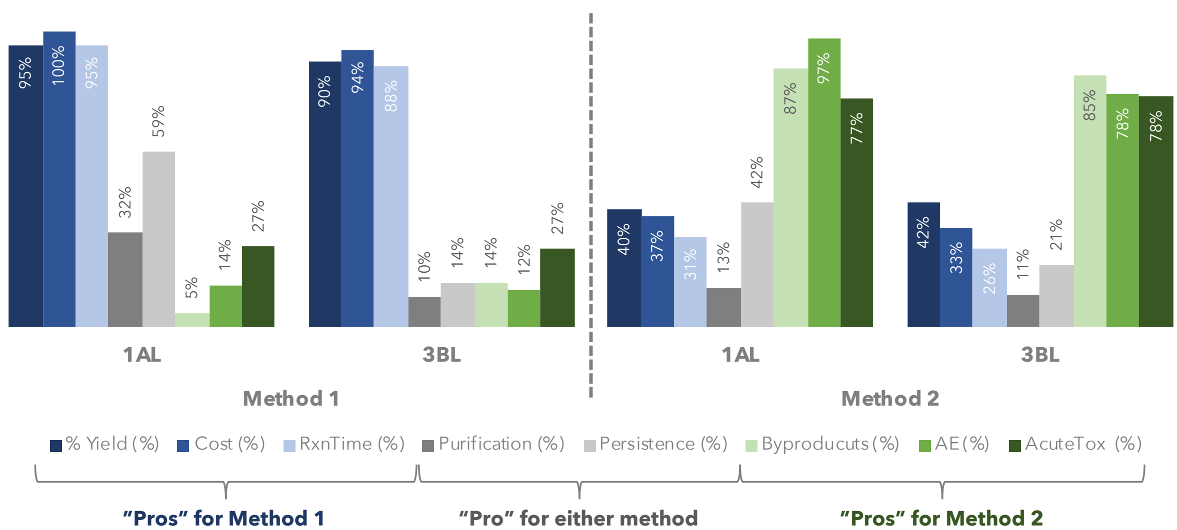


Figure 5.3. Overall responses patterns for method 1 (traditional) and method 2 (green) by course. Certain provided measures were assets or ‘pros’ for method 1 (% yield, cost, reaction time) while other measures were ‘pros’ for method 2 (number of byproducts, atom economy, acute toxicity of reactants). Two measures (purification method and persistence of reactants) could have been used to support either method choice depending on student reasoning.

Overwhelmingly, regardless of course, students who chose method 1 tended to mention the high percent yield, low cost for making the desired product, and quick reaction time (all assets for their method choice) with a small minority (27%) including the (high) acute toxicity of the reactants for their method choice (Figure 5.3). Interestingly, Chem 1AL students included mentions of the low persistence of reactants (59%) and purification method (32%) in their method 1 response at much higher rates than the 3BL students. While it wasn't unexpected that Chem 1AL students would focus on persistence (as this was a green chemistry concept introduced and used in the course they had just completed) it was surprisingly that they mentioned the purification method more often than students who had just completed their second semester of organic chemistry – a course that focuses heavily on purification methods. Additionally, Chem 1AL students who included the purification method in their response were more likely to do so correctly compared to Chem 3BL students (46% versus 31%) though this difference was not significant, $\chi^2(2, N = 108) = 4.87$, $p = .09$.

As with method 1, students who chose method 2 tended to mention the measures that served as assets or 'pros' for their chosen method. Regardless of course, most method 2 responses mentioned the low number of byproducts, high atom economy, and low toxicity of reactants (all assets to their chosen method) with a minority of responses (less than 40%) also including the cost of the reaction, percent yield, and reaction time. As with method 1, the proportion of Chem 1AL students that included the persistence of the reactants in their response was significantly higher than the proportion from Chem 3BL students (42% versus 21%), $\chi^2(1, N = 787) = 27.48$, $p < .001$. The only other measure that showed a significant relationship between the two courses was atom economy. Chem 1AL students were more likely than 3BL students to mention atom economy in their response with nearly 100% of responses including this measure in contrast to only 78% of Chem 3BL responses, $\chi^2(1, N = 787) = 76.23$, $p < .001$. Once again, this difference wasn't unexpected since Chem 1AL students had just completed a course that introduced and used the concept of atom economy multiple times. Additionally, the Chem 1AL exam also had an atom economy question, which may have primed students to include this metric in their subsequent responses. However, this difference in atom economy usage persisted within Chem 3BL between students who had completed Chem 1AL with the explicit green chemistry curriculum (GC^2) and those who had not. Chem 3BL students who had taken GC^2 included atom economy 84% of the time if they chose method 2 while students who had taken Chem 1AL prior to GC^2 only mentioned atom economy in 70% of their responses, $\chi^2(1, N = 186) = 4.80$, $p = .03$.

In What Ways Is the Provided Information (Measures) Used?

Students both selected specific measures that aligned with their choice of method and used these measures in four main ways to support their choice of method. Most frequently, students used these measures to show that their chosen method was superior ("pro"). Instead of saying that a measure was only a detriment to their chosen method ("con"), students instead argued that the measure was within an acceptable rage; they acknowledged that the measure was 'better' for the other method, but it was still sufficient for their chosen method ("acceptable"). Additionally, some responses equated measures between methods saying that the differences between the methods for a particular measure was small enough that it were essentially equivalent between the two method ("equivalent").

Unsurprisingly, most students chose to use and discuss measures that put their chosen method in the best possible light. For both methods across both courses the most common way of using a measure was as a "pro" – to illustrate that this measure provided evidence that their chosen method was more desirable than the alternative method (Figure 5.4). Kamilah provides a clear example of a response that uses measures (percent yield, cost, purification method, persistence) as evidence for why her chosen method is the better relative choice:

> *Method 1 generates a larger percent yield of the desired product and requires less time to react than method 2. Method 1 also uses less solvent to purify since recrystallization is done with minimal solvent. Method 1 is also cheaper to produce than method 2 and persists for a shorter time in the environment.*

Kamilah's reasoning for his choice of method 1 also showcased common difference between method 1 and method 2. Most method 1 responses tended to only use measures as "pros" for their choice of method (over 90% of the total measures used were used this way) while only 80% of the total measures used for method 2 were used as "pros". Instead, students supported their choice of method 2 by using a more nuanced combination of "pros" and "acceptables" for their selected measures. Students still selected measures that provided evidence that method 2 was the superior choice but also acknowledged that some of the other measures (like cost or percent yield) were technically 'better' for method 1 but were not so much better that it ruled out method 2. Shiv engaged in line of reasoning for his choice of method 2 by acknowledging that method 1 was stronger also several dimensions but ultimately that didn't outweigh the benefits of method 2:

> *Though method 1 has a higher % yield, faster reaction time, lower persistence of reactants, and lower cost, method 2 is still preferable because it has a lower harmful impact on the environment. It's high atom economy, % yield, and 1 byproduct means little waste is generated. The toxicity and persistence is [sic] also low as well, meaning little harm is done to the health of humans the environment.*

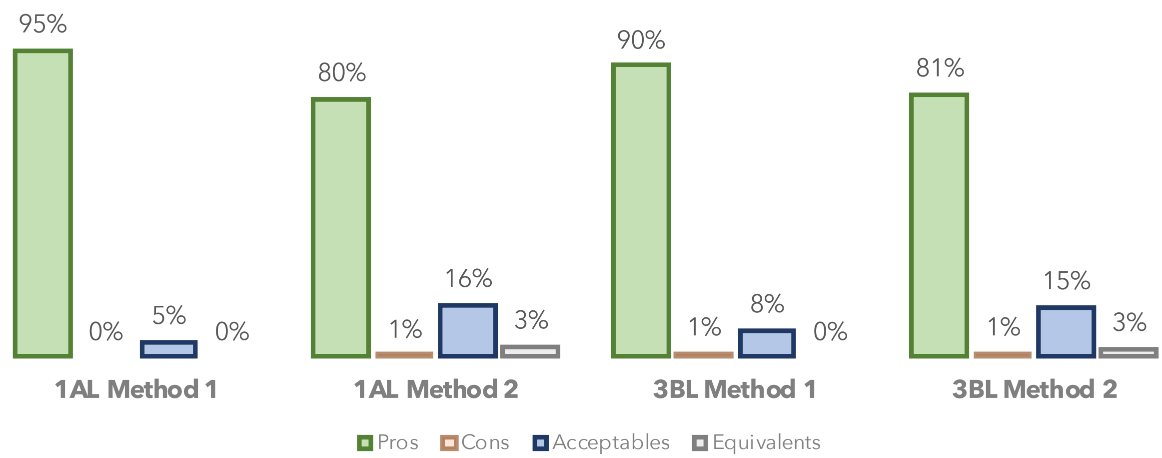


Figure 5.4. Percentage breakdown of the ways in which the measures were used to support students' chosen method by course. Pros indicate that students thought a measure showed their chosen method was superior, cons indicate that students thought that a measure showed that the unchosen method was actually superior, acceptable indicate that students thought that a measure was 'better' for the other method but was still sufficient for their chosen method, and equivalent indicate that students thought that the differences between the methods for a measure was small enough that the measure was essentially the same for the two methods.

Most students used measures to illustrate why their chosen method was the better choice; very few responses (less than 1%) simply stated why a measure was a detriment or "con" for their chosen method. The avoidance of this measure usage and adoption of "acceptable" usage instead, which acknowledged the limitations of the measure for their chosen method, showed the sophistication of student responses to this item.

Additionally, most responses used the measures correctly for the chosen method. Across both method choices and courses over 90% of measures were used correctly with near 100% correct application of persistence of reactants, percent yield, cost of methods, and reaction time measures. The most difficult measure to use correctly was the purification method; only 46% of Chem 1AL and 31% of Chem 3BL students who used this measure did so correctly. Different purification methods were listed for both methods (recrystallization for method 1 and extraction for method 2) but neither of those methods were clearly better than the other (as is, for example, lower acute toxicity of a chemical). However, 57% of all students who used this measure either asserted that one purification method was superior (providing no evidence for this claim) or made a vague or incorrect statement about how, for example, extraction uses less energy than recrystallization.

In contrast to purification method, the provided information about the persistence of the reactants was used correctly for both methods and both courses but was used much more frequently for Chem 1AL responses. Nearly 42% of the Chem 1AL students that chose method 2 mentioned this measure while an even more impressive 60% of responses that chose method 1 mentioned persistence. In contrast, 3BL students only mentioned persistence in 14% method 1 responses and 21% of method 2 responses. This was a missed opportunity since the persistence of the reactants is the lowest for method 1 – a clear positive for that method choice – and yet many students who chose method 1, especially Chem 3BL students, never mentioned it.

In general, Chem 3BL responses included a lower total number of measures, on average, than Chem 1AL responses (Table 5.5). Chem 1AL students included, on average, over four correct measures in their responses while Chem 3BL students hovered between 3 and 4 measures per response. This difference was also consistent between methods with Chem 1AL students applying over four measures, on average, for either method while Chem 3BL student responses still had between three and four measures for either method. However, for both courses, the number of incorrect measures was not consistent between methods with more incorrect measures used for method 1 compared to method 2. A Wilcoxon signed-rank test showed that students who chose method 1 had a significantly higher number of incorrect measures compared to those who chose method 2 ($z = 5.05$, $p < .001$). This indicates that students who chose method 1 both used fewer and more incorrect measures to support their choice of method compared to those who chose method 2.

Table 5.5. Descriptive statistics (mean and standard deviation) for the number of correct and incorrect measures used 1) by course and 2) by course and method choice. A two-sample Wilcoxon rank-sum (Mann-Whitney) test was used to test if there was a statistically significant difference in number of measures for Chem 1AL versus Chem 3BL students.

Measures	**Overall**			**Method 1 (traditional)**		**Method 2 (green)**	
	1AL (N = 614)	**3BL (N = 244)**	**p-value (z)**	**1AL (N = 22)**	**3BL (N = 49)**	**1AL (N = 592)**	**3BL (N = 195)**
# of Correct Measures (SD)	4.13 (1.42)	3.55 (1.36)	<0.001 (5.38)	3.82 (1.01)	3.18 (1.05)	4.14 (1.44)	3.64 (1.42)
# of Incorrect Measures (SD)	0.09 (0.3)	0.14 (0.43)	0.32 (-0.99)	0.36 (0.49)	0.31 (0.65)	0.08 (0.29)	0.10 (0.34)
Total # of Measures (SD)	4.23 (1.46)	3.69 (1.45)	<0.001 (4.89)	4.27 (1.24)	3.49 (1.31)	4.23 (1.47)	3.74 (1.48)

How Do Students Justify a Measure Being Relevant or Valuable?

In addition to examining *which* measures students used to support their choice of method, how students *justified a measure* as providing relevant or valuable information for making a decision was also explored (Table 5.3). For example, almost all students who chose method 1 said that the higher percent yield of the desired product, faster reaction time, and lower cost of the method were reasons why method 1 was superior to method 2. However, not all these responses provided a justification for *why* having a higher percent yield, faster reaction time, or lower cost was important or necessary information for making a chemical decision (as seen in Kamilah's answer above).

However, most students, especially those that chose method 2, did not simply assert that a measure was 'better' but at least attempted to justify why it was important that the measure was 'better' (Table 5.6). Overall, approximately 80% of students from both courses provided a justification or reason for including at least one measure with 56% of Chem 1AL students and 50% of Chem 3BL students including a specific justification using normative green chemistry language. Simone provides support for her choice of method 2 by connecting the given reactant toxicity and persistence information to general ideas of human health and environmental harm, but doesn't link acute toxicity or persistence to specific outcomes or impacts:

> …*The toxicity and persistence [of the reactants] is [sic] also low as well, meaning little harm is done to the health of humans and the environment.*

Sri also provides support for his choice of method 2 by focusing on the high atom economy and low number of byproducts for this method. He connects the low number of byproducts to the reduction of waste and the high atom economy to the more efficient production of the desired product. However, he stops just short of explicitly connecting all three of these ideas into one continuous line of reasoning:

> …*The atom economy is higher for method 2 (80%). It yields only one byproduct, which means less waste is generated. Since the atom economy is high, more useful product is formed….*

Overall, for both courses, students were highly successful at providing support for at least one of their chosen measures. While no significant differences were seen between courses for these overall support scores ($z = 1.36$, $p = 0.17$) there were significant differences depending on the choice of method. For both courses, students who chose method 1 ($N = 71$) had a mean support score of 1.39 while students who chose method 2 (N = 787) had a mean support score of 2.25, nearly a full point higher than method 1; and a Wilcoxon signed-rank test showed that students who chose method 1 had a significantly lower support scores compared to those who chose method 2 ($z = -6.63$, $p < 0.001$). This indicated that students who chose method 1 had not yet reached a correct measure justification while students who chose method 2 were providing correct measure justifications (using colloquial green language or specific green chemistry language or showed a holistic understanding of reaction process/lifecycle).

Table 5.6. Support score (justification or reason for including a measure) for each course by method; 0 = no justification, 1 = incorrect link between measure and justification, 2 = link between measure and vague justification, 3 = link between measure and specific justification

Course	N	Support Score		
		Median	Mean	St. Deviation
1AL	**614**	**3**	**2.21**	**1.11**
Method 1 (traditional)	22	2	1.59	1.18
Method 2 (green)	592	3	2.23	1.10
3BL	**244**	**3**	**2.13**	**1.10**
Method 1 (traditional)	49	1	1.31	1.12
Method 2 (green)	195	3	2.33	1.00
Total	**858**	**3**	**2.18**	**1.11**

Interestingly, Chem 3BL students who had previously completed Chem 1AL with GC^2 had higher support scores for method 1 than Chem 3BL students who had completed Chem 1AL before the implementation of GC^2 (no difference was seen for Method 2). While both groups still had lower support scores compared to Chem 3BL students who chose method 2, the Chem 3BL students who had taken Chem 1AL with GC^2 had, on average, a support score of 1.75 for method 1 while the remaining Chem 3BL students had a mean support score of only 1.00 points with 46% of this latter group providing no support for their measure selection; this difference in support score between Chem 3BL groups was significant ($z = 2.12$, $p = .03$). This indicated that while method choice appeared to have a large impact on the support students did or did not provide for their chosen measures, the depth and breadth of prior green chemistry instruction (and/or the immediacy of that instruction) may also play a role in how students justify the value or relevance of data while making chemistry decisions.

Are Multiple Variables Considered in Relationship to One Another?

Since almost every student response included multiple measures or variables it was important to document the ways in which these variables were used in relation to one another. For both courses, a significant minority of students (approximately 20%) discussed tradeoffs between measures while around 15% off responses prioritized certain measures for decision making (Table 5.7).

Table 5.7. Percentage of responses that mentioned tradeoffs between measures or that one measure was more or less important than others (prioritization) for each course by method (method 1 = traditional, method 2 = green)

Course (total N)	Mentions tradeoffs between measures (N)	Measure is more/less important than others (N)
1AL (614)	**26% (162)**	**14% (87)**
Method 1 (22)	9% (2)	0% (0)
Method 2 (592)	27% (160)	15% (87)
3BL (244)	**22% (54)**	**13% (32)**
Method 1 (49)	10% (5)	0% (0)
Method 2 (195)	25% (49)	16% (32)
Total (858)	**25% (216)**	**14% (119)**

Tradeoff considerations were similar to talking about how measures were "acceptable", but tradeoff reasoning explicitly and logically linked together two or more related measures and discussed how to balance the competing information present in those measures. Eleanor engaged in this line of reasoning by acknowledging that her chosen method, method 2, did cost more and take longer to produce the desired product but that the extra time and money was worth it to avoid the high reactant toxicity for the alternative method:

> *I chose method 2 because it had a higher atom economy, less byproducts, low persistence and toxicity of reactants, even though it had slightly higher cost and takes longer. I felt that the fact that method 1 had high acute toxicity was very bad, and spending 21 extra hours and $500 to make sure the reaction is safer would be well worth it.*

As seen with previous results, the proportion of students who engaged in tradeoffs was not significantly different between courses (χ^2 (1, N = 858) = 1.68, p = 0.20) but there were significant differences depending on choice of method. Regardless of course, the proportion of students who utilized tradeoff reasoning was significantly higher for method 2 than for method 1 (χ^2 (1, N = 858) = 9.64, p = 0.002). Only 10% of students who chose method 1 discussed tradeoffs between variables compared to 27% of students who chose method 2.

Similar trends were seen for the prioritization of measures with no significant differences seen between courses (χ^2 (1, N = 858) = 0.16, p = 0.69) but rather between method choices (χ^2 (1, N = 858) = 12.46, $p < 0.001$) as no students who chose method 1 engaging in this line of reasoning. Approximately 15% of students who chose method 2 talked about how certain measures were more important and thus provided more weight for their choice of method. Tahani's response illustrates how his prioritization of toxicity data over more traditional metrics like percent yield greatly influenced his choice of method:

> *I chose Method 2 mostly due the persistence and acute toxicity of the reactants. If the reactants are toxic then regardless of how high the % yield is, that's too dangerous in my opinion (especially since the % yield in method 2 is only slightly smaller: 8% difference). Additionally, there is a high atom economy so to me this is better because we're wasting less by proceeding with this method.*

Chidi's response is even more explicit in both his prioritization of measures and how the differential value he places of them impact his choice of method. His response first outlines the holistic criteria he argues constitutes a 'good' method (i.e., safety, conservation, environmental impact) and that money and time are not valid reasons for ignoring his more important criteria:

> *A good method includes the safety of the reactants, ability to conserve and recycle, and the prevention of damage to the environment. Efficiency and cost should not be a valid excuse for compromise. Method 2 conserves atoms, produces less waste/byproducts, persists at a low level, and is not very toxic. Method 1 compromises toxicity and atom economy for a faster and less costly process, which is not good for me, or the planet.*

Overall, this once again indicates that the choice of method rather than chemistry course has the greater impact on whether students use tradeoff consideration or prioritization of measures while making (green) chemistry decisions.

Why Are There Differences in Response Quality Between Method Choices?

Together, these results indicate that choice of method, rather than chemistry course, had a larger impact on both the content and quality of student justifications. Students who chose method 1 (the traditional method) were more likely to apply the given information (measures) incorrectly than students who chose method 2. They also were more likely to have lower support scores and less likely to discuss tradeoffs between measures or prioritize measures.

However, this may have been due to differences in the type of student who selected method 1 versus method 2. Perhaps the students who chose method 2 tended to perform better on the overall exam and thus differences between methods weren't due to the choice of method but rather student ability to answer free response questions within the context of a closed book in-class test. Thus, student performance on the overall laboratory exam for Chem 1AL and 3BL was used as a measure of exam ability (Table 5.8). While students who chose method 1 did indeed have lower exam scores compared to those who chose method 2 this difference was not significant for Chem 1AL ($t = -0.11$, d.f. = 612, $p = 0.92$) or Chem 3BL ($t = -081$, d.f. = 242, $p = 0.42$). A more detailed analysis of Chem 1AL exam scores showed that both student groups performed equally well on the qualitative and quantitative exam items (Appendix X). Additionally, there were no differences in the demographics (for gender, first-generation college status, underrepresented minority status) of students who chose either method across both courses (Appendix X). Thus, it appears that students who chose method 1 had similar overall exam performances and characteristics compared to those that chose method 2.

Table 5.8. Exam scores for Chem 1AL and Chem 3BL students overall and by those who chose method 1 or method 2. Each exam had a minimum possible score of 0 and a maximum possible score of 100.

Course	N	Mean Exam Score	Standard Deviation
1AL	**614**	**82.1**	**11.0**
Method 1 (traditional)	22	81.8	11.7
Method 2 (green)	592	82.1	10.9
3BL	**244**	**79.0**	**16.5**
Method 1 (traditional)	49	77.3	16.9
Method 2 (green)	195	79.4	16.4

However, significant differences in exam performance were seen for Chem 3BL students based on when they had taken Chem 1AL (Table 5.9). The majority of Chem 3BL students included in this study (54%) had taken Chem 1AL during the Fall 2018 semester or later, which meant they had been exposed to the new general chemistry green curriculum or GC^2 (Chapter 3). However, there was a significant minority (40%) of students who had completed Chem 1AL prior to this curriculum implementation (and 6% of respondents did not report when they had completed Chem 1AL/general chemistry).

Table 5.9. Exam scores for Chem 3BL students who had previously taken Chem 1AL with or without the updated green chemistry curriculum (GC^2). GC^2 was implemented starting in Fall 2018.

Course	N	Mean Exam Score	Standard Deviation
Took Chem 1AL with GC^2	**132**	**82.2**	**15.1**
Method 1 (traditional)	16	85.7	9.3
Method 2 (green)	116	81.7	15.7
Took Chem 1AL before GC^2	**98**	**73.3**	**17.6**
Method 1 (traditional)	28	70.1	18.1
Method 2 (green)	70	74.6	17.3

Thus, this grouping was both a measure of time since general chemistry and which green general chemistry curriculum students had completed. Chem 3BL students who had completed Chem 1AL with GC^2 were estimated to score 8.9-points higher on their Chem 3BL laboratory exam compared to students who had taken Chem 1AL prior to the Fall 2018 semester ($t = 4.11$, d.f. = 228, $p < 0.001$). However, there were no significant differences in exam scores between students who chose method 1 and method 2 for either group (took Chem 1AL with GC^2: $t = 0.99$, d.f. = 130, $p = 0.32$; took Chem 1AL before GC^2: $t = 1.13$, d.f. = 96, $p = 0.26$). Thus, while there were differences in exam performance based on when students had previously completed general chemistry, there was once again no difference in exam performance by choice of method for either of these groups.

Together, this indicated students who chose method 1 did not have significantly different exam performances compared to students who chose method 2. Additionally, both method choices had nearly identical demographic compositions by gender, first-generation status, and URM status (Appendix X). Thus, the differences seen in student justifications between method 1 and method 2 appear to be due to the choice of method itself.

Regression. Linear regression was used to investigate the association more fully between student performance on the green chemistry decision item and choice of method, after controlling for the course and total lab exam score. Multiple linear regression was performed to create the regression model. The Green Chemistry Decision total item score was regressed on categorical variables for course (Chem 1AL or Chem 3BL) and method (Method 1 or Method 2) and a continuous variable for total lab exam score for either course (standardized as a z-score for comparison across courses). The results of this linear regression model are shown in Table 4.9.

Table 5.10. Estimated regression coefficients (robust standard errors), 95% confidence intervals, and p-values for the effect of choice of method and other selected variables on the total score for the green chemistry decision item ($N = 858$, $F = 44.55$, $R^2 = 0.12$).

Variable	Est. Coeff. (Standard Error)	95% Confidence Interval		p-value
Method 2 (green)	1.8 (0.19)	1.43	2.17	< 0.001
Chem 3BL	-0.14 (0.12)	-0.37	0.09	0.22
Total Lab Exam Score	0.21 (0.05)	0.11	0.32	< 0.001
Intercept	2.78 (0.19)	2.40	3.16	< 0.001

The choice of method and total lab exam score were both significant explanatory variables in this model. This indicated that students who had higher overall laboratory exam scores also had higher overall scores on the green chemistry decision item. Indeed, the mean green chemistry decision score increased by 0.21 points for each additional standard deviation the total lab exam score was above the mean ($t = 3.89$, d.f. = 854, $p < 0.001$), after controlling for the course and choice of method. Most interestingly, even after controlling for overall lab exam performance and course, the choice of method was still a strong predictor of overall Green Chemistry Decision performance. Students who chose method 2 were estimated to score on average 1.80 points higher than students who chose method 1 ($t = 9.50$, d.f. = 854, $p < 0.001$). Unsurprisingly given the prior analysis, course (whether a student was in Chem 1AL or Chem 3BL) was not a significant predictor for green chemistry decision performance ($t = -1.22$. d.f. = 854, $p = 0.22$) after controlling for the other variables in the model.

Together, this indicated that differences in student response content and quality between method 1 and method 2 do not seem due solely to differences in test taking ability or course content knowledge (if one accepts that a summative exam performance is a good measure of both). These differences could be due to the methods themselves necessitating different prior knowledge or activating different modes of reasoning. These differences in student justifications between method 1 (traditional) and method 2 (green) may indicate that students who are more green chemistry focused (i.e., they chose the greener method choice) were also better at providing green chemistry justifications; students who aligned more strongly with green chemistry were also more likely to have (and use) the skills that green chemistry helps to build (weighing choices and crucially evaluating different characteristics).

Additionally, students who chose the more traditional method (method 1) tended to list correct pieces of information for their choice of method but did not justify these measures and did not discuss tradeoffs or prioritization of variables at the same level as those who chose method 2. Since method 1 is the more traditional choice it could be that students did not feel like they had to justify the "typical" or "accepted" way of making chemical decisions. Percent yield and economic and temporal efficiency are widely used markers of reaction success and thus students may not have felt the need to justify something so 'obvious' to fellow chemists. Since the green method choice (method 2) went against conventional chemistry wisdom students may have been more motivated to explain why one would choose the costlier, slower, and lower yielding reaction.

Limitations

The purpose of this work was to 1) develop and demonstrate an effective item design for measuring student ability to make green decisions using data and 2) investigate the how this decision making changed with additional chemistry experience (i.e., general chemistry versus organic chemistry experience). While there is mild evidence that Chem 3BL who had previously taken Chem 1AL with GC^2 were more likely to choose the greener of the two methods these results are confounded by the many other differences between these two populations especially since students who completed Chem 1AL with GC^2 had more recently experienced general (and green) chemistry than those who took Chem 1AL prior to Fall 2018. Additionally, as this was a not a longitudinal study but rather a comparison of two populations with different levels of chemistry experience, even the Chem 3BL students who completed Chem 1AL with GC^2 received a different version of the curriculum than the current (Fall 2019) Chem 1AL students did. Thus, one cannot assume that the current Chem 1AL performance on this green chemistry decision item mirrors the performance the Chem 3BL students would have had after completing Chem 1AL as they received a different version of GC^2.

As with the previous chapter, the generalizability of these results must be carefully considered. Students who consented to this research had similar laboratory exam scores compared to the entire population though Chem 1AL students included in this study had a significantly higher mean exam scores compared to the overall class while Chem 3BL students included in this study had slightly lower mean exam score compared to the overall class (Table 5.11).

Table 5.11. Comparison of laboratory exam scores for entire course population and study population for Chem 1AL and 3BL

	Course	N	Exam Score Mean (Standard Deviation)
Chem 1AL	All students	1025	80.5 (11.9)
	Students not in study	411	78.1 (12.83)
	Students in study	614	82.1 (10.97)
Chem 3BL	All students	472	79.4 (16.3)
	Students not in study	228	79.9 (16.1)
	Students in study	244	79.1 (16.5)

For Chem 1AL, the students in this study scored significantly higher on their laboratory exam (by an estimated 3.99-points) compared to students who were not part of the study ($p < 0.001$, $t = 5.33$, d.f. = 1023). However, for chem 3BL, while the students in this study did score an estimated 0.86 points lower on their laboratory exam than the students who were not a part of the study, this difference was not significant ($p = 0.57$, $t = .57$, d.f. = 470). Thus, it's possible that the sample student population used for this work was not representative of the entire course population (especially for Chem 1AL).

Conclusions

Green chemistry is a broad term that encompasses many concepts, practices, and metrics with different uses and desired outcomes. One of the core practices of green chemistry is collecting, analyzing, and evaluating multiple pieces of information (at both a local and global scale) to determine the 'greener' choice between two or more options. Previous work in this dissertation (Chapter 4) explored the ways in which students defined green chemistry and recognized and used green chemistry concepts and principles. It also investigated how students approached choosing between two broad alternatives from a green chemistry perspective. This current chapter continued this line of inquiry by developing a comprehensive item to investigate how students used data to make and justify green decisions.

This work showed that students can engage in green chemistry reasoning at a high level when provided with traditional and green data. When asked to decide between two alternative methods students used the given data to justify their choice in ways that showed their green chemistry knowledge and modes of reasoning. Students tended to correctly use data to illustrate why their chosen method was better than the alternative and a minority of students carefully discussed how certain provided measures weren't ideal for their chosen method but were still within acceptable ranges. Overall, students justified their use of at least one of these measures by providing evidence for why or how this chosen measure showed their method was the better choice. They were able to correctly link the measure to normative justifications (Linn & Eylon, 2006, 2011) using colloquial green language or specific green chemistry terms or concepts. A significant minority of students also discussed tradeoffs between variables and the prioritization of specific measures showcasing reasoning that aligned with the value and interactions dimensions seen with Morin et al.'s (2014) student socioscientific reasoning framework and Sevian & Talanquer's (2014) linear causal and multicomponent mode of reasoning. Students who engaged in tradeoff reasoning explicitly and logically linked together two or more related measures and discussed how to balance the competing information present in those measures, which showed understanding of the interactions between different factors within a dynamic and complex system. Students who prioritized specific measures recognized that not all data are equal, and that values and ethics must be used to inform the weight given to available date during decision making.

Differences in Student Reasoning by Method Choice

While student reasoning in response to this green chemistry decision item was interesting and complex, differences were seen in reasoning content and quality by the method students chose. The context of this research allowed for the exploration of green chemistry reasoning with two distinct populations: general chemistry and organic chemistry students. Surprisingly, the largest difference in response quality was not seen between the general chemistry and organic chemistry students but rather between the two possible methods. Students who chose the more traditional chemistry method (method 1) for making the desired product were more likely to apply the given information incorrectly compared to students who chose the greener method (method 2). They also were more likely to simply assert that a given measure was 'good' or 'bad' and were less likely to discuss tradeoffs between variables or prioritize any measures. Even after controlling for course and exam performance, the choice of methods was still a significant predictor of overall performance on this green chemistry decision item. This difference in response quality by method choice, consistent across both general chemistry and organic chemistry, could ultimately be due to the activation of different modes of reasoning. While all chemical choices can and should utilize comparative analysis, green chemistry explicitly integrates this practice with its focus on researching and evaluating alternative methodologies/products/processes and prioritizes comparison, tradeoffs, and systems thinking. Thus, students who chose the greener method may have consciously or unconsciously thought about decision making from this more explicitly comparative perspective.

Additionally, since green chemistry is a relatively new addition to chemistry with different priorities than traditional chemistry, students may have felt the need to justify their choice of green method more fully. The traditional method choice – since it aligned with typical chemistry metrics and methods – may not have motivated students to think more deeply about *why* they were making this choice. Indeed, Morin et al. (2014) found that the more familiar or personally relevant a question was a student the lower the level of scientific learning (in this case, critical analysis of their ideas, knowledge appropriation, socio-epistemological thinking about the knowledge involved). In contrast, the greener method did not align with traditional markers of reaction efficiency (i.e., it was more expensive, took much longer, and had a lower percent yield) so students may have felt like they needed to explain and defend their data and choice.

However, this difference in response quality by method choice could also be due to the inherent difficulty of each measure. Students, especially the current Chem 1AL students, had recently completed at least one course that explicitly introduced them to green chemistry concepts such as acute toxicity, persistence, and atom economy. Metrics like cost and time, while common in everyday science discourse, were not explicitly introduced or explained. Percent yield was introduced in organic chemistry as a measure of reaction efficiency but is typically used more as a measure of a student's own proficiency with a synthesis rather than as a criterion for making decisions between multiple reactions or methods. Thus, students who chose the greener method (which aligned with acute toxicity, persistence, and atom economy) may have justified these measures more easily since there was explicit instruction around those metrics and practice using these metrics to make decisions or recommendations. Students who chose the traditional method (which aligned with cost, reaction time, and percent yield) may have found it more difficult to justify those measures since they had not been introduced to economic arguments related to chemistry.

However, this does not fully explain why students who chose the traditional method did not provide counterarguments for measures that were 'better' for the greener method. Students who chose the greener method were more likely to include measures that provided stronger evidence for the traditional method but were, by the student's argument, still sufficient for their chosen method. Far fewer students who chose the traditional method engaged in this type of data use, which would have allowed them to discuss acute toxicity and atom economy – measures they had been taught about. It could be that students implicitly or explicitly recognized the potential ethical quandaries of prioritizing cost and time over toxicity considerations and thus did not want to introduce that line of inquiry into their response especially since no economic instruction had been included in their chemistry courses to help provide nuanced insight into this dilemma.

Differences in Student Reasoning by Course

While the most dramatic differences in student reasoning were observed for the choice of method, there were still differences between general chemistry and organic chemistry responses to this item. Current general chemistry students were more likely to choose the greener method compared to organic chemistry students though this could be due to different exam item prompts as discussed in the results and discussion section. However, even within organic chemistry differences were seen depending on when students had completed general chemistry. Organic chemistry students that completed general chemistry with the new general chemistry green curriculum (GC^2) were much more likely to choose the greener method compared to students who had completed general chemistry prior to that explicit green chemistry curriculum implementation. Regardless, organic chemistry students still overwhelmingly chose the greener method even after two or more semesters since any green chemistry instruction or reinforcement. This indicated that organic chemistry students still remembered and valued green chemistry principles and methods to the point of choosing and justifying the greener method on a high-stake summative exam.

For both courses, student use of the provided information was similar for both methods. However, general chemistry students were more likely to include more measures in their response regardless of method choice. This difference was mainly due to the use of three measures: reactant persistence, purification method, and atom economy. General chemistry students who chose the more traditional method mentioned persistence of the reactants and the purification method much more frequently than organic chemistry students. Similarly, general chemistry students who chose the greener method once again mentioned persistence more frequently as well as atom economy. These results are consistent with the experience general chemistry students had in completing an explicit green chemistry laboratory course. Students who recently studied green chemistry would be more likely to include green chemistry topics in their justifications. However, it's unclear why organic chemistry students didn't do the same for a topic they had much more experience with – purification. These students were well positioned to discuss this topic as their organic chemistry laboratories focused heavily on purification methods. Even when organic chemistry students did discuss purification, they were more likely to do so incorrectly compared to general chemistry students though this difference was not significant. This could be because purification wasn't taught in the context of decision making but rather as a technical skill to use towards a particular goal for a given experiment.

Overall, both general and organic chemistry students' responses showed that green chemistry was valued. Further, green chemistry knowledge was used several semesters after learning about green chemistry. This is especially impressive given that organic chemistry students received no additional green chemistry instruction through their chemistry courses or opportunities to engage in green evaluation or tradeoff analysis after general chemistry (though they certainly had opportunities to analyze data and synthesize information in their chemistry courses). Additionally, the current general chemistry students received the arguably most robust version of GC^2 while the organic chemistry student experienced early versions of this curriculum or completed general chemistry with the original green chemistry laboratory curriculum (Chapter 3). The fact that most organic chemistry students would still value and use green chemistry many semesters after its introduction indicates the significance students place on green chemistry.

Pedagogical Implications

A goal of this research was to document and explore student reasoning in a green chemistry context and to design an item that effectively elicited such reasoning. Previous work (Chapter 4) and previous versions of this green chemistry decision item illustrated the difficulties in successfully creating prompts and providing data that would allow students to demonstrate the full range of their knowledge and reasoning ability. It was important to develop an item that presented students with real alternatives and with clear prompts to elicit justifications for their choices (Linn & Eylon, 2011). This step ensures that students evaluate the alternatives. It allows us to truly evaluate student use and integration of ideas and reasoning.

Additionally, providing students with data (and thereby constraining and scaffolding their choice) allowed for much richer and deeper reasoning in novice students. In

Chapter 4, a similar question structure was used (choose one of two options and justify this choice from a green chemistry perspective) but no specific data was provided. This had the benefit of allowing students to apply any and all relevant knowledge they held. Yet the open-ended structure also made it a complex and unbounded problem especially for introductory students. Students tended to use broad or vague terms to justify their choice of method and few students explained for what or why these metrics were important. In contrast, when these same general chemistry students were presented with the item for this current analysis, they were able to use the provided data to make detailed justifications for their choice of method.

Thus, when considering how best to elicit student reasoning or provide students with opportunities to engage in and practice green chemistry reasoning, care should be taken to provide bounded and focused problems that support students in integrating knowledge (Linn & Eylon, 2006, 2011). These problems should provide students with information if in constrained situation (like an exam) or support students in gathering and sorting new information. These problems should also allow students to engage in comparative analysis by directly comparing and contrasting alternatives, stating and explaining assumptions and values, providing criteria for how and why data is used, thinking about risk and uncertainty, and/or weighing the interactions of multiple variables. Finally, the assessment of these problems should prioritize both normative content knowledge and modes of reasoning; simply listing ideas or terms is not sufficient for green decision making. Instead, it is both the type of ideas and the way students link those ideas together that provide a full picture of student reasoning.

Chapter 6: Concluding Thoughts on Green Chemistry Assessment and Pedagogy

Research Review

This dissertation focused on both curriculum development and assessment of self-reported and demonstrated student understanding of green chemistry. The first research chapter of this dissertation (Chapter 2) explored student experiences and learning in the context of the original green chemistry curriculum for Chem 1AL (non-chemistry majors' general chemistry laboratory). This work explored if students believed they had learned green chemistry and if they valued green chemistry after completing a course with implicit and explicit green chemistry contexts and content. It was also the first step towards developing items to measure student demonstrated understanding of green chemistry. Overall, students valued green chemistry and showed an increased ability to define green chemistry and apply green chemistry concepts to a novel scenario. Students self-report significant gains in how well they understood green chemistry and were able to identify more components of green chemistry after completing general chemistry. In addition, low and high prior knowledge students reach near equivalent green chemistry understanding by the end of the course. Most students reported that green chemistry was the most meaningful part of the course and a significant minority identified green chemistry as the main concept they would take to another class. However, this analysis of student learning showed that students needed more practice applying green chemistry in a diverse range of situations and more exposure to real green chemistry scenarios and metrics.

Additionally, the analysis of the original green chemistry curriculum for Chem 1AL showed opportunities for improvement. Only 20 prelab or postlab questions (11%) had any green chemistry content and only one question explicitly referenced green chemistry. This analysis highlighted a mismatch between the original curriculum design goals – to integrate "sustainability and green chemistry concepts into every aspect of the curriculum" – and the implemented laboratory curriculum. While many of the Chem 1AL laboratory experiments used greener reagents or had green chemistry contexts there wasn't the corresponding explicit instruction on green chemistry concepts and metrics in the written laboratory curriculum. This finding, coupled with the gaps in student green chemistry outcomes, prompted the redesign of the green chemistry curriculum starting for the Fall 2018 semester.

The second research chapter (Chapter 3) built off the analysis of the original green chemistry curriculum to iteratively develop the general chemistry green curriculum (GC^2) using the Knowledge Integration (KI) framework (Linn & Eylon, 2006, 2011). This curriculum development process was an opportunity to use a constructivist framework to build curricular content and assessments that were designed to elicit students' prior knowledge, promote discovering new ideas and distinguishing between prior knowledge and new ideas, and support reflection on newly constructed knowledge (Linn & Eylon, 2006). As the iteration of the curriculum progressed, the KI framework helped restructure curricular material to support students in discovering and building connections within and between chemistry and green chemistry concepts, practices, and applications and in learning how to make 'greener' choices by engaging in comparative analysis and critical reflection on a given choice.

In addition to using the KI framework for curriculum design, utilization-focused evaluation (Patton, 2008) was used to monitor the implementation of all versions of GC^2 and ultimately assess if the main goals of the curricular redesign were met. The main goals of GC^2 were to teach students about green chemistry concepts and practices and provide them with opportunities to use that knowledge to engage in green chemistry decision making – a core green chemistry activity (Andraos & Dicks, 2012). This necessitated the development and validation of a set of fixed response survey items to measure student self-reported understanding of green chemistry and the use of several free response items to assess the value students placed on green chemistry. Overall, students reported that their ability to define green chemistry and green chemistry principles, identify and reduce hazards and waste, and identify factors that make a reaction green all increased significantly after completing GC^2. Many students also reported that green chemistry was the most valuable component and most meaningful connection of this introductory course.

The final two dissertation research chapters explored ways to assess student demonstrated understanding of green chemistry (Chapter 4) and students' ability to make and justify a green chemistry decision (Chapter 5). This necessitated the careful selection of assessment methodology as general chemistry at UC Berkeley is a large enrollment course with thousands of students. Interviews, observations, or focus groups, which are resource intensive to conduct and analyze, were not possible with such a large course while still retaining a representative sample of students. Thus, a combination of fixed and free response green chemistry items was developed to document the ways in which students' abilities to define and use green chemistry changed after completing the GC^2 laboratory course. Overall, students demonstrated increased green chemistry understanding after completing the GC^2 laboratory course as seen through their ability to define green chemistry and specific green chemistry concepts, choose between generalized processes from a green chemistry perspective, and apply green chemistry principles to novel scenarios.

Additionally, this chapter also investigated the impact that student *characteristics* (gender, first-generations status, underrepresented minority status) and/or *prior chemistry or green chemistry experience* had on gains made in green chemistry understanding after completing the new GC^2 laboratory course. While differences in student understanding by demographics and prior experience were found for pretest scores no significant differences across these demographic factors were found for the gains students made over the semester, which indicated that the GC^2 laboratory course was equally serving most students across these measured green chemistry outcomes. This analysis provided evidence that while students may enter a course with different levels of understanding, these differences are not necessarily perpetuated or enhanced through the green chemistry curriculum used for Chem 1AL.

The fifth and final chapter (Chapter 5) used the analysis from Chapter 4 to explore how students make and justify green decisions when presented with real data and metrics. This chapter included both general chemistry students (who had just completed the new GC^2 laboratory course) and organic chemistry students (half of whom had previously completed an earlier iteration of GC^2), which allowed for a comparison in green decision making by chemistry experience. This work showed that both general and organic chemistry students engaged in sophisticated green chemistry reasoning when provided with traditional and green data and metrics. When asked to decide between two alternative methods students used the given data to justify their choice in ways that showed their green chemistry knowledge and modes of reasoning. Students tended to correctly use data to illustrate why their chosen method was better than the alternative and a minority of students carefully discussed how certain provided measures weren't ideal for their chosen method but were still within acceptable ranges. They were able to correctly link the measure to normative justifications (Linn & Eylon, 2006, 2011) and a significant minority were also able to identify and evaluate multiple interconnected variables (Sevian & Talanquer, 2014) and explain how certain variables should be prioritized for decision making (Morin et al., 2014). Overall, both general and organic chemistry students' overwhelmingly chose and correctly justified the 'greener' method choice – showing similar value for and ability in making green chemistry decisions. This was especially impressive given that organic chemistry students received no additional green chemistry instruction through their chemistry courses after general chemistry. The fact that organic chemistry students would choose the green chemistry option on a high-stake summative exam indicated the value they still held for green chemistry and the confidence they had in their understanding of green chemistry principles and practices even two or more semesters after learning about green chemistry.

Areas of Development and Exploration

Ultimately, if green chemistry is a philosophy for doing chemistry – and not an add on or separate niche field – that needs to be reflected within chemistry practices and chemistry education. Ideally, green chemistry should be present in all chemistry courses. This requires a coherent learning progression developed and agreed upon by all instructors. Instead, green chemistry courses and curricula are often implemented in isolated courses without 'top down' support (Bodner, 2016). Currently, green chemistry is only present in the general chemistry laboratory courses at UC Berkeley with most recent curricular development situated in the non-chemistry major's laboratory course. Green chemistry is not part of any further chemistry progression students take. That will soon change with the development of green chemistry modules for the non-chemistry major organic chemistry laboratory (spearheaded by a grant obtained by the chemistry laboratory instructional staff). This extension of green chemistry into the organic chemistry classes is not only logical from an instructional standpoint but also desired by students. Most non-major organic chemistry students surveyed during the Spring 2019 semester said that green chemistry concepts should/could have been utilized in their subsequent chemistry courses and nearly 80% said they had taken or wished they could take another course on green chemistry. These students discussed how they saw value in additional green chemistry instruction as it had connections to their everyday life or to their major/career and because they saw green chemistry as an ethical imperative for chemistry, which has been well established in literate around green chemistry education (Bodner, 2016; Burmeister et al., 2012; Haack & Hutchison, 2016, 2016). The development of a new student led DeCal (Democratic Education at Cal) course during the Spring 2020 semester provided additional evidence of student desire for green chemistry education. *Making Green: The Chemistry of Consumer Products* focused on making green chemistry accessible to a wide range of undergraduate and graduate students by introducing students to green chemistry principles and applying those principles in weekly "case studies" of common chemical consumer products. Green chemistry has often focused its attention solely within chemistry to the exclusion of societal input; until recently, it had not been seen as a relevant strategy or framework for governmental or non-governmental environmental action or consumer decision making (Iles, 2011). It is inspiring to see the development of a student-driven green chemistry curriculum that aims to be inclusive and relevant for all students and provides an important reminder of how to design green chemistry curricula to create a more socially robust understanding and use of green chemistry.

Pedagogical Opportunities

Green chemistry is a new way of conceptualizing chemistry and engaging in chemistry practices (Linthorst, 2009; Sjostrom et al., 2016) yet it is often treated as only a new set of content to insert into an existing chemistry curriculum. Introducing students to only the *12 Principles of Green Chemistry* doesn't prepare them for the "social, economic, political, environmental, ecological, and ethical benefits, costs and risks at various levels" (Sjöström & Talanquer, 2018). Future green chemistry education needs to move towards holistic and embedded curricula, value-driven frameworks, participatory decision-making, and critical-reflexive theory, which are present in education for sustainable development and eco-reflexive science education – two fields closely aligned with green chemistry.

Sustainable development is "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (Burmeister et al., 2012). The central focus of education for sustainable development (ESD) is to prepare the younger generation to participate in a democratic society and to help shape future society in a sustainable fashion. In contrast to green chemistry, ESD has clear pedagogical goals that involve more than a simple rearrangement of curricula (Burmeister et al., 2012) . These goals include embedding ESD within the entire chemistry curriculum, allowing ethical values to guide chemistry education, promoting critical thinking and problem solving to address sustainability issues, using multi-dimensional methods to construct pedagogical approaches, involving learners in decision making, using relevant contexts for learning, and addressing local as well as global issues (Burmeister et al., 2012).

Education for Sustainability (EfS) or eco-reflexive science education calls for a much higher degree of transformation than ESD as it moves towards a critical pedagogy for critical citizenship (Sjöström & Eilks, 2017; Sjöström & Talanquer, 2018). Critical pedagogy focuses on the relationship between knowledge and power and the transformation of knowledge (e.g., curriculum) and pedagogy (e.g., teaching). The goal of this critical pedagogy is to break the cycle of uncritical citizenship where the private/individual sphere is expected to affect change while the larger institutions and process continue with 'business as usual' (Sjostrom et al., 2016). Eco-reflexive education is also interested in developing 'reflective awareness' about sustainability, which can include intra-relations or self-awareness (how your own actions impact on the environment; influencing lifestyle choices or consumer choices), interrelations or social awareness (how society influences individual choices; the cultural or social factors that influence consumer choices), and eco-relations or environmental awareness (how society impacts on ecosystems through political actions).

Applied to education, eco-reflexive science education seeks to create "dialogical relations between the dimensions of Science, Technology, Society and Environment so that the pretense of neutrality, linearity, a-historicity and the lack of diversity that can pervade these dialogues is criticized" (Sjostrom et al., 2016). Strong sustainability/transformative education should focus on developing socio-political skills for affecting change instead of focusing on knowledge transmission and learning to be a 'good' consumer. Teaching for socio-political action is not an easy task but there are a several cases that provide theoretical frameworks and models for activist science and technology education (Bencze & Carter, 2011) and socio-scientific sustainability reasoning (Morin et al., 2014).

Students who enter chemistry courses right now do so at pivotal a moment in time. Climate change and related environmental and humanitarian crises have made it clear that immense change – societally, technically, scientifically – is needed. STEM majors, with their unique knowledge and skills, have a critical role to play in this 'grand challenge' but not solely in knowledge construction and transmission. Green chemistry curriculum designers and instructors should carefully consider what content and practices are important to and for students at this moment. While the *12 Principles of Green Chemistry* are a foundational mainstay for green chemistry, they are not an exclusive or exhaustive set of criteria. For both chemistry and non-chemistry majors, green chemistry education needs to move towards a more holistic approach (as is seen with systems-thinking, e.g., Constable et al., 2019) that uses green chemistry principles and practices to address critical issues that are prevalent in public discourse (e.g., clean energy, renewability, carbon neutrality, climate change, ocean acidification, deforestation). Green chemistry education needs to attend to both content *and* pedagogy – to build curricula that elicits students' prior green knowledge (which often has many specific green ideas and beliefs) , promotes discovering and distinguishing between prior knowledge and new normative ideas, and supports reflection on newly constructed knowledge (Linn & Eylon, 2006) – to help to ensure students have opportunities to integrate green chemistry content, practices, and applications. Green chemistry should aid students in not just their chemistry practice but support them in becoming more socially and environmentally conscious actors in a global society. It should help students understand how their knowledge can be translated into action. Ultimately, all students deserve an education that prepares them to not only enter chemistry as it is right now but to have the vision to imagine and create chemistry (and the world) as it should be for their future.

References

ACS Green Chemistry Institute. (2015). *Design Principles for Sustainable Green Chemistry & Engineering*. https://www.acs.org/content/dam/acsorg/greenchemistry/resources/2015-gci-design-principles.pdf

ACS Green Chemistry Module Development. (2021). American Chemical Society. https://www.acs.org/content/acs/en/greenchemistry/students-educators/module-development.html

Adams, R., & Khoo, S.-T. (1996). ACER Quest: The interactive test analysis system. Version 2.1. *Measurement and Statistics*. https://research.acer.edu.au/measurement/3

Ambady, N., Shih, M., & Kim, A. (2001). Stereotype susceptibility in children: Effects of identity activation on quantitative performance. *Psychological \ldots*, *12*(5), 385–390. https://doi.org/10.1111/1467-9280.00371

American Chemical Society. (2013). *Advancing Graduate Education in the Chemical Sciences: Summary Report of an ACS Presidential Commission Advance the broader chemistry enterprise and its practitioners for the benefit of Earth and its people Summary Report of an ACS Presidential Commission*. https://www.acs.org/content/dam/acsorg/about/governance/acs-commission-on-graduate-education-summary-report.pdf

Anastas, P. T. (2011). Twenty Years of Green Chemistry. *Chemical & Engineering News*, *26*(89), 62–65.

Anastas, P. T., & Allen, D. T. (2016). Twenty-Five Years of Green Chemistry and Green Engineering: The End of the Beginning. *ACS Sustainable Chemistry & Engineering*, *4*(11), 5820–5820. https://doi.org/10.1021/acssuschemeng.6b02484

Anastas, P. T., & Beach, E. S. (2009). Changing the Course of Chemistry. In P. T. Anastas, I. J. Levy, & K. E. Parent (Eds.), *Green Chemistry Education* (Vol. 1011, pp. 1–18). American Chemical Society. http://pubs.acs.org/doi/abs/10.1021/bk-2009-1011.ch001

Anastas, P. T., & Kirchhoff, M. M. (2002). Origins, Current Status, and Future Challenges of Green Chemistry. *Accounts of Chemical Research*, *35*(9), 686–694. https://doi.org/10.1021/ar010065m

Anastas, & Warner, J. C. (1998). *Green Chemistry: Theory and Practice*. 30.

Andraos, J., & Dicks, A. P. (2012). Green chemistry teaching in higher education: A review of effective practices. *Chem. Educ. Res. Pract.*, *13*(2), 69–79. https://doi.org/10.1039/C1RP90065J

Andraos, J., & Dicks, A. P. (2015). The State of Green Chemistry Instruction at Canadian Universities. In V. Zuin & L. Mammino (Eds.), *Worldwide Trends in Green Chemistry Education* (pp. 179–212). Royal Society of Chemistry. https://doi.org/10.1039/9781782621942-00179

Armstrong, L. B., Rivas, M. C., Douskey, M. C., & Baranger, A. M. (2018). Teaching students the complexity of green chemistry and assessing growth in attitudes and understanding. *Current Opinion in Green and Sustainable Chemistry*, *13*, 61–67. https://doi.org/10.1016/j.cogsc.2018.04.003

Armstrong, L. B., Rivas, M. C., Zhou, Z., Irie, L. M., Kerstiens, G. A., Robak, M. T., Douskey, M. C., & Baranger, A. M. (2019). Developing a Green Chemistry Focused General Chemistry Laboratory Curriculum: What Do Students Understand and Value about Green Chemistry? *Journal of Chemical Education*, *96*(11), 2410–2419. https://doi.org/10.1021/acs.jchemed.9b00277

Aubrecht, K. B., Bourgeois, M., Brush, E. J., MacKellar, J., & Wissinger, J. E. (2019). Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability. *Journal of Chemical Education*, *96*(12), 2872–2880. https://doi.org/10.1021/acs.jchemed.9b00354

Aubrecht, K. B., Padwa, L., Shen, X., & Bazargan, G. (2015). Development and Implementation of a Series of Laboratory Field Trips for Advanced High School Students to Connect Chemistry to Sustainability. *Journal of Chemical Education*, *92*(4), 631–637. https://doi.org/10.1021/ed500630f

Aurandt, J. L., & Butler, E. C. (2011). Sustainability Education: Approaches for Incorporating Sustainability into the Undergraduate Curriculum. *Journal of Professional Issues in Engineering Education and Practice*, *137*(2), 102–106. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000049

Bada, D., & Olusegun, S. (2015). Constructivism Learning Theory: A Paradigm for Teaching and Learning. *IOSR Journal of Research & Method in Education*, *5*(6), 66–70.

Beltman, R. J., Dierker, T. M., Fei, A. G., Fuchs, W. K., Katsimpalis, A. M., Ponkowski, M. J., Wong, R., & Mio, M. J. (2015). An Advanced Organic Chemistry Laboratory Course Incorporating Writing/Reviewing Scientific Manuscripts and Green Chemistry Metrics. In K. C. Lanigan, E. S. Roberts-Kirchhoff, K. R. Evans, M. A. Benvenuto, & A. Rihana-Abdallah (Eds.), *Chemistry and the Environment: Pedagogical Models and Practices* (Vol. 1214, pp. 91–104). American Chemical Society. http://pubs.acs.org/doi/10.1021/bk-2015-1214.ch008

Bencze, L., & Carter, L. (2011). Globalizing students acting for the common good. *Journal of Research in Science Teaching*, *48*(6), 648–669. https://doi.org/10.1002/tea.20419

Benvenuto, M. A., & Bodner, G. M. (2017). The Quadruple Bottom Line: The Advantages of Incorporating Green Chemistry into the Undergraduate Chemistry Major. *Physical Sciences Reviews*, *2*(9). https://doi.org/10.1515/psr-2017-0003

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, *63*(10), 873. https://doi.org/10.1021/ed063p873

Bodner, G. M. (2016). The quadruple bottom line: The advantages of incorporating Green Chemistry into the undergraduate chemistry major. In *Green Chemical Processes* (pp. 1–23). De Gruyter. https://doi.org/10.1515/9783110445923-002

Bopegedera, A. M. R. P., & Perera, K. N. R. (2017). "Greening" a Familiar General Chemistry Experiment: Coffee Cup Calorimetry to Determine the Enthalpy of Neutralization of an Acid-Base Reaction and the Specific Heat Capacity of Metals. *Journal of Chemical Education*, *94*(4), 494–499. https://doi.org/10.1021/acs.jchemed.6b00189

Brécard, D. (2017). Consumer misperception of eco-labels, green market structure and welfare. *Journal of Regulatory Economics*, *51*(3), 340–364. https://doi.org/10.1007/s11149-017-9328-8

Buckley, H. L., Beck, A. R., Mulvihill, M. J., & Douskey, M. C. (2013). Fitting It All In: Adapting a Green Chemistry Extraction Experiment for Inclusion in an Undergraduate Analytical Laboratory. *Journal of Chemical Education*, *90*(6), 771–774. https://doi.org/10.1021/ed300510s

Budescu, D., & Bar-Hillel, M. (1993). To Guess or Not to Guess: A Decision-Theoretic View of Formula Scoring. *Journal of Educational Measurement*, *30*(4), 277–291. https://doi.org/10.1111/j.1745-3984.1993.tb00427.x

Burmeister, M., Rauch, F., & Eilks, I. (2012). Education for Sustainable Development (ESD) and chemistry education. *Chem. Educ. Res. Pract.*, *13*(2), 59–68. https://doi.org/10.1039/C1RP90060A

Burmeister, M., Schmidt-Jacob, S., & Eilks, I. (2013). German chemistry teachers' understanding of sustainability and education for sustainable development—An interview case study. *Chem. Educ. Res. Pract.*, *14*(2), 169–176. https://doi.org/10.1039/C2RP20137B

Burton, R. F. (2004). Multiple choice and true/false tests: Reliability measures and some implications of negative marking. *Assessment & Evaluation in Higher Education*, *29*(5), 585–595. https://doi.org/10.1080/02602930410001689153

Byrnes, J. P., Miller, D. C., & Schafer, W. D. (1999). Gender differences in risk taking: A meta-analysis. *Psychological Bulletin*, *125*(3), 367–383. https://doi.org/10.1037/0033-2909.125.3.367

Cecilio-Fernandes, D., Medema, H., Collares, C. F., Schuwirth, L., Cohen-Schotanus, J., & Tio, R. A. (2017). Comparison of formula and number-right scoring in undergraduate medical training: A Rasch model analysis. *BMC Medical Education*, *17*. https://doi.org/10.1186/s12909-017-1051-8

Cheung, D. (2007). Students' Attitudes Toward Chemistry Lessons: The Interaction Effect between Grade Level and Gender. *Research in Science Education*, *39*(1), 75–91. https://doi.org/10.1007/s11165-007-9075-4

Connections Between Green and Sustainable Chemistry, Systems Thinking and Existing Chemistry Curricula (pp. 1–37). (2020). ACS Green Chemistry Institute.

Constable, D. J. C. (2017). The practice of chemistry still needs to change. *Current Opinion in Green and Sustainable Chemistry*, *7*, 60–62. https://doi.org/10.1016/j.cogsc.2017.08.002

Constable, D. J. C., Jiménez-González, C., & Matlin, S. A. (2019). Navigating Complexity Using Systems Thinking in Chemistry, with Implications for Chemistry Education. *Journal of Chemical Education*, *96*(12), 2689–2699. https://doi.org/10.1021/acs.jchemed.9b00368

Cousins, A. (2007). Gender Inclusivity in Secondary Chemistry: A study of male and female participation in secondary school chemistry. *International Journal of Science Education*, *29*(6), 711–730. https://doi.org/10.1080/09500690600823508

Cousins, A., & Mills, M. (2015). Gender and high school chemistry: Student perceptions on achievement in a selective setting. *Cambridge Journal of Education*, *45*(2), 187–203. https://doi.org/10.1080/0305764X.2014.934202

Davis, D. A., Mazmanian, P. E., Fordis, M., Harrison, R. V., Thorpe, K. E., & Perrier, L. (2006). Accuracy of Physician Self-assessment Compared With Observed Measures of Competence: A Systematic Review. *JAMA*, *296*(9), 1094–1102. https://doi.org/10.1001/jama.296.9.1094

DeHaan, R. L. (2009). Teaching Creativity and Inventive Problem Solving in Science. *Cell Biology Education*, *8*(3), 172–181. https://doi.org/10.1187/cbe.08-12-0081

Delmas, M. A., & Burbano, V. C. (2011). The Drivers of Greenwashing. *California Management Review*, *54*(1), 64–87. https://doi.org/10.1525/cmr.2011.54.1.64

Dicks, A. P., D'eon, J. C., Morra, B., Kutas Chisu, C., Quinlan, K. B., & Cannon, A. S. (2019). A Systems Thinking Department: Fostering a Culture of Green Chemistry Practice among Students. *Journal of Chemical Education*, *96*(12), 2836–2844. https://doi.org/10.1021/acs.jchemed.9b00287

Dickson-Spillmann, M., Siegrist, M., & Keller, C. (2011). Attitudes toward chemicals are associated with preference for natural food. *Food Quality and Preference*, *22*(1), 149–156. https://doi.org/10.1016/j.foodqual.2010.09.001

Dunlap, R. E. (2008). The New Environmental Paradigm Scale: From Marginality to Worldwide Use. *The Journal of Environmental Education*, *40*(1), 3–18. https://doi.org/10.3200/JOEE.40.1.3-18

Duranti, A., Goodwin, C., & PhD, P. of A. L. C. G. (1992). *Rethinking Context: Language as an Interactive Phenomenon*. Cambridge University Press.

Ecolabel Index | Who's deciding what's green? (2021). http://www.ecolabelindex.com/

Eissen, M. (2012). Sustainable production of chemicals – an educational perspective. *Chem. Educ. Res. Pract.*, *13*(2), 103–111. https://doi.org/10.1039/C2RP90002E

Epicoco, M., Oltra, V., & Saint Jean, M. (2014). Knowledge dynamics and sources of eco-innovation: Mapping the Green Chemistry community. *Technological Forecasting & Social Change*, *81*(C), 388–402. https://doi.org/10.1016/j.techfore.2013.03.006

Evagorou, M., Korfiatis, K., Nicolaou, C., & Constantinou, C. (2009). An Investigation of the Potential of Interactive Simulations for Developing System Thinking Skills in Elementary School: A case study with fifth-graders and sixth-graders. *International Journal of Science Education*, *31*(5), 655–674. https://doi.org/10.1080/09500690701749313

Examples of Green Chemistry and Sustainable Chemistry. (2021). American Chemical Society. https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/examples.html

Farrell, J. J., Moog, R. S., & Spencer, J. N. (1999). A Guided-Inquiry General Chemistry Course. *Journal of Chemical Education*, *76*(4), 570. https://doi.org/10.1021/ed076p570

Fay, M. E., Grove, N. P., Towns, M. H., & Bretz, S. L. (2007). A rubric to characterize inquiry in the undergraduate chemistry laboratory. *Chemistry Education Research and Practice*, *8*(2), 212–219.

Flynn, A. B., Orgill, M., Ho, F. M., York, S., Matlin, S. A., Constable, D. J. C., & Mahaffy, P. G. (2019). Future Directions for Systems Thinking in Chemistry Education: Putting the Pieces Together. *Journal of Chemical Education*, acs.jchemed.9b00637. https://doi.org/10.1021/acs.jchemed.9b00637

Galgano, P. D., Loffredo, C., Sato, B. M., Reichardt, C., & El Seoud, O. A. (2012). Introducing education for sustainable development in the undergraduate laboratory: Quantitative analysis of bioethanol fuel and its blends with gasoline by using solvatochromic dyes. *Chem. Educ. Res. Pract.*, *13*(2), 147–153. https://doi.org/10.1039/C1RP90061G

Garner, N., Huwer, J., Siol, A., Hempelmann, R., & Eilks, I. (2015). On the Development of Non-formal Learning Environments for Secondary School Students Focusing on Sustainability and Green Chemistry. In V. Zuin & L.

Mammino (Eds.), *Worldwide Trends in Green Chemistry Education* (pp. 76–92). Royal Society of Chemistry. https://doi.org/10.1039/9781782621942-00076

Garner, N., Siol, A., & Eilks, I. (2015). The Potential of Non-Formal Laboratory Environments for Innovating the Chemistry Curriculum and Promoting Secondary School Level Students Education for Sustainability. *Sustainability*, *7*(2), 1798–1818. https://doi.org/10.3390/su7021798

Gerard, L. F., Ryoo, K., Mcelhaney, K. W., Liu, O. L., Rafferty, A. N., & Linn, M. C. (2016). Automated guidance for student inquiry. *Journal of Educational Psychology*, *108*(1), 60–81. https://doi.org/10.1037/edu0000052

Gilbert, J. K. (2006). On the Nature of "Context" in Chemical Education. *International Journal of Science Education*, *28*(9), 957–976. https://doi.org/10.1080/09500690600702470

Good, C., Rattan, A., & Dweck, C. S. (2012). Why do women opt out? Sense of belonging and women's representation in mathematics. *Journal of Personality and Social Psychology*, *102*(4), 700–717. https://doi.org/10.1037/a0026659

Graham, K. J., Jones, T. N., Schaller, C. P., & McIntee, E. J. (2014). Implementing a Student-Designed Green Chemistry Laboratory Project in Organic Chemistry. *Journal of Chemical Education*, *91*(11), 1895–1900. https://doi.org/10.1021/ed5000394

Gron, L. U., Bradley, S. B., McKenzie, J. R., Shinn, S. E., & Teague, M. W. (2013). How to Recognize Success and Failure: Practical Assessment of an Evolving, First-Semester Laboratory Program Using Simple, Outcome-Based Tools. *Journal of Chemical Education*, *90*(6), 694–699. https://doi.org/10.1021/ed200523w

Guron, M., Paul, J. J., & Roeder, M. H. (2016). Incorporating Sustainability and Life Cycle Assessment into First-Year Inorganic Chemistry Major Laboratories. *Journal of Chemical Education*, *93*(4), 639–644. https://doi.org/10.1021/acs.jchemed.5b00281

Haack, J. A., & Hutchison, J. E. (2016). Green Chemistry Education: 25 Years of Progress and 25 Years Ahead. *ACS Sustainable Chemistry & Engineering*, *4*(11), 5889–5896. https://doi.org/10.1021/acssuschemeng.6b02069

Harding, J., & Parker, L. H. (1995). Agents for change: Policy and practice towards a more gender-inclusive science education. *International Journal of Science Education*, *17*(4), 537–553. https://doi.org/10.1080/0950069950170412

Henrie, S. A. (2017). *Green chemistry laboratory manual for general chemistry*. CRC Press.

Honebein, P. C. (1996). Seven Goals for the Design of Constructivist Learning Environments. In B. G. Wilson (Ed.), *Constructivist Learning Environments: Case Studies in Instructional Design* (pp. 11–24). Englewood Cliffs: Educational Technology Publications.

Howard-Grenville, J., Nelson, A. J., Earle, A. G., Haack, J. A., & Young, D. M. (2017). "If Chemists Don't Do It, Who Is Going To?" Peer-driven Occupational Change and the Emergence of Green Chemistry. *Administrative Science Quarterly*, *62*(3), 524–560. https://doi.org/10.1177/0001839217690530

Hutchison, J. E. (2019). *Systems Thinking and Green Chemistry: Powerful Levers for Curricular Change and Adoption*. 1–7. https://doi.org/10.1021/acs.jchemed.9b00334

Hyslop-Margison, E. J., & Strobel, J. (2007). CONSTRUCTIVISM AND EDUCATION: MISUNDERSTANDINGS AND PEDAGOGICAL IMPLICATIONS. *The Teacher Educator*, *43*(1), 72–86. https://doi.org/10.1080/08878730701728945

Iles, A. (2011). Greening chemistry: Emerging epistemic political tensions in California and the United States. *Public Understanding of Science*, *22*(4), 460–478. https://doi.org/10.1177/0963662511404306

Iles, A. (2013). Greening chemistry: Emerging epistemic political tensions in California and the United States. *Public Understanding of Science*, *22*(4), 460–478.

Iles, A., Martin, A., & Rosen, C. M. (2017). Undoing Chemical Industry Lock-ins: Polyvinyl Chloride and Green Chemistry. *International Journal for Philosophy of Chemistry*, *23*, 29–60.

Karpudewan, M., Hj Ismail, Z., Ismail, Z. H., & Mohamed, N. (2009). The integration of green chemistry experiments with sustainable development concepts in pre-service teachers' curriculum. *International Journal of Sustainability in Higher Education*, *10*(2), 118–135. https://doi.org/10.1108/14676370910945936

Karpudewan, M., Ismail, Z., & Roth, W.-M. (2012a). Ensuring sustainability of tomorrow through green chemistry integrated with sustainable development concepts (SDCs). *Chem. Educ. Res. Pract.*, *13*(2), 120–127. https://doi.org/10.1039/C1RP90066H

Karpudewan, M., Ismail, Z., & Roth, W.-M. (2012b). The Efficacy of a Green Chemistry Laboratory-Based Pedagogy: Changes in Environmental Values of Malaysia Pre-Service Teachers. *International Journal of Science and Mathematics Education*, *10*(3), 497–529. https://doi.org/10.1007/s10763-011-9295-y

Karpudewan, M., Ismail, Z., & Roth, W.-M. (2012c). Fostering Pre-service Teachers' Self-Determined Environmental Motivation Through Green Chemistry Experiments. *Journal of Science Teacher Education*, *23*(6), 673–696. https://doi.org/10.1007/s10972-012-9298-8

Karpudewan, M., Michael Roth, W., & Sinniah, D. (2016). The role of green chemistry activities in fostering secondary school students' understanding of acid–base concepts and argumentation skills. *Chem. Educ. Res. Pract.*, *17*(4), 893–901. https://doi.org/10.1039/C6RP00079G

Karpudewan, M., Roth, W.-M., & Ismail, Z. (2015a). Education in Green Chemistry: Incorporating Green Chemistry into Chemistry Teaching Methods Courses at the Universiti Sains Malaysia. In V. G. Zuin & L. Mammino (Eds.), *Worldwide Trends in Green Chemistry Education*.

Karpudewan, M., Roth, W.-M., & Ismail, Z. (2015b). The Effects of "Green Chemistry" on Secondary School Students' Understanding and Motivation. *Asia-Pacific Education Researcher*, *24*(1), 35–43. https://doi.org/10.1007/s40299-013-0156-z

Kelly, S., & Dennick, R. (2009). Evidence of gender bias in True-False-Abstain medical examinations. *BMC Medical Education*, *9*(1), 32. https://doi.org/10.1186/1472-6920-9-32

Kennedy, S. A. (2016). Design of a Dynamic Undergraduate Green Chemistry Course. *Journal of Chemical Education*, *93*(4), 645–649. https://doi.org/10.1021/acs.jchemed.5b00432

Khuong, K. S. (2017). Greener Oxidation of Benzhydrol: Evaluating Three Oxidation Procedures in the Organic Laboratory. *Journal of Chemical Education*, *94*(4), 534–537. https://doi.org/10.1021/acs.jchemed.6b00433

Kitchens, C., Charney, R., Naistat, D., Farrugia, J., Clarens, A., O'Neil, A., Lisowski, C., & Braun, B. (2006). Completing Our Education. Green Chemistry in the Curriculum. *Journal of Chemical Education*, *83*(8), 1126. https://doi.org/10.1021/ed083p1126

Klara, K., Hou, N., Lawman, A., Wu, L., Morrill, D., Tente, A., & Wang, L.-Q. (2014). Developing and Implementing a Simple, Affordable Hydrogen Fuel Cell Laboratory in Introductory Chemistry. *Journal of Chemical Education*, *91*(11), 1924–1928. https://doi.org/10.1021/ed4007875

Klingshirn, M. A., & Spessard, G. O. (2009). Integrating Green Chemistry into the Introductory Chemistry Curriculum. In P. T. Anastas, I. J. Levy, & K. E. Parent (Eds.), *Green Chemistry Education* (Vol. 1011, pp. 79–92). American Chemical Society. http://pubs.acs.org/doi/abs/10.1021/bk-2009-1011.ch005

Klingshirn, M. A., Wyatt, A. F., Hanson, R. M., & Spessard, G. O. (2008). Determination of the Formula of a Hydrate: A Greener Alternative. *Journal of Chemical Education*, *85*(6), 819. https://doi.org/10.1021/ed085p819

Lee, N. E., Gurney, R., & Soltzberg, L. (2014). Using Green Chemistry Principles as a Framework To Incorporate Research into the Organic Laboratory Curriculum. *Journal of Chemical Education*, *91*(7), 1001–1008. https://doi.org/10.1021/ed300283y

Levy, Irv. (2017). *Lab: Lettuce Seed Assay*. Beyond Benign. https://www.beyondbenign.org/lessons/lettuce-seed-assay/

Linn, M. C. (2006). Inquiry Learning: Teaching and Assessing Knowledge Integration in Science. *Science*, *313*(5790), 1049–1050. https://doi.org/10.1126/science.1131408

Linn, M. C., & Eylon, B. S. (2006). *Science education: Integrating views of learning and instruction*. Handbook of educational psychology. https://doi.org/10.4324/9780203874790.ch22

Linn, M. C., & Eylon, B. S. (2011). *Science Learning and Instruction: Taking Advantage of Technology to Promote Knowledge Integration* (1st ed.). Routledge. https://doi.org/10.4324/9780203806524

Linthorst, J. A. (2009). An overview: Origins and development of green chemistry. *Foundations of Chemistry*, *12*(1), 55–68. https://doi.org/10.1007/s10698-009-9079-4

Machado, A. S. C. (2015). Holistic Green Chemistry Metrics for Use in Teaching Laboratories. In V. Zuin & L. Mammino (Eds.), *Worldwide Trends in Green Chemistry Education* (pp. 111–136). Royal Society of Chemistry. https://doi.org/10.1039/9781782621942-00111

Mahaffy, P. G., Matlin, S. A., Whalen, J. M., & Holme, T. A. (2019). Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking. *Journal of Chemical Education*, *96*(12), 2730–2741. https://doi.org/10.1021/acs.jchemed.9b00390

Mammino, L. (2019). *Roles of Systems Thinking within Green Chemistry Education: Reflections from Identified Challenges in a Disadvantaged Context*. 1–7. https://doi.org/10.1021/acs.jchemed.9b00302

Mandler, D., Mamlok-Naaman, R., Blonder, R., Yayon, M., & Hofstein, A. (2012). High-school chemistry teaching through environmentally oriented curricula. *Chem. Educ. Res. Pract.*, *13*(2), 80–92. https://doi.org/10.1039/C1RP90071D

Marteel-Parrish, A. E. (2014). Teaching Green and Sustainable Chemistry: A Revised One-Semester Course Based on Inspirations and Challenges. *Journal of Chemical Education*, *91*(7), 1084–1086. https://doi.org/10.1021/ed400393b

Marteel-Parrish, A., & Newcity, K. M. (2017). Highlights of the Impacts of Green and Sustainable Chemistry on Industry, Academia and Society in the USA. *Johnson Matthey Technology Review*, *61*(3), 207–221.

Martin, A., Iles, A., & Rosen, C. (2021). Applying Utilitarianism and Deontology in Managing Bisphenol-A Risks in the United States. In J. Schummer & T. Børsen, *Ethics of Chemistry* (pp. 249–278). WORLD SCIENTIFIC. https://doi.org/10.1142/9789811233548_0010

Masters, G. N. (1996). *Educational Measurement*. Australian Council for Educational Research.

Masters, G. W., & Wright, B. D. (1981). *Model for Partial Credit Scoring*. University of Chicago, Department of Education, Statistical Laboratory. https://www.ncjrs.gov/App/Publications/abstract.aspx?ID=85947

Masters, Geoff N. (1982). A rasch model for partial credit scoring. *Psychometrika*, *47*(2), 149–174. https://doi.org/10.1007/BF02296272

Matsui, J., Liu, R., & Kane, C. M. (2003). Evaluating a Science Diversity Program at UC Berkeley: More Questions Than Answers. *Cell Biology Education*, *2*(2), 117–121. https://doi.org/10.1187/cbe.02-10-0050

Matus, K. J. M., Xiao, X., & Zimmerman, J. B. (2012). Green chemistry and green engineering in China: Drivers, policies and barriers to innovation. *Journal of Cleaner Production*, *32*(C), 193–203. https://doi.org/10.1016/j.jclepro.2012.03.033

Meyers, N. M., & Nulty, D. D. (2009). How to use (five) curriculum design principles to align authentic learning environments, assessment, students' approaches to thinking and learning outcomes. *Assessment & Evaluation in Higher Education*, *34*(5), 565–577. https://doi.org/10.1080/02602930802226502

Milfont, T. L., & Duckitt, J. (2010). The environmental attitudes inventory: A valid and reliable measure to assess the structure of environmental attitudes. *Journal of Environmental Psychology*, *30*(1), 80–94. https://doi.org/10.1016/j.jenvp.2009.09.001

Morin, O, Simonneaux, L., Simmoneaux, J., Tytler, R., & Barraza, L. (2014). Developing and Using an S3R Model to Analyze Reasoning in Web-Based Cross-National Exchanges on Sustainability. *Science Education*, *98*, 517–542. https://doi.org/10.1002/sce.21113

Morin, Olivier, Simonneaux, L., Simonneaux, J., & Tytler, R. (2013). Digital technology to support students' socioscientific reasoning about environmental issues. *Journal of Biological Education*, *47*(3), 157–165. https://doi.org/10.1080/00219266.2013.821748

Morin, O., Simonneaux, L., & Tytler, R. (2017). Engaging with socially acute questions: Development and validation of an interactional reasoning framework. *Journal of Research in Science Teaching*, *54*(7), 825–851. https://doi.org/10.1002/tea.21386

Morra, B., & Dicks, A. P. (2016). Recent Progress in Green Undergraduate Organic Laboratory Design. In J. T. Fahey & L. E. Maelia (Eds.), *Green Chemistry Experiments in Undergraduate Laboratories* (Vol. 1233, pp. 7–32). American Chemical Society.

Moscato, E. M., & Machin, J. E. (2018). Mother natural: Motivations and associations for consuming natural foods. *Appetite*, *121*, 18–28. https://doi.org/10.1016/j.appet.2017.10.031

Muijtjens, A. M., Mameren, H. V., Hoogenboom, R. J., Evers, J. L., & van der Vleuten, C. P. (1999). The effect of a "don't know" option on test scores: Number-right and formula scoring compared. *Medical Education*, *33*(4), 267–275. https://doi.org/10.1046/j.1365-2923.1999.00292.x

Orgill, M., York, S., & MacKellar, J. (2019). Introduction to Systems Thinking for the Chemistry Education Community. *Journal of Chemical Education*, acs.jchemed.9b00169. https://doi.org/10.1021/acs.jchemed.9b00169

Paek, I., & Wilson, M. (2011). Formulating the Rasch differential item functioning model under the marginal maximum likelihood estimation context and its comparison with Mantel-Haenszel procedure in short test and small sample conditions. *Educational and Psychological Measurement*, *71*(6), 1023–1046. https://doi.org/10.1177/0013164411400734

Paluri, S. L. A., Edwards, M. L., Lam, N. H., Williams, E. M., Meyerhoefer, A., & Pavel Sizemore, I. E. (2015). Introducing "Green" and "Nongreen" Aspects of Noble Metal Nanoparticle Synthesis: An Inquiry-Based Laboratory Experiment for Chemistry and Engineering Students. *Journal of Chemical Education*, *92*(2), 350–354. https://doi.org/10.1021/ed5004806

Patton, M. Q. (2008). *Utilization-Focused Evaluation*. SAGE Publications. http://books.google.com/books?id=DFYXBAAAQBAJ&pg=PA37&dq=inauthor:Patton+intitle:utilization+focused+evaluation&hl=&cd=1&source=gbs_api

Phillips, D. C. (1995). The Good, the Bad, and the Ugly: The Many Faces of Constructivism. *Educational Researcher*, *24*(7), 5–12. https://doi.org/10.3102/0013189X024007005

Prescott, S. (2013). Green Goggles: Designing and Teaching a General Chemistry Course to Nonmajors Using a Green Chemistry Approach. *Journal of Chemical Education*, *90*(4), 423–428. https://doi.org/10.1021/ed300538d

Purcell, S. C., Pande, P., Lin, Y., Rivera, E. J., Latisha, P. U., Smallwood, L. M., Kerstiens, G. A., Armstrong, L. B., Robak, M. T., Baranger, A. M., & Douskey, M. C. (2016). Extraction and Antibacterial Properties of Thyme Leaf Extracts: Authentic Practice of Green Chemistry. *Journal of Chemical Education*, *93*(8), 1422–1427. https://doi.org/10.1021/acs.jchemed.5b00891

Rand, D., Yennie, C. J., Lynch, P., Lowry, G., Budarz, J., Zhu, W., & Wang, L.-Q. (2016). Development and Implementation of a Simple, Engaging Acid Rain Neutralization Experiment and Corresponding Animated Instructional Video for Introductory Chemistry Students. *Journal of Chemical Education*, *93*(4), 722–728. https://doi.org/10.1021/acs.jchemed.5b00635

Rauch, F. (2015). Education for Sustainable Development and Chemistry Education. In V. Zuin & L. Mammino (Eds.), *Worldwide Trends in Green Chemistry*

Education (pp. 16–26). Royal Society of Chemistry. https://doi.org/10.1039/9781782621942-00016

Ravesloot, C. J., Van der Schaaf, M. F., Muijtjens, A. M. M., Haaring, C., Kruitwagen, C. L. J. J., Beek, F. J. A., Bakker, J., Van Schaik, J. P. J., & Cate, Th. J. T. (2015). The don't know option in progress testing. *Advances in Health Sciences Education*, *20*(5), 1325–1338. https://doi.org/10.1007/s10459-015-9604-2

Rickey, D., & Stacy, A. M. (2000). The role of metacognition in learning chemistry. *Journal of Chemical Education*, *77*(7), 915–920.

Riegle-Crumb, C., King, B., Grodsky, E., & Muller, C. (2012). The More Things Change, the More They Stay the Same? Prior Achievement Fails to Explain Gender Inequality in Entry Into STEM College Majors Over Time. *American Educational Research Journal*, *49*(6), 1048–1073. https://doi.org/10.3102/0002831211435229

Roesky, H. W., Kennepohl, D. K., & Lehn, J.-M. (Eds.). (2009). *Experiments in green and sustainable chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA.

Román, S., Sánchez-Siles, L. M., & Siegrist, M. (2017). The importance of food naturalness for consumers: Results of a systematic review. *Trends in Food Science & Technology*, *67*, 44–57. https://doi.org/10.1016/j.tifs.2017.06.010

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education*, *89*(4), 634–656. https://doi.org/10.1002/sce.20065

Savery, J. R., & Duffy, T. M. (1995). Problem Based Learning: An Instructional Model and Its Constructivist Framework. *Educational Technology*, *35*(5), 31–38.

Sevian, H., & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. *Chem. Educ. Res. Pract.*, *15*(1), 10–23. https://doi.org/10.1039/C3RP00111C

Shamuganathan, S., & Karpudewan, M. (2017). Science writing heuristics embedded in green chemistry: A tool to nurture environmental literacy among pre-university students. *Chemistry Education Research and Practice*, *18*(2), 386–396. https://doi.org/10.1039/c7rp00013h

Simon, R. M., Wagner, A., & Killion, B. (2016). Gender and choosing a STEM major in college: Femininity, masculinity, chilly climate, and occupational values. *Journal of Research in Science Teaching*, *54*(3), 299–323. https://doi.org/10.1002/tea.21345

Sitzmann, T., Ely, K., Brown, K. G., & Bauer, K. N. (2010). Self-Assessment of Knowledge: A Cognitive Learning or Affective Measure? *Academy of Management Learning & Education*, *9*(2), 169–191.

Sjöström, J., & Eilks, I. (2017). Reconsidering Different Visions of Scientific Literacy and Science Education Based on the Concept of Bildung. In *Cognition,*

Metacognition, and Culture in STEM Education (pp. 65–88). Springer International Publishing. https://doi.org/10.1007/978-3-319-66659-4_4
Sjostrom, J., Eilks, I., & Zuin, V. G. (2016). Towards Eco-reflexive Science Education A Critical Reflection About Educational Implications of Green Chemistry. *Science & Education*, *25*(3–4), 321–341. https://doi.org/10.1007/s11191-016-9818-6
Sjostrom, J., & Talanquer, V. (2014). Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problematization. *Journal of Chemical Education*, *91*(8), 1125–1131. https://doi.org/10.1021/ed5000718
Sjöström, J., & Talanquer, V. (2018). Eco-reflexive chemical thinking and action. *Current Opinion in Green and Sustainable Chemistry*, *13*, 16–20. https://doi.org/10.1016/j.cogsc.2018.02.012
Spencer, J. N. (1999). New Directions in Teaching Chemistry: A Philosophical and Pedagogical Basis. *Journal of Chemical Education*, *76*(4), 566. https://doi.org/10.1021/ed076p566
Stuckey, M., Hofstein, A., Mamlok-Naaman, R., & Eilks, I. (2013). The meaning of 'relevance' in science education and its implications for the science curriculum. *Studies in Science Education*, *49*(1), 1–34. https://doi.org/10.1080/03057267.2013.802463
Tate, E. D., & Linn, M. C. (2005). How Does Identity Shape the Experiences of Women of Color Engineering Students? *Journal of Science Education and Technology*, *14*(5–6), 483–493. https://doi.org/10.1007/s10956-005-0223-1
Thompson, J. E. (2013). *Biodiesel Synthesis- Chem Lab*. GEMS.
Tucker, J. L. (2010). Green Chemistry: Cresting a Summit toward Sustainability. *Organic Process Research & Development*, *14*(2), 328–331. https://doi.org/10.1021/op9000548
United Nations Decade of Education for Sustainable Development (2005-2014): International Implementation Scheme (pp. 1–31). (2005). UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000141629(Accessed August 23, 2019)
US EPA, O. (2013, March 12). *Presidential Green Chemistry Challenge: 2011 Designing Greener Chemicals Award* [Overviews and Factsheets]. US EPA. https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2011-designing-greener-chemicals-award
Van Aalsvoort, J. (2004). Logical positivism as a tool to analyse the problem of chemistry's lack of relevance in secondary school chemical education. *International Journal of Science Education*, *26*(9), 1151–1168. https://doi.org/10.1080/0950069042000205369
von Blottnitz, H., Case, J. M., & Fraser, D. M. (2015). Sustainable development at the core of undergraduate engineering curriculum reform: A new introductory

course in chemical engineering. *Journal of Cleaner Production*, *106*, 300–307. https://doi.org/10.1016/j.jclepro.2015.01.063

Wilson, M. (2005). *Constructing measures: An item response modeling approach*. Lawrence Erlbaum Associates.

Woodhouse, E. J., & Breyman, S. (2005). Green Chemistry as Social Movement? *Science, Technology, & Human Values*, *30*(2), 199–222. https://doi.org/10.1177/0162243904271724

Appendix I. Assessment of Chemistry Knowledge (Chapter 2)

Students completed a comprehensive survey at before and after completing the new general chemistry laboratory. They were asked how much they understood about a broad range of chemistry topics and laboratory techniques. Student chemistry content knowledge was measured using 21 fixed response survey items. Sixteen Likert items were used to measure students' self-assessment of their chemistry content knowledge and technique ability and five multiple choice chemistry content question were used to measure students' knowledge of core general chemistry concepts (e.g., intermolecular interactions, absorbance, titration curves). These items were analyzed for the Fall 2016 semester concurrent with the in-class green chemistry analysis.

Students were asked how much the understood specific concepts and techniques; *Not at all* was assigned a value of 0, *a little* a value of 1, somewhat a value of 2, *a good deal* a value of 3, and *a great deal* a value of 4. Students were allowed to select one fixed response answer. Students were encouraged to select "I don't know" if they were unsure of the answer to decrease random guessing. These items were categorized as *correct*, *incorrect*, or *I don't know*.'

Survey results showed that students' self-reported understanding of a wide range of chemistry topics (e.g., chemical bonding, reaction equilibrium, acid-base reactivity) and laboratory techniques (e.g., titration, UV/Vis spectroscopy, calorimetry) increased significantly between the beginning and end of the Fall 2016 semester. For all questions there was a significant difference in mean scores before and after completing the course (d.f. = 516, $p < 0.\ 001$).

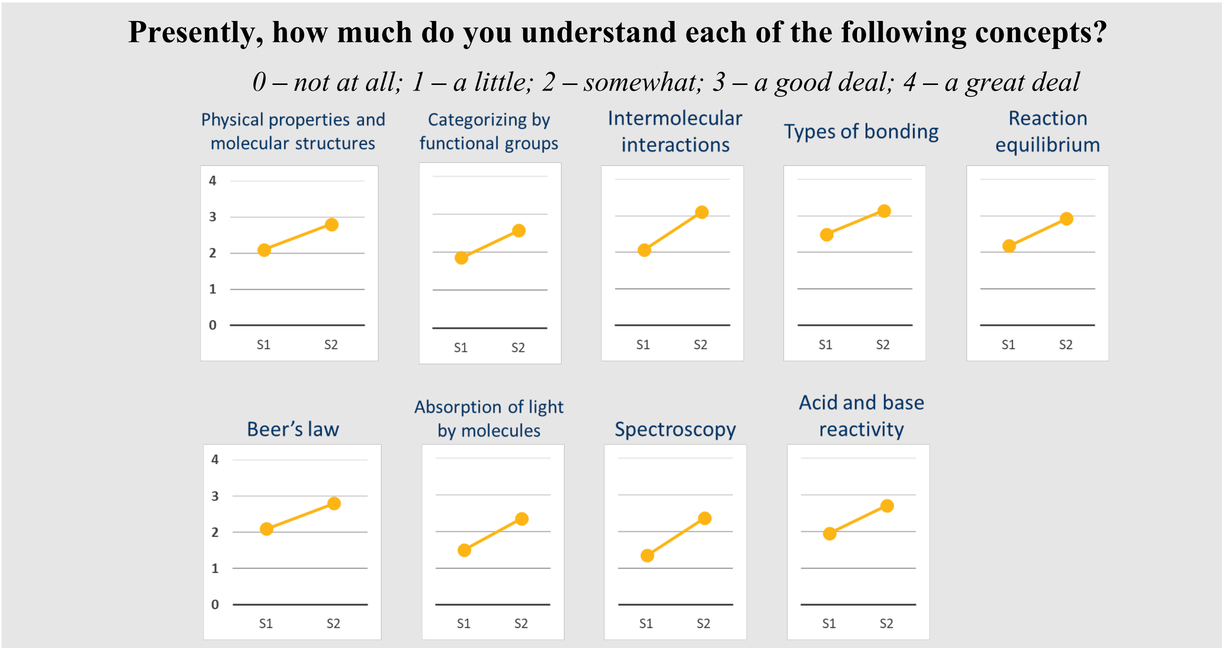


Figure A I. Student self-reported understanding of chemistry concepts before and after completing Chem 1AL. For all questions there was a significant difference in mean scores before and after completing the course (d.f .= 516, $p < 0.001$).

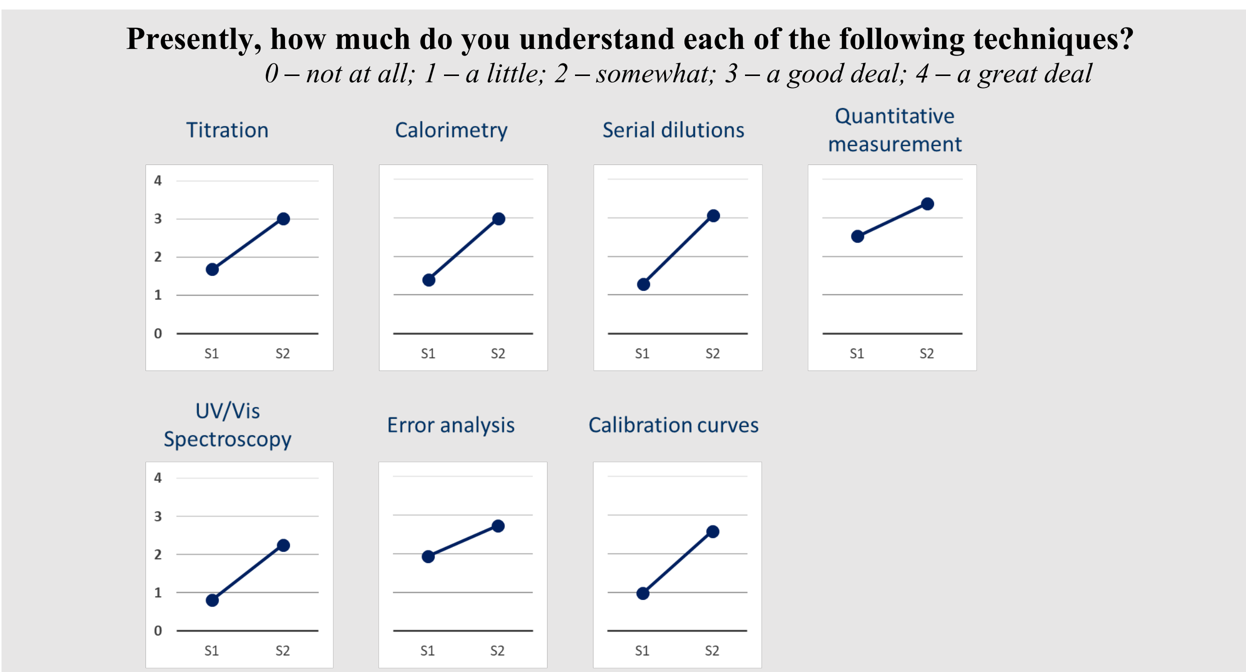


Figure A II. Student self-reported understanding of chemistry techniques before and after completing Chem 1AL. For all questions there was a significant difference in mean scores before and after completing the course (d.f.= 516, $p < 0.001$).

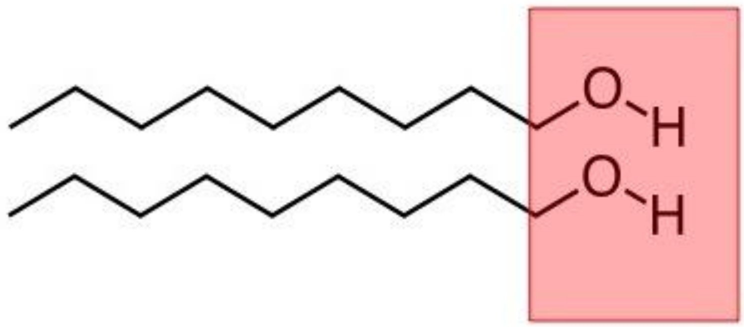
In the same survey, students were asked to complete five multiple choice questions to demonstrate their chemistry content knowledge of intermolecular forces (IMFs), titration, absorbance and bond energy. The percentage of students answered correctly, incorrectly and “I don’t know” were calculated. For all questions, there was a significant difference in the percentage of students who answered correctly before and after completing the course. Students showed the greatest improvement on questions about IMFs, and least improvement on the question about bond energy. They also showed least understanding of titration both pre- (25.63%) and posttest (44.25%), although there was an improvement in the percentage of correct answers after students complete the course.

Table A I. Pre and posttest scores for chemistry content survey items (Fall 2016, N = 515). Complete questions are shown below.

	Pretest (%)			**Posttest (%)**			**p-value**
	Correct	Incorrect	I don’t know	Correct	Incorrect	I don’t know	
IMF 1	62.21	8.91	28.88	93.23	3.87	2.90	< 0.001
IMF 2	42.55	13.54	43.91	89.75	5.42	4.84	< 0.001
Titration	25.63	22.72	51.65	44.25	32.55	23.20	< 0.001
Absorbance	57.81	25.59	16.60	64.98	27.04	7.98	< 0.01
Bond Energy	67.76	21.24	11.00	73.11	23.40	3.48	< 0.05

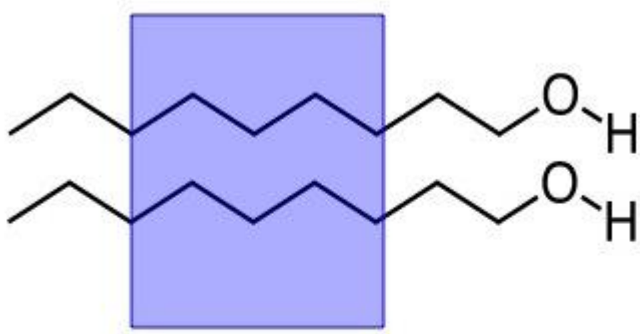
Chemistry content multiple choice items

Please do your best to answer the following questions honestly. If you do not know the answer or how to attempt the problem, please do not guess; mark "I don't know."



IMF 1: Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above.

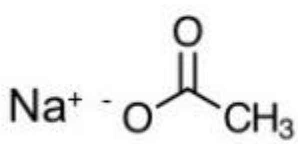
- ◯ Ionic interactions
- ◯ Hydrogen bonding interactions
- ◯ London dispersion interactions (induced dipole-induced dipole interactions)
- ◯ I don't know.



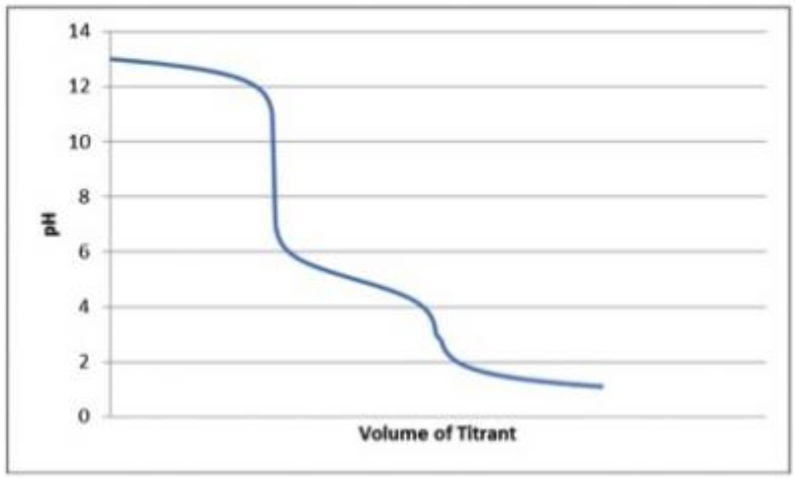
IMF 2: Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above.

- ◯ Ionic interactions
- ◯ Hydrogen bonding interactions
- ◯ London dispersion interactions (induced dipole-induced dipole interactions)
- ◯ I don't know.

Titration: For the next question consider the following information: In lab you use hydrochloric acid (HCl) to titrate a mixture of sodium hydroxide (NaOH) and sodium acetate (NaC2H3O2). You measure the pH during the titration, and the titration curve shown below is the result.



sodium acetate

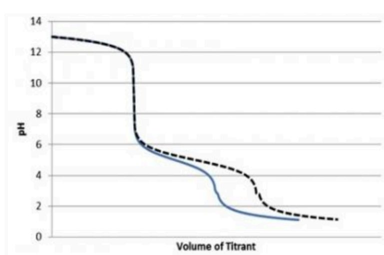
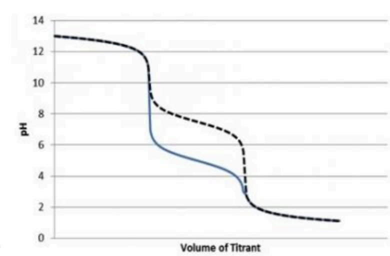
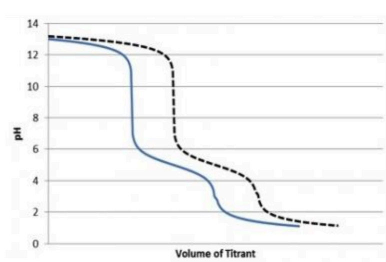
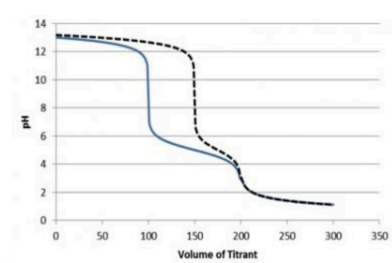


Your lab partner has a different sample, one with a greater amount of NaOH and the same amount of NaC2H3O2.

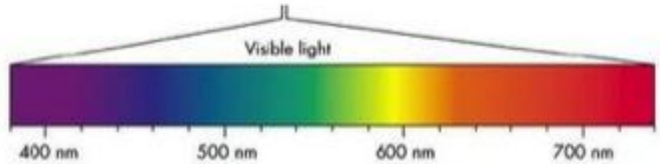
Your data

Your lab partner's data

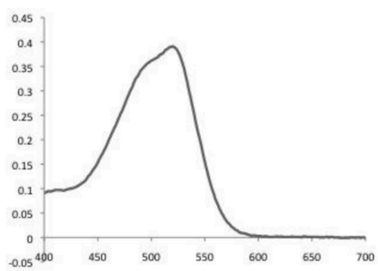
What would the titration curve for this sample look like compared to yours?

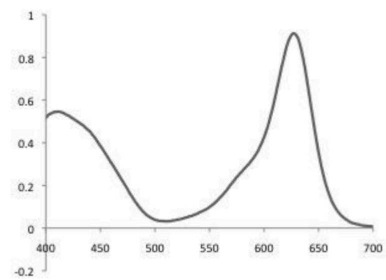
- ◯ 
- ◯ 
- ◯ 
- ◯ 
- ◯ I don't know.

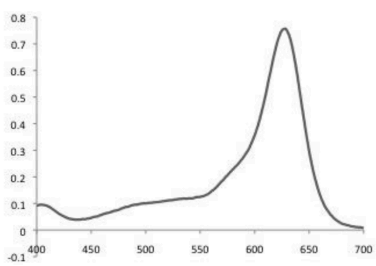
Absorbance: For the next question, refer to the spectrum provided below:



Which absorbance spectrum (absorbance versus wavelength in nm) would correspond to a green solution?

○ 

○ 

○ 

○ I don't know.

Bond Energy: Heat is given off when hydrogen burns in air according to the equation: $2H_2 + O_2 \rightarrow 2H_2O$ Which of the following is responsible for the heat?

○ A. Breaking bonds between hydrogen atoms gives off energy.

○ B. Breaking bonds between oxygen atoms gives off energy.

○ C. Forming bonds between hydrogen and oxygen atoms gives off energy.

○ Both answers A and B are correct.

○ Answers A, B, and C are correct.

○ I don't know

Appendix II. Detailed Demographics (Chapter 2 and 4)

For the Fall 2016 semester, approximately half of the students enrolled in Chem 1AL consented to be part of our study and provided demographic data. An additional subgroup of students who had completed every green chemistry item at each assessment time point were selected for additional analysis. For both study populations, respondent characteristics were like the demographics of the entire class population. The ethnicity of the study respondents closely matched the class population with the percentage of Asian participants slightly higher and the percentage of Latinx participants slightly lower within the study sample. Like the entire class population, our study population contained more female respondents than male respondents. However, compared to the class population there was a slight overrepresentation of female respondents. This is a well-known phenomenon as women often have much higher response rates then men on surveys.[1,2]

Table A II. Fall 2016 Chem 1AL demographics for study and course populations (Chapter 2)

	Study subgroup[a]		**Study population[b]**		**Course Population[c]**	
	N	**%**	**N**	**%**	**N**	**%**
Race/Ethnicity						
White	69	27.5	126	24.3	257	24.1
Hispanic, Latino or Spanish Origin	23	9.2	49	9.5	153	14.4
African-American/ Black	8	3.2	11	2.1	25	2.3
Asian	123	49.0	270	52.1	477	44.7
Pacific Islander	1	0.4	2	0.4	1	0.1
Native American/ Alaska Native	1	0.4	1	0.2	3	0.3
International	20	8.0	44	8.5	100	9.4
Decline to State	6	2.4	15	2.9	50	4.7
Gender						
Female	149	59.4	323	62.4	628	58.9
Male	95	37.8	182	35.1	403	37.8
Not sure	3	1.2	3	0.6	N/A	N/A
Transgender	1	0.4	1	0.2	N/A	N/A
Decline to state	3	1.2	9	1.7	35	3.3
Total	**251**		**518**		**1066**	

[a]Students who consented to be part of our research, completed all the green chemistry assessment items, and provided demographic information

[b]Students who consented to be part of our research and provided demographic information

[c]Entire course population data were obtained from Berkeley Office of Planning and Analysis

[1] Underwood, D.; Kim, H.; Matier, M. *To Mail or To Web: Comparisons of Survey Response Rates and Respondent Characteristics. AIR 2000 Annual Forum Paper*; 2000.

[2] Sax, L. J.; Gilmartin, S. K.; Lee, J. J.; Hagedorn, L. S. Using Web Surveys to Reach Community College Students: An Analysis of Response Rates and Response Bias. *Community Coll. J. Res. Pract.* **2008**, *32* (9), 712–729. https://doi.org/10.1080/10668920802000423.

Table A III. Fall 2018 and Fall 2019 demographic data for research population. Demographic and full class data provided for comparison (Chapter 4)

	Study Population[1]						Course Population[2]	
	Fall 2019		Fall 2018		Fall 2016		Fall 2016	
	N	%	N	%	N	%	N	%
Race/Ethnicity								
Asian	403	52.1	368	47.8	270	52.1	477	44.7
White	186	24.0	193	25.1	126	24.3	257	24.1
Hispanic, Latino or Spanish Origin	98	12.7	85	11.0	49	9.5	153	14.4
African American/Black	11	1.4	11	1.4	11	2.1	25	2.3
Pacific Islander	6	0.8	14	1.8	2	0.4	1	0.1
Native American/Alaska Native	4	0.5	14	1.8	1	0.2	3	0.3
International	64	8.3	78	10.1	44	8.5	100	9.4
Decline to State	2	0.3	7	0.9	15	2.9	50	4.7
Gender								
Female	512	66.1	507	65.8	323	62.4	628	58.9
Male	251	32.4	244	31.7	182	35.1	403	37.8
Non-binary	3	0.4	6	0.8	N/A	N/A	N/A	N/A
Not sure		0.0	2	0.3	3	0.6	N/A	N/A
Transgender	0	0.0	0	0.0	1	0.2	N/A	N/A
Decline to state	8	1.0	11	1.4	9	1.7	35	3.3
Total	**774**		**770**		**518**		**1066**	

[1] Students who consented to be part of our research and provided demographic information

[2] Entire course population data were obtained from Berkeley Office of Planning and Analysis

Appendix III. Original Green Chemistry Prelab and Postlab Questions (Chapter 2)

Table A IV. Green chemistry prelab and postlab questions in the Chem 1AL curriculum (Fall 2016)

Experiment	Placement	Question	Inquiry component
Designing a Model Airbag	Postlab	Would this method be suitable for inflating automobile airbags? Why or why not?	Understanding impact, conclusions about model
Polymers: Cross-Linking and Toy Design Part 1	Prelab[1]	Part of any successful experiment is cleaning up your lab space at the end of lab. As always, you are expected to thoroughly clean up the lab space, put equipment back where it belongs, and dispose of waste in the proper container. Liquid waste will have a special place in the fume hood and solid, chemically contaminated waste should be placed in containers. Materials that have not been exposed to chemicals can go in the regular trash. Each week, waste disposal information will be posted by the ISF in the experiment notes on bCourses. Review what should be done with each of the following.	N/A
Polymers: Cross-Linking and Toy Design Part 2	Postlab	You have been promoted to Chief Sustainability Officer for the toy company. Your R&D division has given you three possible starting materials for making a toy, and you have to choose which one to use. From doing this week's lab, you have some information about the properties of these polymers that would make a fun toy. However, as the CSO you also need to consider effects on human health and the environment. Based on your experience of doing the lab and the data shown in the table below, choose a polymer and make an argument as to why you chose it. Note: there are no wrong answers. (They refer to a data table that includes toxicity and environmental persistence.)	Understanding impact, analyzing data, conclusions about model, proposing explanations

[1] This question was asked at the end of every prelab.

Experiment	Placement	Question	Inquiry component
Biofuels Part 1	Prelab	Green chemistry is a field of decision making based off the trade-offs of environmental impacts, safety, efficiency, and opportunity cost. In the following experiments, we will look at data based off the toxicity, practicality, and efficiency of several biofuels to try to assess the relative merit of each as a fossil fuel alternative. Toxicity is often measured through the Dose-Response relationship of test subjects to the chemical. Based on the Dose-Response plot, what is the LD for the biofuel shown below.	Calculations from data
Biofuels Part 1	Prelab	Look up the LD and melting temperature for the following fuels from the Material Safety Data Sheets (MSDS) located in the files section of bCourses for this class (in a folder titled "biofuels_MSDS").	Literature search
Biofuels Part 1	Postlab	Rank the substances from most to least toxic.	Analyzing data, calculations from data
Biofuels Part 1	Postlab	Guess which substance claims the most human lives every year. Explain your reasoning.	Understanding impact
Biofuels Part 1	Postlab	Doctors have recommended against giving children aspirin, and instead recommend acetaminophen. How many 500 mg tablets of aspirin would it take to reach the LD50 threshold for a 22 lb. (10 kg) child? How many 500 mg tablets of acetaminophen?	Calculations from data
Biofuels Part 1	Postlab	Read the “Pro-Biodiesel” and “Anti-Biodiesel” excerpts in the introduction to this experiment. These represent two opposing perspectives about the use of biodiesel as a fuel source. After reading this information, do you feel better informed? Do you think that using biodiesel is practical? Is there any information that the excerpts did not provide that you would want in order to make a decision? Write a	Understanding impact, literature search, communicating results, proposing explanations

Experiment	Placement	Question	Inquiry component
		paragraph about your thoughts on the topic.	
Biofuels Part 2	Postlab	According to the class data, which biofuel was the most toxic according to the weight percent solutions? a. Which biofuel was the most toxic according to the molarity of the solutions? b. Compare and contrast these values. Which is more relevant in practical use?	Understanding impact, calculations from data, analyzing data, conclusions about hypothesis
Acids in the Environment Part 1	In-lab prompt	What benefits are there to using serial dilutions to make solutions? What are the drawbacks?	Designing and experiment, analyzing data
Acids in the Environment Part 3	Postlab	Explain conceptually the process by which the limestone can protect the lakes in the Midwest from the effects of acid rain.	Understanding impact, proposing explanations

Appendix IV. Evaluation Instruments (Chapters 3 – 5)

Online survey (Qualtrics)

Chem 1AL Posttest, Fall 2019

Investigating New General Chemistry Curriculum in the College of Chemistry

My name is Laura Armstrong and I am a graduate student working with the Director of Undergraduate Chemistry, Anne Baranger, and other faculty and graduate students in the College of Chemistry. We are planning to conduct a research study, which we invite you to take part in.

We are inviting you to participate in this study because you are enrolled in general chemistry. The purpose of this research is to understand the effects of this new curriculum to not only improve chemistry education at UCB but also to improve chemistry education at other institutions by sharing our results with the chemistry education community.

If you agree to be in this study, you will be asked to do the following:

- Complete this online survey. The survey will include questions about your background in chemistry and your experiences in the course. It will take approximately 15-20 minutes to complete. The surveys will be administered at the beginning and end of the semester.
- Allow us (the researchers) access to materials you submit as part of the course (assessments, homework, midterm exams, final exams, quizzes, etc.). The assessments will be administered in a variety of formats. This is not extra class work but material that all students enrolled in the course will complete.

Benefits
Although there is no direct benefit to you from participating in this research, we hope that this research will benefit society by improving our understanding of the Berkeley chemistry curriculum. This will also give you a chance to have a voice in the curriculum development process.

Risks/Discomforts
You are free to decline to answer any questions you don't wish to or to stop participating at any time.

Breach of confidentiality: as with all research, there is a chance that confidentiality could be compromised; however, we are taking precautions to minimize this risk.

Confidentiality
Your study data will be handled as confidentially as possible. If the results of this study are published or presented, individual names and other personally identifiable information will not be used.

To minimize the risks to confidentiality, we will assign you a unique participant ID number that will be used to replace identifying information, such as your name, in your data. Your data (video included) will be stored in a locked cabinet in our lab or electronically in password-protected files. The list that links participant numbers to identity will be kept in a locked cabinet separate from study data.

When the research is completed, we may save the study data for use in future research done by ourselves or by others. We will retain these records for up to six years after the study is over. The same measures described above will be taken to protect the confidentiality of this study data.

Compensation
Two bonus points will be awarded for the completion of this survey. If you do not wish to participate but would still like to receive these bonus points, you may complete the alternate assignment outlined in the invitation announcement.

Rights
Participation in research is completely voluntary.

You have the right to decline to participate or to withdraw at any point in this study without penalty or loss of benefits to which you are otherwise entitled; your standing in the class or school will in no way be affected by your decision.

Questions
If you have any questions or concerns about this study, you may contact Laura Armstrong at armstronglaura@berkeley.edu.

If you have any questions or concerns about your rights and treatment as a research subject, you may contact the office of UC Berkeley's Committee for the Protection of Human Subjects, at 510-642-7461 or subjects@berkeley.edu.

If you agree to take part in the research please select the button below.

☐ I agree to have my survey responses and course materials collected.

Please indicate your level of agreement with the following statements:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I try to reduce my energy usage.	○	○	○	○	○
I think about how my decisions impact the environment.	○	○	○	○	○
I try to conserve natural resources such as water.	○	○	○	○	○
I don't worry about how much waste I create; one person can't make much of a difference.	○	○	○	○	○
When choosing a new product, I think about what was required to make it (starting materials, safety, waste, etc.).	○	○	○	○	○
I buy products that I consider 'green.'	○	○	○	○	○
I talk with friends about problems related to green chemistry.	○	○	○	○	○
I have pointed out 'non-green' behavior to someone.	○	○	○	○	○
Energy usage is not a major concern during chemistry experiments.	○	○	○	○	○
Chemistry experiments should reduce their use of limited natural resources (e.g. water, minerals).	○	○	○	○	○
We don't need to make chemistry experiments safer - that's why we use goggles, lab coats, and gloves.	○	○	○	○	○
Chemistry should focus on advancing research and chemical understanding. The impact these advances have on humans and the environment is a secondary concern.	○	○	○	○	○
Cleaning up or treating chemical waste is a good alternative to minimizing the amount of experimental waste.	○	○	○	○	○
Industry should use renewable materials even if this costs more than using nonrenewable materials.	○	○	○	○	○
Chemistry experiments should use nonrenewable materials if this leads to lower costs or better results, even if it means the raw materials will eventually be used up.	○	○	○	○	○

Green Chemistry Understanding

How well can you define green chemistry?

- ○ I cannot define green chemistry.
- ○ I can define green chemistry in broad terms, but I cannot provide explanations or examples.
- ○ I can define green chemistry and provide **simple** explanations or examples.
- ○ I can define green chemistry and provide **a few detailed** explanations or examples.
- ○ I can define green chemistry and provide **many detailed** explanations or examples.

How well can you evaluate the 'greenness' of a chemical reaction?

- ○ I don't understand how green chemistry can be used to evaluate something.
- ○ I can identify that evaluation is needed but I might not know what principles to apply to the reaction. I could probably make some broad suggestions.
- ○ I can identify a few factors or principles to evaluate the greenness of the reaction. I might struggle with identifying all of the needed factors.
- ○ I can identify the needed factors or principles to evaluate the greenness of the reaction.
- ○ I can identify the needed factors or principles and make recommendations to improve the greenness of the reaction.

How well can you define green chemistry principles (e.g. waste prevention, energy efficiency, atom economy)?

- ○ I cannot define green chemistry principles.
- ○ I can define **a few** green chemistry principles.
- ○ I can define **about half** of the green chemistry principles.
- ○ I can define **most** green chemistry principles.
- ○ I can define **most** green chemistry principles and provide examples for these terms.

Please indicate your level of agreement with the following statements about **green chemistry**:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I want to acquire more green chemistry knowledge.	○	○	○	○	○
I find green chemistry interesting.	○	○	○	○	○
I believe that I can understand green chemistry.	○	○	○	○	○
I can do green chemistry.	○	○	○	○	○
Green chemistry has connections to my daily life.	○	○	○	○	○
Green chemistry is **NOT** useful for other fields I am interested in.	○	○	○	○	○
I think green chemistry is important for advancing society.	○	○	○	○	○
I think green chemistry is important in advancing knowledge.	○	○	○	○	○
I think about the green chemistry I experience in everyday life.	○	○	○	○	○
Learning green chemistry changes my ideas about how the world works.	○	○	○	○	○
The subject of green chemistry has little relation to what I experience in the real world.	○	○	○	○	○
Green chemistry plays an important role in my life because I use many products of the chemical industry.	○	○	○	○	○
I think green products are very important.	○	○	○	○	○

Please do your best to answer the following questions honestly and without outside help. We want to hear from you - not Google :)

It's okay if you don't know how to answer or attempt the problem, don't guess - just mark “I don’t know.”

The reaction below can be used to fill an automobile airbag.

	$2NH_4NO_3(s)$ (ammonium nitrate)	→	$4\ H_2O(l)$ (water)	+	$2\ N_2(g)$ (nitrogen)	+	$O_2(g)$ (oxygen)
M.W. (g/mol)	80.04		18.02		28.01		32.00
LD_{50} (mg/kg in rats)	2217		>90,000		none available		none available

The atom economy for this reaction is 55%. This means that:
(Select all that are accurate.)

- ☐ 45% of the starting material ends up as waste in the form of water
- ☐ 55% of the starting material ends up as waste in the form of water
- ☐ 55% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag
- ☐ 45% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag
- ☐ The theoretical yield of the reaction is 55%.
- ☐ The theoretical yield of the reaction is 45%.
- ☐ I don't know.

The reaction below can be used to fill an automobile airbag.

	$2NH_4NO_3(s)$ (ammonium nitrate)	→	$4\ H_2O(l)$ (water)	+	$2\ N_2(g)$ (nitrogen)	+	$O_2(g)$ (oxygen)
M.W. (g/mol)	80.04		18.02		28.01		32.00
LD_{50} (mg/kg in rats)	2217		>90,000		none available		none available

The LD50 for the starting material, ammonium nitrate, is shown above. LD50 tells you:
(Select all statements that are accurate.)

- ☐ The amount of a chemical that it takes to cause death in half the members of a test population
- ☐ The amount of a chemical that it takes to cause mutations in an entire test population
- ☐ The amount of a chemical that it takes to cause bioaccumulation in half the members of a test population
- ☐ The amount of a chemical that it takes to cause endocrine disruption in an entire test population
- ☐ The amount of a chemical that it takes to cause birth defects in half the members of a test population
- ☐ The amount of a chemical that it takes to cause cancer in an entire test population
- ☐ I don't know.

The LD50 for the starting material is 2217 mg/kg for rats. This indicates that:
(Select all statements that are accurate.)

- ☐ The compound is NOT acutely toxic to humans (it safe to be exposed to this compound for single or short period of time).
- ☐ The compound is acutely toxic to humans (it unsafe to be exposed to this compound for single or short period of time).
- ☐ This compound is safe for humans to use.
- ☐ This compound is NOT safe for humans.
- ☐ The compound may or may not be safe for humans to use.
- ☐ LD50 doesn't give information on how safe a compound is for humans.
- ☐ This compound is safe to release into the environment.
- ☐ This compound is NOT safe to release into the environment.
- ☐ The compound may or may not be safe to release into the environment.
- ☐ LD50 doesn't give information on how safe a compound is for the environment.
- ☐ I don't know.

Over the last few years, there has been an increased demand for natural and/or renewable resources. Please select all of the following statements that are true.

- [ ] Natural products are sustainable.
- [ ] Renewable products are sustainable.
- [ ] The terms “natural” and “renewable” are interchangeable.
- [ ] Natural products are likely to be safe for humans and the environment.
- [ ] Renewable products are likely to be safe for humans and the environment.
- [ ] Natural products or processes are always preferable to synthetic ones.
- [ ] Renewable products or processes are always preferable to synthetic ones.
- [ ] I don't know.

For the following three questions, please choose the <u>top three</u> green chemistry principles that apply to each scenario.

Drag your top three choices into the box and order them from most (1) to least (3) applicable to the scenario. If you don't know the answer simply drag the “I don’t know” option into the box.

Traditionally, paper has been bleached with chlorine to give it a white appearance. Chlorine and its derivatives (such as chlorine dioxide) are very dangerous for humans and toxic to aquatic organisms. Eliminating the use of chlorine in paper production is an example of which green chemistry principle(s)? (Select all principles that apply.)

- [ ] Prevention
- [ ] Atom Economy
- [ ] Less Hazardous Chemical Syntheses
- [ ] Designing Safer Chemicals
- [ ] Safer Solvents and Auxiliaries
- [ ] Design for Energy Efficiency
- [ ] Use of Renewable Feedstocks
- [ ] Reduce Derivatives
- [ ] Catalysis
- [ ] Design for Degradation
- [ ] Real-time Analysis for Pollution Prevention
- [ ] Inherently Safer Chemistry for Accident Prevention
- [ ] I don't know

[All of these questions have the same fixed responses as the question above but are omitted for length.]

BASF (the largest chemical producer in the world) is currently developing plastic bags made partly from cassava starch and calcium carbonate. These bags completely disintegrate into water, CO2, and biomass in industrial and city composting systems. These bags are examples of which green chemistry principle(s)? (Select all principles that apply.)

Oil-based "alkyd" paints emit high levels of volatile organic compounds (VOCs). As the name suggests, VOCs evaporate from drying paint and can produce many harmful health effects (ranging from eye irritation to liver damage to cancer). Sherwin-Williams won the 2011 Presidential Green Chemistry Challenge Award for the development of low-VOC, water-based paints that are made from recycled plastic bottles and soybean oil. This new paint formulation is an example of which green chemistry principle(s)? (Select all principles that apply.)

Please indicate your level of agreement with the following statements:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I know what the term green chemistry means.	○	○	○	○	○
I can define green chemistry principles (e.g. atom economy, catalysis, renewable feedstocks).	○	○	○	○	○
I can identify hazards associated with a reaction or experiment.	○	○	○	○	○
I can suggest ways to make a reaction or experiment less hazardous.	○	○	○	○	○
I understand how to minimize chemical waste.	○	○	○	○	○
I understand what happens to waste after it leaves the laboratory.	○	○	○	○	○
I can identify factors that make a reaction 'green'.	○	○	○	○	○
I can suggest improvements to make a reaction greener.	○	○	○	○	○

Chemistry Concepts and Techniques

Presently, how much do you understand about each of the following chemistry **concepts or techniques**?

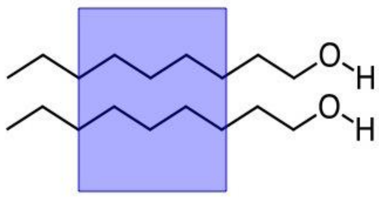
	not at all	a little	somewhat	a good deal	a great deal
Relationships between physical properties and molecular structures	○	○	○	○	○
Intermolecular interactions	○	○	○	○	○
Types of bonding (non-polar covalent, polar covalent, ionic)	○	○	○	○	○
Calorimetry	○	○	○	○	○
Electrochemistry	○	○	○	○	○
Performing a titration using a pH probe	○	○	○	○	○
Performing a titration using indicators	○	○	○	○	○
Creating serial dilutions	○	○	○	○	○
Using a UV/Vis spectrometer	○	○	○	○	○
Generating a calibration curve	○	○	○	○	○
Performing error analysis	○	○	○	○	○

Please indicate your level of agreement with the following statements about **chemistry**:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I want to acquire more chemistry knowledge.	○	○	○	○	○
I find chemistry interesting.	○	○	○	○	○
I believe that I can understand chemistry.	○	○	○	○	○
I can do chemistry.	○	○	○	○	○
Chemistry has connections to my daily life.	○	○	○	○	○
Chemistry is **NOT** useful for other fields I am interested in.	○	○	○	○	○
I think chemistry is important for advancing society.	○	○	○	○	○
I think chemistry is important in advancing knowledge.	○	○	○	○	○
I think about the chemistry I experience in everyday life.	○	○	○	○	○
Learning chemistry changes my ideas about how the world works.	○	○	○	○	○
The subject of chemistry has little relation to what I experience in the real world.	○	○	○	○	○
Chemistry plays an important role in my life because I use many products of the chemical industry.	○	○	○	○	○
I think chemical products are very important.	○	○	○	○	○

Please do your best to answer the following questions honestly and without outside help.

If you do not know the answer or how to attempt the problem, please do not guess; mark "I don't know."

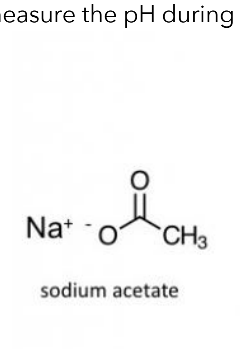


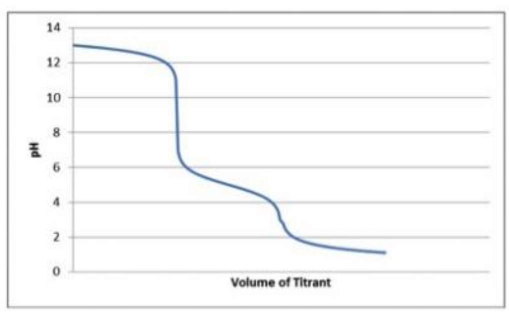
Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above.

- ◯ Ionic interactions
- ◯ Hydrogen bonding interactions
- ◯ London dispersion interactions (induced dipole-induced dipole interactions)
- ◯ I don't know.

For the next question consider the following information:

In lab you use hydrochloric acid (HCl) to titrate a mixture of sodium hydroxide (NaOH) and sodium acetate (NaC2H3O2). You measure the pH during the titration, and the titration curve shown below is the result.





Your lab partner has a different sample, one with a greater amount of NaOH and the same amount of NaC2H3O2.

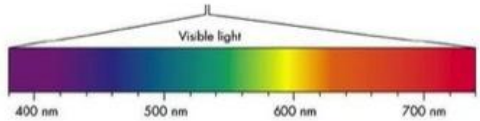
Your data

Your lab partner's data

What would the titration curve for this sample look like compared to yours?

- ◯ Image:Titr choice a
- ◯ Image:Titr choice b
- ◯ Image:Titr choice c
- ◯ Image:Titr choice d
- ◯ I don't know.

For the next question, refer to the spectrum provided below:



Which absorbance spectrum (absorbance versus wavelength in nm) would correspond to a green solution?

- ◯ Image:Abs choice a
- ◯ Image:Abs choice b
- ◯ Image:Abs choice c
- ◯ I don't know.

Heat is given off when hydrogen burns in air according to the equation:

2H2 + O2 → 2H2O

Which of the following is responsible for the heat?

- ◯ A. Breaking bonds between hydrogen atoms gives off energy.
- ◯ B. Breaking bonds between oxygen atoms gives off energy.
- ◯ C. Forming bonds between hydrogen and oxygen atoms gives off energy.
- ◯ Both answers A and B are correct.
- ◯ Answers A, B, and C are correct.
- ◯ I don’t know.

Course Feedback

Please indicate how much you agree with the following statements.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I enjoyed doing the experiments.	○	○	○	○	○
The laboratory manual was clear.	○	○	○	○	○
The pre-lab assignments prepared me effectively.	○	○	○	○	○
The report sheet questions were useful for integrating the concepts learned.	○	○	○	○	○
The green chemistry report sheet questions improved my understanding of green chemistry.	○	○	○	○	○
The green chemistry material in the experiment introductions was useful.	○	○	○	○	○

What was your favorite experiment?

▼ Developing a Model Airbag ... Extraction of Curcumin from Turmeric and Spectroscopic Analysis

From which experiment did you learn the most chemistry content?

▼ Developing a Model Airbag ... Extraction of Curcumin from Turmeric and Spectroscopic Analysis

From which experiment did you learn the most **green** chemistry content?

▼ Developing a Model Airbag ... Extraction of Curcumin from Turmeric and Spectroscopic Analysis

Did your GSI discuss green chemistry during their lab lecture?

- ◯ Always
- ◯ Most of the time
- ◯ About half the time
- ◯ Sometimes
- ◯ Never

Did you ask your GSI questions about green chemistry?

- ◯ Yes
- ◯ No

Was your GSI able to answer your questions about green chemistry?

- ◯ Always
- ◯ Most of the time
- ◯ About half the time
- ◯ Sometimes
- ◯ Never

What would you want to **change** about the green chemistry portion of this course?

____

____

____

What would you want to **stay the same** about the green chemistry portion of this course?

____

____

____

What was the most valuable thing you gained from lab?

____

____

____

What do you wish you had gained from lab but did not?

Describe a connection that was meaningful to you:

Please write any further comments on the course here.

Survey Feedback

Do you have any comments or feedback on the content or organization of this survey? We'd love to use your feedback to improve the survey!

You're done! Just enter your SID to get your bonus points!

We appreciate your feedback and ask for your **student ID** to verify your enrollment in the course. **Make sure you enter your SID correctly so you can receive your bonus points.**

Before this data is reported, your student ID will be removed. Thank you for your participation!

Chem 1AL Pretest, Fall 2019

[The pretest survey items were exactly the same as the posttest survey (shown above) except the 'Course Feedback' section was replaced by a 'Demographics' section shown below.]

Previous Science Experience

How many **semesters** of the following chemistry courses have you completed?

	Semesters
Chemistry	▼ 0 ... 8
Honors chemistry	▼ 0 ... 8
AP chemistry	▼ 0 ... 8
IB chemistry	▼ 0 ... 8
Chemistry at a community college or different university	▼ 0 ... 8
Chemistry at UC Berkeley	▼ 0 ... 8

How many **semesters** of the following science courses have you completed during (or after) high school?

	Semesters
Biology	▼ 0 ... 10
Math	▼ 0 ... 10
Physics	▼ 0 ... 10
Other	▼ 0 ... 10

Had you heard of green chemistry before you entered this course (1AL)?

- ○ Yes
- ○ No

Where had you heard about green chemistry before this course?

____
____
____
____
____

Entering University Information

What is your intended major?

- ◯ Life science
- ◯ Physical science (other than chemistry)
- ◯ Chemistry/chemical biology
- ◯ Humanities
- ◯ Social science
- ◯ Engineering
- ◯ Public health
- ◯ Undeclared
- ◯ Other: ____

When did you first enter UC Berkeley?

- ◯ Fall 2019
- ◯ Summer 2019
- ◯ Spring 2019
- ◯ Fall 2018
- ◯ Summer 2018
- ◯ Spring 2018
- ◯ 2017
- ◯ Other ____

Are you an international student?

- ◯ Yes
- ◯ No

Did you transfer to UC Berkeley from another college or university?

- ◯ Yes
- ◯ No

When did you first begin to attend college?

- ◯ 2019
- ◯ 2018
- ◯ 2017
- ◯ Other ____

Background Information

What is the highest level of education completed by your parent/guardian?

- ◯ Did not complete high school
- ◯ High school degree
- ◯ Some college
- ◯ Two-year degree
- ◯ Four-year degree
- ◯ Some graduate school
- ◯ Graduate degree
- ◯ Not sure

What categories do you identify with? (Choose all that apply.)

- ☐ White/Caucasian
- ☐ Hispanic, Latino, or Spanish origin
- ☐ Black or African American
- ☐ East Asian (e.g., Chinese, Japanese, Korean, Taiwanese)
- ☐ South Asian (e.g., Indian, Pakistani, Nepalese, Sri Lankan)
- ☐ Southeast Asian (e.g., Cambodian, Vietnamese, Hmong)
- ☐ Other Asian
- ☐ Native American or Alaskan Native
- ☐ Middle Eastern or North African
- ☐ Native Hawaiian or other Pacific Islander
- ☐ Decline to state
- ☐ Other: ______________________________

What is your gender identity?

- ○ Male
- ○ Female
- ○ Non-binary
- ○ Not sure
- ○ Decline to state
- ○ Other: ______________________________

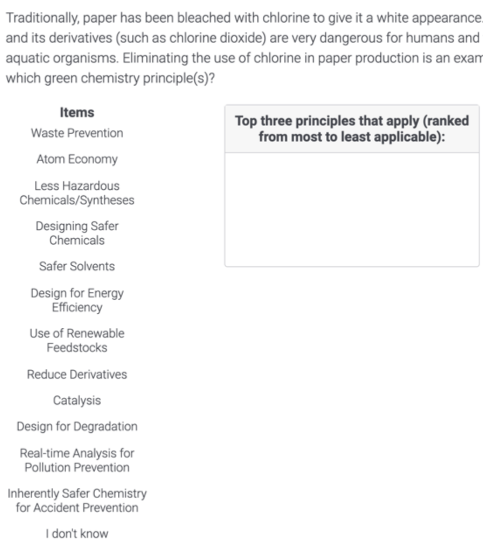
Is English your first language?

- ○ Yes
- ○ No
- ○ I'm bilingual

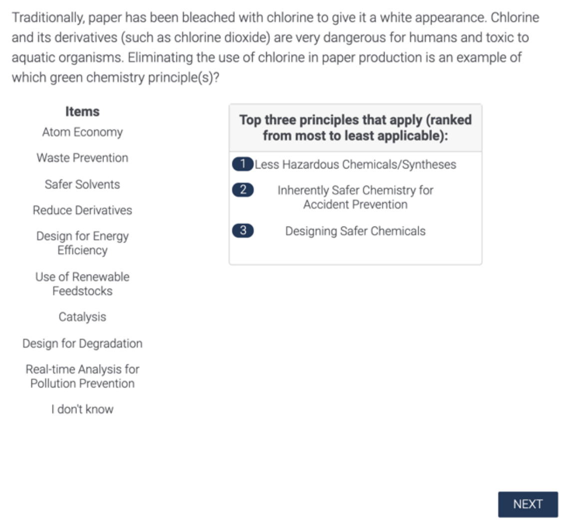
Student View of 12 Principles Ranking Items (Chapter 4)

Internet Browser View

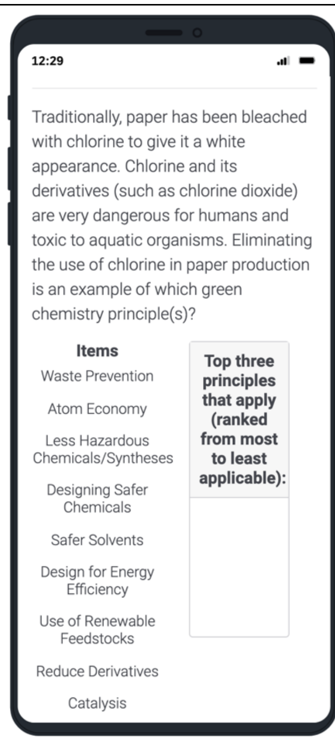
Before selecting principles



After selecting principles



Mobile view



Student Interview Protocol (Chapter 3)

Green chemistry curriculum feedback

This interview protocol was developed for a 30-minute interview with a current Chem 1AL student, seeking to understand what they enjoyed about the course and what could be improved for future semesters. Questions cover both instructional practices and course material.

Protocol

[Overarching Question]

What did students enjoy about Chem 1AL and what do they wish was different [especially in the context of the updated green chemistry content]?

[Introduction]

Hi, my name is Laura Armstrong, and **I'm here to understand better your experience thus far in Chem 1AL – especially what is working well in the course and what you think could be improved for future semesters.** This interview will take about **30 minutes**, during which time we'll go through some questions focused on the experiments you've done so far. Just a note, I'm focusing on 1AL and not the lecture component, 1A, so while I understand that they can feel very linked I only am able to change/work with the laboratory portion.
I want to hear about both the good and bad parts of this course. I'm here to learn from you and my goal is to use your feedback to make changes in time for spring 2019 so I especially need to hear about what isn't working well. Your feedback could directly impact how students experience Chem 1AL next semester.

A couple of things before we start. Your comments will be completely **confidential**. No one from the course, instructors or GSIs, will have access to what you say here today. My research team and I will aggregate all the comments from several interviews we're conducting so that your comments are not connected to you. If we quote you in our final report, we will do so without identifying your name or specific role. If there's anything you really don't want on the record, even if it's anonymized, please let me know that, too. Also, this interview is entirely **voluntary** on your part – if for any reason you want to stop, please let me know. We can end the interview at that point with no repercussions for you of any kind. I can also throw out anything you've told me until that point.

I won't be audio recording you either – I'll simply be taking notes as we talk. Because of this I may need to pause or ask to repeat something occasionally. Do you have any questions for me before we start? All right, then, let's proceed.

[Warm up]

- Let's start by talking about your prior chemistry laboratory experience. What sort of lab experience did you have before 1AL?
- How does this compare to Chem 1AL?
- What did you hope to get out of this laboratory course?
- Has it met your expectations so far? Why or why not?

[Overall course impression]
- What has been your favorite experiment so far? Why?
- What has been your least favorite experiment so far? Why?
- What experiment have you learned the most from? Why?
- What is the most useful part of the course? Why?
- What is one thing you would definitely want to stay the same about 1AL?
- What is one thing you would definitely want to change about 1AL?

[Timing]
- How do you feel about the workload for this course so far? Why?
- What part of the course takes the most time to complete each week. *[If they say the in-lab part ask them for the second most time-consuming task.]* Why?

[Green chemistry content]
- Which experiment had the most green chemistry content/focus?
- Which experiment did you learn the most green chemistry from? What green chemistry did you learn?
- How have you felt about the green chemistry focus of this class so far? Why?
- *[If they seem positive]* What has been your favorite green chemistry part of this class so far?
- What would you like to see changed about the green chemistry content of this course?

[Green chemistry questions/resources]
- How do you feel about the green chemistry questions at the end of each report sheet?
- I want you to think back to the last set of these questions that you answered. *[Flip to those pages in the lab manual.]* Can you walk me through how you approached answering these questions? For example, if you didn't know how to answer these what did you do? Where did you go looking for information?
- Is that what you typically do for these green chemistry questions? [If not ask them what they typically do.]
- Do you ever ask your GSI? Are they able to help you? Why or why not?
- How much time do you usually spend trying to answer these questions? How do you feel about spending that amount of time?
- How useful do you find these questions? Why?

- *[If they seem positive]* Have there been any green chemistry questions that you especially liked?
- Have there been any green chemistry questions that you did not like/found confusing?
- What would make it easier to answer these questions? What sort of resources would you have liked? For example, would you like more written material in the introduction to each experiment? Would you like your GSI to talk about/answer questions?
- Are there any specific examples that you can think of that would have especially benefited from this?

[Other questions]

- Is there anything else you would like to tell me or talk with me about that we haven't covered so far?
- Do you have any questions for me?

[Conclusion]

Thank you – those are all the questions I have for you. If anything else occurs to you after your leave, please don't hesitate to let me know by email. I may be in touch with you again to ask a few follow-up questions. Thanks again!

GSI Questionnaire (Chapter 3)

Name: ______________________________ Lab Section(s): ____________________

For a <u>typical</u> lab section:

How long is your prelab lecture?

How long does your lab section last?

What sort of interactions do you have with your students? *(Circle all that apply, put a star by your <u>top three</u> most frequent interaction types.)*

- Helping students interpret experimental progress
- Helping students find equipment
- Helping students use equipment
- Helping students interpret the procedure
- Checking in with student to see if they have questions or need help
- Making announcements to the class
- Helping students clean up properly
- Helping student dispose of waste properly
- Answering questions about the lab (1AL) course
- Answering questions about grading
- Answering questions about the lecture (1A) course
- Answering questions about turning in notebook pages/report sheets
- Other: ____
- Other: ____
- Other: ____
- Other: ____
- Other: ____
- Other: ____

Do you discuss green chemistry during your prelab lecture? Yes No

If yes, what do you discuss?

For a typical lab section (continued):

Do you discuss green chemistry outside of your prelab lecture? Yes No

If yes, how often?

What In-lab prompts these discussions?

Did students talk/ask about green chemistry during your lab section? Yes No

If yes, how often?

What In-lab prompts these discussions?

For a typical office hour:
Do students talk/ask about green chemistry during your office hours? Yes No

If yes, how often?

What In-lab prompts these discussions?

Other:

Did you have experience with green chemistry before becoming a GSI for this course? If so, describe your experience.

In-Class Green Chemistry Quiz (Chapter 4)

[Pretest Instructions]

This quiz should be completed individually with no outside help. We are interested in what you know about green chemistry before completing this laboratory course.

We are using these quesstions to gauge your current understanding of green chemistry. You are not expected to be a green chemistry expert! If you do not know the answer, please write '*I don't know, but my best guess is…*'. **The assignment will be graded based solely on effort.**

[Posttest Instructions]

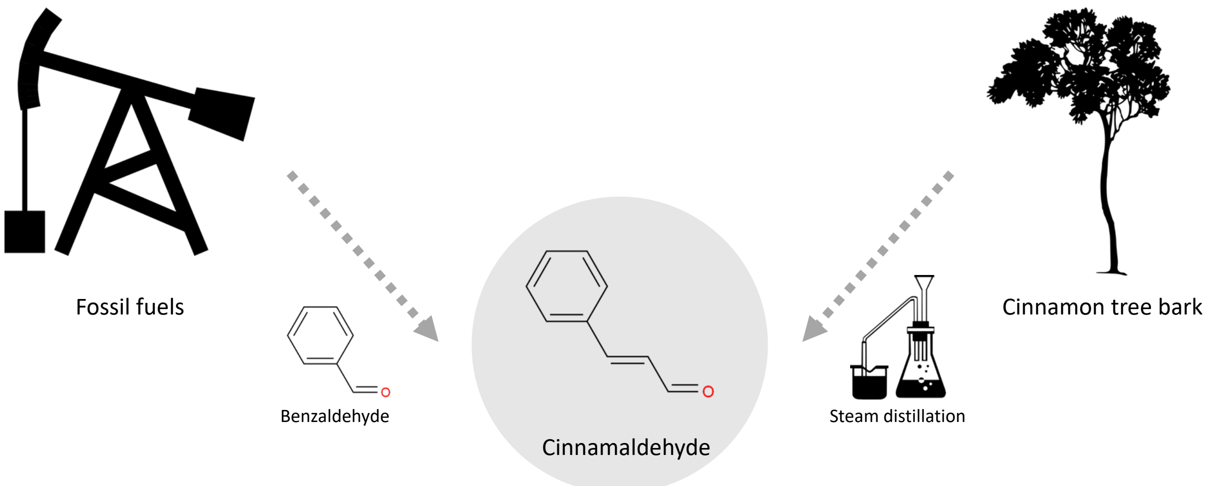
Congratulations on completing your final laboratory experiment of the semester! Now that you're near the end of this course we'd like to once again ask you two green chemistry questions. These are the same questions you completed at the start of the semester; we plan on using both sets of quizzes to see how your green chemistry understanding shifted after completing this laboratory course.

This quiz will be graded based on effort; **please be as specific and detailed as possible with your answers to demonstrate the full range of your green chemistry understanding**. We truly appreciate your responses and read every single one of them. Good luck with the end of the semester and your future classes!

1. In my own words, green chemistry means:

The fall season typically brings an increased demand for pumpkin spice flavored… everything! For large scale production it's hard to get consistent flavors using natural spices. It's much easier to use synthesized flavor molecules like eugenol for clove, zingiberene for ginger, and cinnamaldehyde for cinnamon.

2. There are several different ways of making cinnamaldehyde, two of which are shown below:



From a green chemistry perspective, why would one method be preferable to the other? **Be as specific as possible.**

If you do not know the answer, please write '*I don't know, but my best guess is…*'.

GSI Instructions for Green Chemistry Quiz (Chapter 4)

1. Pass the quiz out to the students. There should be ~30 quizzes in each folder.

2. As you pass out the quiz you can introduce it to the students.

    a. Quiz should take 10 minutes.

    b. It should be completed without outside help (no talking, no phones). We want to hear from the individual students.

    c. **[Pretest only]** Remind students that correctness isn't important. We're just trying to see what they already know – but we don't expect them to be experts at green chemistry yet! This shouldn't be a stressful assignment for them. Hopefully, this course will help them learn more about this topic.

    d. **[Posttest only]** Students may recognize these questions from the beginning of the semester. The reason we're asking these again is to see how their green chemistry understanding shifted after completing this laboratory course. Remind students that while this quiz will be graded based on effort they should be as specific and detailed as possible with their answers so that we can see the full range of their green chemistry understanding.

    e. Ask the students to not discuss this quiz with other students in the course. We don't want students in later lab sections to already know about this quiz (as much as possible).

3. Give the students 10 minutes to finish the quiz.

4. Collect the quizzes from the students and place the quizzes back into the folder. Leave the folder on the GSI bench in your lab room.

5. If you have any questions or issues, please don't hesitate to contact me at <<email>>.

Green Chemistry Exam Question, Fall 2019 (Chapter 5)

As you have learned this semester, there are often many different ways to achieve the same chemical goal. Examine the data below detailing two different methods for making *p*-cymene for use in plastic recycling.

	METHOD 1	**METHOD 2**
% yield of *p*-cymene	91%	83%
atom economy	40%	80%
# of byproducts	4	1
reaction time	3 hours	24 hours
purification method	Recrystallization	Extraction
persistence of **reactants**	Very low	Low
Acute toxicity of **reactants**	High	Low
cost to make 1kg of *p*-cymene	$2,250	$2,710

Which method would you choose for making *p*-cymene?
(Hint: There is no one correct answer! You will be graded based on your explanation and not which method you choose.)

○ **METHOD 1** ○ **METHOD 2**

Why did you choose this method over the other method? Please be as specific as possible with your reasoning (for example, instead of stating that particular measure is 'good' explain what 'good' means to you in this context and how it influenced which method you chose).

Appendix V. Example Curricular Question Redesign

I chose the following question as my test question to redesign. It asks students to use (a) data they have gathered in lab and (b) provided toxicity data to choose a polymer that will make the best children's toy.

> You have been promoted to Chief Sustainability Officer for the toy company. Your R&D division has given you three possible starting materials for making a toy, and you have to choose which one to use. From doing this week's lab, you have some information about the properties of these polymers that would make a fun toy. However, as the CSO you also need to consider effects on human health and the environment. Based on your experience of doing the lab and the data shown in the table below, choose a polymer and make an argument as to why you chose it. Note: there are no wrong answers.

Polymeric Starting Material	CAS No.	Human Health Effects	Persistent in the Environment	Accumulates in Organisms	Fish LC50 (µg/L water)	Soluble in Water
Guar Gum	9000-30-0	none known	unknown	unknown	218,000	yes
Polyvinyl alcohol	9002-89-5	suspected	no	no	86,000-118,000	yes
Polyvinyl acetate	9003-20-7	suspected	yes	no	data not available	no

Data retrieved from EPA databases: ACToR (http://actor.epa.gov) and ECOTOX (http://www.epa.gov/ecotox/)

I first examine what context and KI attributes this question already had. The focal event for this question is toxicity of a children's toy at a research and development division of an unspecified company. My first question was if students valued this context and found it relevant to their daily life. Most likely students have not had experience developing and designing products in a corporate environment. Almost certainly none of them have been or known anyone who was a chief sustainability officer. It is also unclear what specific tasks and chemical language is used for this type of focal event from the question In-lab prompt and how the purpose of this question connects to relevant chemical concepts. This question does explicitly ask students to refer to previous information and incorporate it in their answer (*From doing this week's lab, you have some information about the properties of these polymers that would make a fun toy.*).

However, while this question does elicit ideas from students and asks them to add new ideas (...*as the CSO you also need to consider effects on human health and the environment*) it doesn't provide much structure or scaffolding to help student develop a coherent response by evaluating and reflecting on their ideas. Thus, my redesigned question builds on these identified issues.

Redesigned question: Round 1

I redesigned this question to have a more relevant focal event for a general chemistry student and used the KI framework to elicit student ideas and add and evaluate additional ideas.

[More relevant focal event] You are a summer research intern in the Research and Development (R&D) department at a company that creates children's toys. [Explicitly connects question to green chemistry] This company also uses green chemistry to improve the safety and sustainability of their products. You've talked to the scientists you work with about your experience with polymers in general chemistry. One researcher, Mariana, asks you to help with a toy design project that is considering three possible starting materials - guar gum, polyvinyl alcohol, and polyvinyl acetate. The toy needs to be fun but also non-toxic since the target audience for the new product is young children. From your experience in general chemistry, you have some information about the properties of these polymers that would make a fun toy. However, based on this company's green chemistry focus you also know you need to consider the environmental and human health impact of each polymer.

[Eliciting] Summarize your guar gum, polyvinyl alcohol, and polyvinyl acetate data for the other scientists on your team. Provide your coworkers with some of your qualitative observations and quantitative data to show what polymer mixtures make the best toys. Based purely on properties that would make a good toy, recommend one polymer or polymer mixture that would work best.

[Adding] Mariana is interested in the toy formulation you suggested but also wants make sure that it is safe for children. She provides you with some environmental and human health data for each polymer. What trends do you notice in the provided toxicity data? How do you account for data that is missing? Does that indicate the polymer is safe? What additional information would you like to ask Mariana for that is not present in this table?

Polymeric Starting Material	CAS No.	Human Health Effects	Persistent in the Environment	Accumulates in Organisms	Fish LC50 (μg/L water)	Soluble in Water
Guar Gum	9000-30-0	none known	unknown	unknown	218,000	yes
Polyvinyl alcohol	9002-89-5	suspected	no	no	86,000-118,000	yes
Polyvinyl acetate	9003-20-7	suspected	yes	no	data not available	no

[Evaluating] Based on this environmental and human health data would you change your recommendation for which polymer or polymer mixture would make the best toy? Why or why not?

Redesigned question piloting

The goal of this pilot testing is not to see if this one redesigned question changes students views on the inclusivity of the laboratory course. One question is not going to influence their overall experience in chemistry. Rather I am interested in students' response process to this question. Do they interpret the question the way I intend? Do they enjoy the question? Do they think it's relevant to their future interests? Can they comprehend the material? Does the question elicit their prior ideas? Does it ask them to add and distinguish new ideas? Does the language and tasks used clearly connect to the focal event?

Participants

I asked two students to complete this question while I observed and asked follow up questions. Both students had taken general chemistry at UC Berkeley and were in their first and second year. One student is a chemistry major while the other is a life science major.

Test conditions

I asked each student volunteer to complete the redesigned question as if they were students in Chem 1AL. Each student completed the question in front of me. I observed and took notes as each student completed the question. I did not ask any questions or have the students explain their thinking while they were completing the question. After the students had completed the entire question I asked for their feedback. This allowed me to record how they initially interpreted the question while also obtaining more detailed information about their experience with the question. I asked her open-ended question such as:

- What was your impression of the question?
- Were the question parts clear? What the content clear?
- Were you able to answer the question with the provided information? Was the question doable?
- Did the context of the question seem relevant and meaningful?
- What would you change?

Student feedback on unit

Student responses to the redesigned question quickly showed that the scaffolded questions I'd added did not elicit the intended responses. For the first sub-question (*Summarize your guar gum, polyvinyl alcohol, and polyvinyl acetate data…*) students choose a polymer that they thought had the best properties and then only summarized the data for that one polymer. They also only included qualitative data as evidence for their choice, even though the question specifically asks for both qualitative and quantitative data.

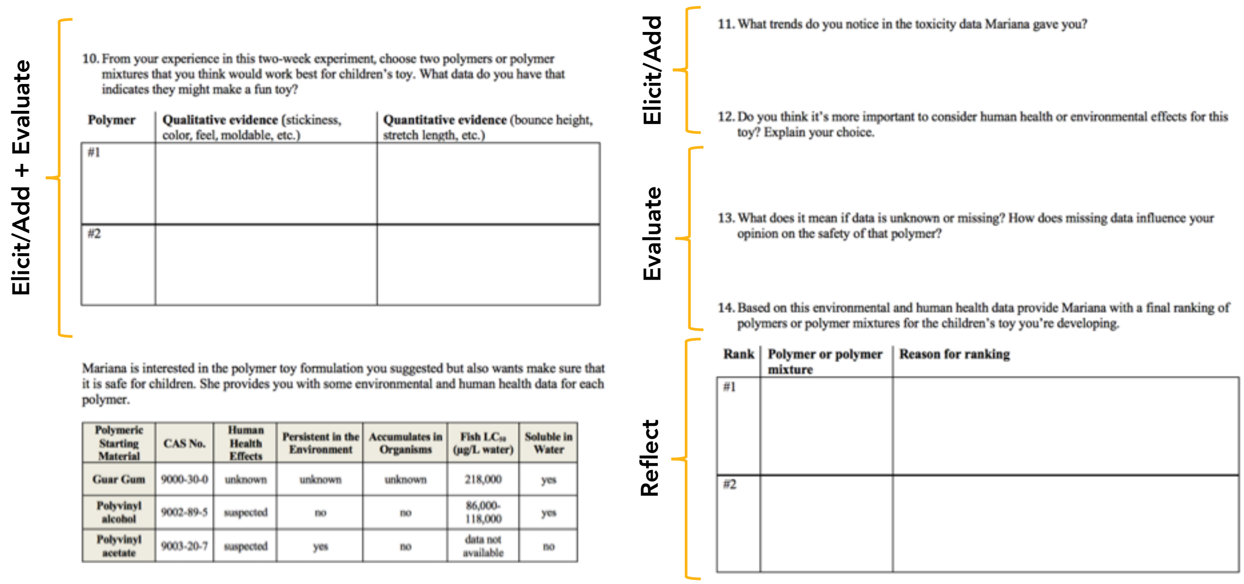
For the second sub-question, I quickly realized that I had four questions within this one sub-question (e.g. *What trends do you notice in the provided toxicity data? How do you account for data that is missing? Does that indicate the polymer is safe? What additional information would you like to ask Mariana for that is not present in this table?*). Not surprisingly students did not answer all of these questions and had trouble distinguishing what pieces of data were needed for each question. One of the students discussed data gaps while the other did not (which is a major concern of green chemistry and one of the learning goals of this question). For the third sub-question (*Based on this environmental and human health data would you change your recommendation for which polymer…*), students were able to choose a polymer based on property and toxicity data but didn't support their answer since they thought their answers to the previous two sub-questions were sufficient evidence.

Discussion with the students showed that the students appreciated the context of the question though one student wondered if the explicit mention of green chemistry in the introduction to the question remove the students' ability to organically discuss the green chemistry connections in this question. They both agreed that the second sub-question had too many questions and that they had been unsure of how to use all the provided toxicity data. They also discussed how they both had forgotten to include quantitative data for the first sub-question. One student stated that she felt the qualitative data had been sufficient evidence to answer the question while the other stated she had forgotten about this portion of the question after she had organized her qualitative data.

Redesigned question: Round 2

Based on this student feedback I redesigned my first draft of this question. I redesigned my three guiding sub-questions into six more targeted questions. I now provide designated space for each answer, which helps scaffold which pieces of information are relevant for each question. Two of my 'answer boxes' now specifically ask for quantitative and qualitative data and provide examples of each type of data. Two additional answer boxes help students organize the toxicity data into two different categories – that which is relevant to human health and that which is relevant to the environment. I also explicitly ask about data gaps and how that impacts their ability to determine which polymer is safe for a children's toy.

Further pilot testing is needed to assess the logic and clarity of this newly redesigned question. My main concern is that this question now appears very long (taking up at least two pages though it contains space for students to write their answers down). My aim is that the entire first half of this question (that asks students to summarize their data from their experiment) can be incorporated into previous questions in this postlab. I also worry that students or instructors won't like the workbook nature of this question (with clearly delimitated space for answers). While I hope this format improves readability/grading efficiency and helps students more clearly see the intent of the question it is a feature that still needs students and instructor feedback.



10. From your experience in this two-week experiment, choose two polymers or polymer mixtures that you think would work best for children's toy. What data do you have that indicates they might make a fun toy?

Polymer	**Qualitative evidence** (stickiness, color, feel, moldable, etc.)	**Quantitative evidence** (bounce height, stretch length, etc.)
#1		
#2		

Mariana is interested in the polymer toy formulation you suggested but also wants make sure that it is safe for children. She provides you with some environmental and human health data for each polymer.

Polymeric Starting Material	CAS No.	Human Health Effects	Persistent in the Environment	Accumulates in Organisms	Fish LC_{50} (µg/L water)	Soluble in Water
Guar Gum	9000-30-0	unknown	unknown	unknown	218,000	yes
Polyvinyl alcohol	9002-89-5	suspected	no	no	86,000-118,000	yes
Polyvinyl acetate	9003-20-7	suspected	yes	no	data not available	no

11. What trends do you notice in the toxicity data Mariana gave you?

12. Do you think it's more important to consider human health or environmental effects for this toy? Explain your choice.

13. What does it mean if data is unknown or missing? How does missing data influence your opinion on the safety of that polymer?

14. Based on this environmental and human health data provide Mariana with a final ranking of polymers or polymer mixtures for the children's toy you're developing.

Rank	Polymer or polymer mixture	Reason for ranking
#1		
#2		

Figure A III. Redesigned green chemistry postlab question

Appendix VI. Green Chemistry Content in Chem 1AL (Chapter 3)

Table A V. Overview of green chemistry **content** in Chem 1AL during the 2013-2017, Fall 2018, Spring 2019, and Fall 2019 semesters

	Fall 2019 (GC² V2)			Spring 2019 (GC² V1b)			Fall 2018 (GC² V1a)			2013-2017 Curriculum (Original)		
Experiment	% GC Intro[1]	% GC Total[2]	# GC Mentions[3]	% GC Intro	% GC Total	# GC Mentions	% GC Intro	% GC Total	# GC Mentions	% GC Intro	% GC Total	# GC Mentions
Intro	46%	46%	40	46%	46%	37	45%	45%	33	45%	45%	10
Airbags	64%	36%	3	64%	32%	4	58%	30%	2	33%	13%	0
How the Nose Knows	12%	13%	1	24%	19%	3	14%	16%	4	10%	3%	0
Polymers Toy Design I	16%	22%	2	16%	21%	3	4%	12%	2	5%	7%	0
Polymers Toy Design II	37%	29%	2	37%	29%	3	10%	22%	4	0%	1%	0
Biofuels I	55%	41%	5	54%	41%	6	52%	39%	4	68%	42%	1
Biofuels II	43%	25%	3	36%	17%	4	32%	16%	3	4%	3%	0
Biofuels III	14%	13%	3	14%	13%	5	14%	13%	5	4%	2%	0
Acids in the Environment I	32%	28%	2	N/A	N/A	N/A	29%	26%	3	20%	9%	0
Acids in the Environment II	30%	27%	2	28%	22%	2	24%	20%	2	22%	13%	0
Acids in the Environment III	7%	9%	1	22%	23%	3	7%	10%	2	3%	3%	0
Light Inquiry	23%	20%	6	23%	18%	8	10%	15%	6	10%	5%	0
Total	**35%**	**27%**	**70**	**35%**	**26%**	**78**	**30%**	**23%**	**70**	**27%**	**14%**	**11**

[1] Percentage of green chemistry content (# of words) in the introduction of each experiment relative to the total content (# words) in the introduction

[2] Percentage of green chemistry content/questions (# of words) in the entire experiment relative to the total content/questions (# of words) in the experiment

[3] Number of times the term "green chemistry" was used in a given experiment

Table A VI. Overview of green chemistry **questions** in Chem 1AL during the 2013-2017, Fall 2018, Spring 2019, and Fall 2019 semesters

	Fall 2019 (GC^2 V2)			Spring 2019 (GC^2 V1b)			Fall 2018 (GC^2 V1a)			2013-2017 Curriculum (Original)		
Experiment	# Pre-lab[1]	# Post-lab[2]	# Obs.[3]	# Pre-lab Qs	# Post-lab Qs	# Obs.	# Pre-lab	# Post-lab	# Obs.	# Pre-lab	# Post-lab	# Obs.
Airbags	0	7	3	0	5	2	0	6	1	0	1	0
How the Nose Knows	0	4	1	0	6	0	0	7	0	0	0	0
Polymers Toy Design I	2	5	5	2	3	5	0	0	0	1	1	0
Polymers Toy Design II	4	5	4	4	5	4	4	8	3	1	0	0
Biofuels I	2	9	8	2	9	8	3	10	3	3	4	0
Biofuels II	4	5	7	4	2	5	4	2	3	1	1	0
Biofuels III	2	4	3	2	3	3	2	4	3	1	0	0
Acids in the Environ-ment I	4	3	4	N/A	N/A	N/A	4	4	3	1	0	1
Acids in the Environ-ment II	2	4	2	4	3	2	2	4	3	1	0	0
Acids in the Environ-ment III	1	1	4	3	3	4	1	3	3	1	1	0
Light Inquiry	4	5	6	4	3	6	4	5	3	1	0	0
Total	**25**	**52**	**47**	**25**	**42**	**39**	**24**	**53**	**25**	**11**	**8**	**1**

[1] Number of green chemistry prelab questions (required questions completed by students before experiment begins)
[2] Number of green chemistry postlab questions (required questions completed by students after experiment ends)
[3] Number of green chemistry in-lab observations prompts (questions students encounter within the written experimental procedure; students are asked to think about the answers to these prompts while completing their experiment in lab).

General Chemistry Green Curriculum version 1a (GC^2 v1b), Spring 2019

Table A VII. Green chemistry prelab and postlab questions in the Chem 1AL General Chemistry Green Curriculum version 1a (Spring 2019)

<table>
<tr><th>Experiment</th><th>Placement</th><th>Question</th></tr>
<tr><td>Designing a Model Airbag</td><td>In-lab prompt</td><td>Typically, modern airbags are inflated using sodium azide. Why are you using $NaHCO_3$ (sodium bicarbonate or baking soda) instead of sodium azide in this experiment?</td></tr>
<tr><td>Designing a Model Airbag</td><td>In-lab prompt</td><td>What can you do to reduce the amount of waste you generate? Why would you want to reduce waste?</td></tr>
<tr><td>Designing a Model Airbag</td><td>In-lab prompt</td><td>Why is it important to dispose of waste in the proper containers?</td></tr>
<tr><td>Designing a Model Airbag</td><td>Postlab</td><td>The reaction below generates a lot of gas molecules and in theory could be used to fill an automobile airbag. It is called barking dogs because of the loud noise it makes.
<table>
<tr><th>Reaction</th><th>$8\ N_2O\ (g)$</th><th>+</th><th>$4\ CS_2\ (l)$</th><th>→</th><th>$S_8\ (s)$</th><th>+</th><th>$4\ CO_2\ (g)$</th><th>+</th><th>$8\ N_2\ (g)$</th></tr>
<tr><td>M.W. (g/mol)</td><td>44.01</td><td></td><td>76.14</td><td></td><td>256.48</td><td></td><td>44.01</td><td></td><td>28.01</td></tr>
<tr><td>Hazards</td><td>Flammable, displaces O_2</td><td></td><td>Irritant, chronic organ damage and lung irritation</td><td></td><td>Flammable, skin irritation</td><td></td><td>Displaces O_2</td><td></td><td>Displaces O_2</td></tr>
</table>
a. Assuming this reaction goes all the way to completion, what is the approximate % atom economy? (Look at the Atom Economy section of this experiment's introduction for an example of how to calculate atom economy.)
b. How does this compare to the atom economy of the sodium azide (NaN_3) reaction?
c. How do the hazards of the 'barking dog' reaction compare to the sodium azide (NaN_3) airbag?
d. Would you recommend using the 'barking dog' reaction for an airbag? Why or why not?</td></tr>
<tr><td>Designing a Model Airbag</td><td>Postlab</td><td>Atom economy is one metric for measuring the efficiency of a reaction. Name one other factor would want to use to judge the efficiency of a reaction and explain why you chose it.</td></tr>
<tr><td>How the Nose Knows</td><td>Postlab</td><td>One of the most immediately recognizable fragrances is vanilla. While vanilla is most often used as a flavoring ingredient it is also a common component in perfumes and other scented products. Vanilla is so popular that there is actually a shortage of vanilla beans! Faced with this challenge, suppliers have to confront difficult questions about what is "natural." There are many methods for making vanillin (the flavor and scent compound in vanilla) as shown in the figure. Of these six sources, which ones would you label as natural resources? Which ones are renewable resources? What is the main difference between renewable and natural resources? (It may be useful to re-read the Green Chemistry Connections section for a description of renewable versus natural resources.)</td></tr>
</table>

Experiment	Placement	Question
How the Nose Knows	Postlab	As mentioned above, the high demand for vanilla flavor exceeds the production of vanilla beans. The questions and data below are from a report on vanilla manufacturing operations by the Food and Agriculture Organization of the United Nations. Each year we produce and use about 18,000 metric tons of vanilla flavor. Of this 18,000 tons, 85% of vanilla flavor is synthesized from fossil fuels. If we wanted to replace all of the vanilla synthesized from fossil fuels with vanillin extracted from vanilla beans, how many metric tons of vanilla would need to be produced?
How the Nose Knows	Postlab	Currently, Madagascar produces 59% of the vanilla beans in the world. Assuming this percentage stays the same, how many metric tons of vanilla would Madagascar need to produce if we wanted to replace all of the vanilla synthesized from fossil fuels with vanillin extracted from vanilla beans?
How the Nose Knows	Postlab	The optimum yearly harvest (in 2006) of vanilla was 3 kg of fresh vanilla per hectare. How many hectares would need to be dedicated vanilla production in Madagascar? (1000 kg = 1 metric ton)
How the Nose Knows	Postlab	In 2015, 6% of the total land in Madagascar was arable (suitable for growing crops). What percentage of arable land in Madagascar would need to be dedicated to vanilla bean production? (Madagascar is 58.68 million hectares.)
How the Nose Knows	Postlab	Based on these results, would you still consider vanilla beans a renewable resource? Why or why not? What other factors should be considered when choosing renewable substitutes?
Polymers: Cross-Linking and Toy Design Part 1	Prelab	Match sustainability, safety, and green chemistry with the correct definition. a. Less likely to harm b. Meeting the needs to the present generation without compromising the needs of the future generation c. The design of products and processes that are benign to both people and the environment d. The study of the chemical processes that occur in nature. e. The design of products and processes that only use natural materials. f. The study of how chemicals move through the environment (e.g. soil and water). g. The removal of pollution from environment (e.g. soil or water). h. The process of converting/incorporating waste materials into new materials or products.
Polymers: Cross-Linking and Toy Design Part 1	Prelab	The polymers used in this experiment are non-toxic and soluble in water allowing you to conduct the crosslinking reactions using Inherently Safer Chemistry and a Safer Solvent in lab this week. These crosslinking reactions also have high Atom Economy since the majority of the reactants are used to form your bouncy polymer toy. However, this lab still generates waste. Read the notes from the storeroom on bCourses. How will you properly dispose of this waste? Match each item with the correct method of disposal/cleanup.

Experiment	Placement	Question
Polymers: Cross-Linking and Toy Design Part 1	In-lab prompt	Make sure to pay attention to how much solution and material you're using. While it might not seem like much to take an extra 1-2 mL if each solution or a few more plastic pipets think about what would happen if every student group did that for this experiment (there are approximately 800 students in this course). How much more waste would that generate?
Polymers: Cross-Linking and Toy Design Part 1	In-lab prompt	How safe are these chemicals? What does it mean to do Inherently Safer Chemistry? What are the benefits of this approach? What are the drawbacks?
Polymers: Cross-Linking and Toy Design Part 1	In-lab prompt	Why is it important to dispose of waste in the proper containers? What happens to this waste once your lab section is finished? What could you have done during this lab to reduce the amount of waste you generated?[1]
Polymers: Cross-Linking and Toy Design Part 1	Postlab	In your prelab, you identified the waste generated from this experiment and how to properly dispose of it in your lab room. The polymer waste you generated from this lab is incinerated to dispose of it. What are the advantages to this approach? What are the disadvantages?

[1] This In-lab prompt is asked at the end of every experiment starting with this experiment

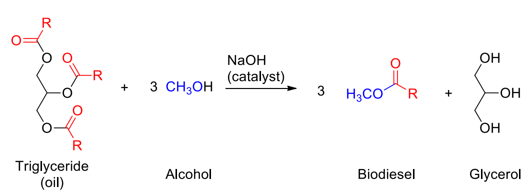
Experiment	Placement	Question
Polymers: Cross-Linking and Toy Design Part 1	Postlab	Polymers are ubiquitous in our daily lives – plastics are probably the most well-known application. Plastics can take on many different forms (flexible, brittle, clear, opaque, rigid, etc.) and are very durable. All the properties that make plastics excellent products also make them very difficult to use sustainably. Their resistance to degradation means that plastic waste stays in our environment for hundreds to thousands of years. Additionally, plastics are traditionally synthesized from non-renewable sources like fossil fuels. A recent National Geographic article (2018) stated "approximately nine million tons of plastic end up in the ocean each year—the equivalent of five plastic grocery bags stuffed with plastic trash on every foot of coastline around the world. Plastic pollution in the ocean has dire implications for all marine life as well as humans, indeed our entire planet." There are many proposed solutions to the problem of plastic waste such as: A. Create and use biodegradable plastics that decompose under normal environmental conditions. B. Develop chemical additives to help biodegrade any plastic (plant- or fossil fuel-based) more quickly. C. Move towards a "circular economy" model, in which all plastics are reused or recycled – eliminating waste and environmental pollution. D. Create better infrastructure to collect plastic waste – catch the waste before it reaches the ocean. E. Move towards a "zero waste" model – no disposable plastic is used. Choose one of these five options that you think is the most promising solution to reduce plastic waste in the ocean and explain why this target is the most promising. Make sure to define the criteria you're using for your choice (e.g. cost, ease of implementation, short-term/long- term solutions, public perception). You can find some good sources of information in the footnote below."
Polymers: Cross-Linking and Toy Design Part 2	Prelab	The polymers used in this experiment are non-toxic and soluble in water allowing you to conduct the crosslinking reactions using **Inherently Safer Chemistry** and a **Safer Solvent** in lab this week. These crosslinking reactions also have high **Atom Economy** since the majority of the reactants are used to form your bouncy polymer toy. However, this lab still generates waste. ***Read the notes from the storeroom on bCourses.*** How will you properly dispose of this waste? Match each item with the correct method of disposal/cleanup.
Polymers: Cross-Linking and Toy Design Part 2	Prelab	In this experiment and the last experiment, you identified the waste you generated and how to dispose of it. The first principle of green chemistry says that *it is better to prevent waste than to treat or clean up waste after it has been created*. What strategies will you use this week to prevent the generation of unnecessary waste?
Polymers: Cross-Linking and Toy Design Part 2	Prelab	The goal of your experiment this week is to design a fun children's toy. Often products designed for children have much higher safety/toxicity standards associated with them. What information would you want to know to assess the **chemical** safety of your polymer toy? Why?

Experiment	Placement	Question
Polymers: Cross-Linking and Toy Design Part 2	Prelab	Sustainable design is more than simply making sure a product is nontoxic. In last week's prelab you defined sustainability. What factors are important to ensure that your toy design is sustainable?
Polymers: Cross-Linking and Toy Design Part 2	In-lab prompt	In this experiment and the last experiment, you identified the waste you generated and how to dispose of it. The first principle of green chemistry says that it is better to prevent waste than to treat or clean up waste after it has been created. What strategies will you use this week to prevent the generation of unnecessary waste?
Polymers: Cross-Linking and Toy Design Part 2	Postlab	You are a summer research intern in the Research and Development department at a company that creates children's toys. This company works to improve the safety and sustainability of their products. You're asked to present your ideas for a new children's toy. The toy needs to be fun but also non-toxic since it's for young children. From your experience in general chemistry, you have some information about the properties of a few polymers and polymer mixtures. Based on this company's green safety focus you also know you'll also need to consider the environmental and human health impact of each polymer.
Polymers: Cross-Linking and Toy Design Part 2	Postlab	From your experience in this two-week experiment, choose two polymers or polymer mixtures that you think would work best for children's toy. What data do you have that indicates they might make a fun toy?
Polymers: Cross-Linking and Toy Design Part 2	Postlab	To ensure that this toy is safe for children the company gives you the environmental and human health data they have for each polymer. What trends do you notice in the toxicity data?
Polymers: Cross-Linking and Toy Design Part 2	Postlab	Do you think it's more important to consider human health or environmental effects for this toy? Explain your choice.
Polymers: Cross-Linking and Toy Design Part 2	Postlab	What does it mean if data is unknown or missing? How does missing data influence your opinion on the safety of that polymer?
Polymers: Cross-Linking and Toy Design Part 2	Postlab	Based on this environmental/human health data **and** your previously gathered performance data provide a final ranking of polymers/mixtures for the toy you're proposing.

<table>
<tr><th>Experiment</th><th>Placement</th><th>Question</th></tr>
<tr><td>Biofuels Part 1</td><td>Prelab</td><td>A 2018 article published in Environmental Science and Technology measured the amounts of hazardous elements such as antimony, barium, bromine, cadmium, chromium, lead and selenium in over 200 second-hand plastic toys. Red and yellow Lego bricks from the 70s and 80s were one of the most concerning toys. Cadmium released from yellow and red Lego bricks exceeded the European Union's toy safety limits by 1 order of magnitude.

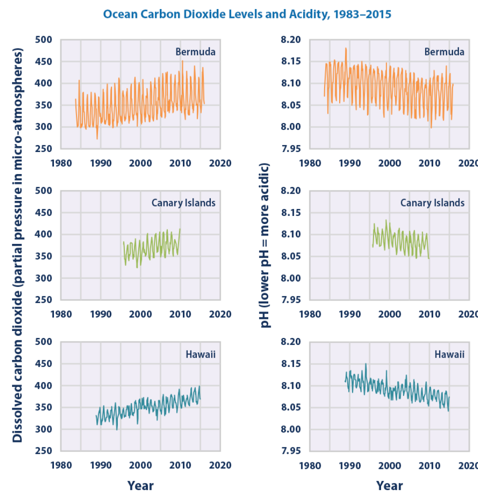
The study author found that red Legos have 274 g of accessible cadmium per gram of Lego brick. The LD_{50} for cadmium is 100 mg/kg. How many red Lego bricks would a 10 kg child need to consume to reach the LD_{50} threshold? The average mass of a Lego brick is 2.5 grams.</td></tr>
<tr><td>Biofuels Part 1</td><td>Prelab</td><td>LD_{50} is one of many toxicity endpoints. What one additional piece of information, besides LD_{50}, would you want to know to assess the chemical safety of Lego bricks? Why? (Hint: Look at the TURI site described in the introduction to get a sense of the types of endpoints exist for human health/safety and the environment.)</td></tr>
<tr><td>Biofuels Part 1</td><td>In-lab prompt</td><td>How safe are these starting materials? If you're not sure, how would you determine the toxicity of these chemicals? (The introduction to this experiment may have some helpful information.)</td></tr>
<tr><td>Biofuels Part 1</td><td>In-lab prompt</td><td>NaOH is a catalyst for your reaction. What is the purpose of a catalyst? Why is the use a catalyst a green chemistry principle?</td></tr>
<tr><td>Biofuels Part 1</td><td>In-lab prompt</td><td>This reaction doesn't require a solvent. Why is a solvent-less reaction a green chemistry principle?</td></tr>
<tr><td>Biofuels Part 1</td><td>In-lab prompt</td><td>Which fuel(s) do you think will be the most toxic to the radish seeds? Which ones will be the least toxic? Why?</td></tr>
<tr><td>Biofuels Part 1</td><td>In-lab prompt</td><td>What are the benefits of serial dilutions? In terms of waste prevention, do you see any advantages to using serial dilutions?</td></tr>
<tr><td>Biofuels Part 1</td><td>Postlab</td><td>Rank the substances from most to least toxic.

Table 1: LD_{50} values for a selection of potentially toxic substances (fill in the missing data)
<table>
<tr><th>Chemical Name</th><th>LD_{50} (mg/kg)</th><th>Estimated Lethal Dose (in grams) for a 60 kg human</th><th>Number of Molecules Needed for Lethal Dose</th></tr>
<tr><td>Sodium Nitrite ($NaNO_2$)</td><td>180</td><td></td><td></td></tr>
<tr><td>Arsenous Acid ($As(OH)_3$)</td><td>14</td><td></td><td></td></tr>
<tr><td>Aspirin (acetylsalicylic acid)</td><td>200</td><td>12 g</td><td></td></tr>
<tr><td>Sodium Cyanide (NaCN)</td><td></td><td>0.38 g</td><td></td></tr>
<tr><td>Polonium-210</td><td>0.00001</td><td></td><td></td></tr>
<tr><td>Mercury (II) Chloride ($HgCl_2$)</td><td></td><td>0.060 g</td><td></td></tr>
<tr><td>Tylenol (acetaminophen)</td><td>1944</td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Biofuels Part 1</td><td>Postlab</td><td>Guess which substance claims the most human lives every year. Explain your reasoning.</td></tr>
<tr><td>Biofuels Part 1</td><td>Postlab</td><td>Doctors have recommended against giving children aspirin, and instead recommend acetaminophen. How many 500 mg tablets of aspirin would it take to reach the LD_{50} threshold for a 22 lb. (10 kg) child? How many 500 mg tablets of acetaminophen?</td></tr>
</table>

Experiment	Placement	Question
Biofuels Part 1	Postlab	Before answering the next question, consider your personal biases toward (or against) biofuels. Have you heard about biofuels in the media? What do you think about biofuels? Most importantly: WHY do you think that about biofuels? (It's important to examine your biases and where they come from before starting any project.)
Biofuels Part 1	Postlab	Read the "Pro-Biodiesel" and "Anti-Biodiesel" excerpts in the introduction to this experiment. These represent two opposing perspectives about the use of biodiesel as a fuel source. After reading this information, do you feel better informed? Do you think that using biodiesel is practical? Is there any information that the excerpts did not provide that you would want in order to make a decision? Write a paragraph about your thoughts on the topic.
Biofuels Part 1	Postlab	Toxicity, especially when thinking about consumer products or pharmaceuticals, often revolves around humans. However, chemicals don't just harm humans – they also can harm the environment (and terrestrial/aquatic organisms). In your LD_{50} worksheet you saw that Tylenol has a very high LD_{50} (1944 mg/kg). Based on this information would you classify Tylenol as safe to humans?
Biofuels Part 1	Postlab	Use TURI to look up persistence, bioaccumulation, and toxicity (PBT) data for Tylenol (chemical name: acetaminophen or paracetamol) in the ECHA – REACH Registration Database. Based on the additional information you find in this database would you revise your assessment of Tylenol safety? Why or why not?
Biofuels Part 1	Postlab	What would you say to a friend that wanted to get rid of expired Tylenol by dumping it down the sink?
Biofuels Part 2	Prelab	What is bioaccumulation? a. Build-up of a chemical in an organism. b. Build-up of a chemical in the environment (since the chemical cannot degrade in through normal environmental processes). c. Build-up of a chemical in an organism from ingesting the chemical through water only. d. Build-up of a chemical in a food chain.
Biofuels Part 2	Prelab	Describe the relationship between bioaccumulation and the octanol-water partition coefficient, $logK_{ow}$.
Biofuels Part 2	Prelab	What is the atom economy of synthesizing biofuel from vegetable oil? Assume the molar mass of the oil is 885.43 g/mol and the molar mass of biofuel is 294.479 g/mol. 
Biofuels Part 2	Prelab	T/F The atom economy for this reaction is very high which tells us that a lot of waste (byproducts) was produced from this reaction.

Experiment	Placement	Question
Biofuels Part 2	In-lab prompt	If you calculated the atom economy for synthesizing biofuel, would the NaCl solution you just added be part of that calculation? (Think about the formula for calculating atom economy – what parts of a reaction process does atom economy include? What parts does it not account for?)
Biofuels Part 2	In-lab prompt	If you calculated the atom economy for synthesizing biofuel, would the MgSO4 you just added be part of that calculation?
Biofuels Part 2	In-lab prompt	According to the class data, which biofuel was the most toxic according to the weight percent solutions? Which biofuel was the most toxic according to the molarity of the solutions? Compare and contrast these values. Do your results match your predictions from last week's pre-lab? If not, how might you adjust your initial prediction?
Biofuels Part 2	Postlab	Use ChemSpider to look up the $\log K_{ow}$ for the following fuels: methanol, ethanol, 2-butanol, biodiesel (methyl linoleate).
Biofuels Part 2	Postlab	In your prelab, you explained the relationship between bioaccumulation and $\log K_{ow}$. Based on the $\log K_{ow}$ for your fuels, which ones would you expect to be bioaccumulative? Explain your reasoning.
Biofuels Part 3	Prelab	Energy is a critical issue for our generation and chemistry is not immune. Why is it important to think about the energy that a reaction (or secondary components of a reaction) requires?
Biofuels Part 3	Prelab	What parts of chemical reaction potentially require energy? a. Synthesizing/processing the reactants b. Running the reaction c. Purifying the desired product d. Disposing of waste
Biofuels Part 3	Postlab	In lab this semester, you synthesized biofuel by manually mixing the NaOH catalyst and vegetable oil together and letting the reaction progress over one week. It is also possible to synthesize biofuel much more quickly using heat. Students used to synthesize biofuel by heating 20-mL of vegetable oil to between 40-50^{o}C while rapidly stirring with a stir bar. They then turned off the heat, added 5 mL of the 0.4 M NaOH in methanol to the warm oil, and continued to stir the reaction for 45 minutes. Describe the advantages and disadvantages for each biofuel synthesis. From a green chemistry perspective, which method is preferable?
Biofuels Part 3	Postlab	What were the green components of your biofuels synthesis? Think about all the components of a reaction (the sourcing of the reactants, the reaction itself, the waste produced, and the hazards associated with each step of the reaction). It may be useful to review the 12 Principles listed in the introduction of this lab manual.
Acids in the Environment Part 1	Prelab	Visit the A-Z list of topics on the Environmental Protection Agency website (https://www.epa.gov/environmental-topics/z-index) and read about acid rain. What are some sources of SOx and NOx in the United States? (Mark all that apply.)

Experiment	Placement	Question
		a. Forest fires b. Volcanic eruptions c. Solar energy d. Wind turbines e. Burning fossil fuels (especially coal) for electricity f. Nuclear power plants g. Vehicles and heavy equipment h. Manufacturing, oil refineries and other industries
Acids in the Environment Part 1	Prelab	According to the EPA what are the primary sources of SOx and NOx in the United States? (Mark all that apply.) a. Forest fires b. Volcanic eruptions c. Solar energy d. Wind turbines e. Burning fossil fuels (especially coal) f. Nuclear power plants g. Vehicles and heavy equipment. h. Manufacturing, oil refineries and other industries.
Acids in the Environment Part 1	Prelab	Sulfate ion concentrations (mg/L) in lakes and rivers and streams greatly decreased from 1985 to 2011 (you can see for yourself at http://nadp.slh.wisc.edu/data/animaps.aspx; click on the PDF link for SO4). What was the main cause for this decrease in water acidification? a. Industry self-regulation b. 1990 Clean Air Act c. Changes in consumer habits
Acids in the Environment Part 1	Prelab	Acid rain effects which of the following: (Mark all that apply.) a. Fish and wildlife b. Plants and trees c. Metal and paint d. Air visibility e. Human health (heart and lung function)
Acids in the Environment Part 1	In-lab prompt	How can you conserve water in the lab? Turning the sink off while you wash glassware! Running the sink while washing glassware can use your volume of water in 10 minutes.
Acids in the Environment Part 1	Postlab	Titration with an indicator is a common technique that chemists use when counting moles.
Acids in the Environment Part 1	Postlab	Would this technique be useful for determining the pH of ocean water? If you don't think it's useful, what would you recommend? Explain your reasoning.
Acids in the Environment Part 1	Postlab	Why would you want to know the pH of the ocean? Of a lake or stream?
Acids in the Environment Part 1	Postlab	Could this technique determine if a lake or stream is affected by acid rain? For example, would this technique allow you to say if the lake or stream was acidified from local industrial facility runoff versus acid rain? Does this type of titration give clues about the source of the acids present?

Experiment	Placement	Question
Acids in the Environment Part 2	Prelab	According to NOAA the ocean absorbs about a quarter of the CO_2 released into the atmosphere every year. At first, scientists thought this was a good way to remove a greenhouse gas from the atmosphere. However, we now know that the increasing levels of CO_2 in the ocean is dramatically changing the ocean environment through ocean acidification. The data below shows amount of carbon dioxide dissolved in the ocean and the corresponding pH of the ocean from 1983-2015. What is the relationship between CO_2 and the pH of the ocean?  Data sources: • Bates, N.R. 2016 update to data originally published in: Bates, N.R., M.H. Best, K. Neely, R. Garley, A.G. Dickson, and R.J. Johnson. 2012. Indicators of anthropogenic carbon dioxide uptake and ocean acidification in the North Atlantic Ocean. Biogeosciences 9:2509–2522. • González-Dávila, M. 2012 update to data originally published in: González-Dávila, M., J.M. Santana-Casiano, M.J. Rueda, and O. Llinás. 2010. The water column distribution of carbonate system variables at the ESTOC site from 1995 to 2004. Biogeosciences 7:3067–3081. • Dore, J. 2015 update to data originally published in: Dore, J.E., R. Lukas, D.W. Sadler, M.J. Church, and D.M. Karl. 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. Proc. Natl. Acad. Sci. USA 106:12235–12240. For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators. [Fill in the blank] As the concentration of CO_2 dissolved in the ocean has **increased** the pH of the ocean has correspondingly **decreased**. This indicates that the ocean is **becoming more acidic**.
Acids in the Environment Part 2	Prelab	Carbon dioxide is a naturally occurring compound. Humans (and other aerobic organisms) produce CO_2 from cellular respiration and plants (and other photosynthetic organisms) use CO_2 for photosynthesis. It is a critically important for many different biological and chemical processes but since the Industrial Revolution there has been a dramatic increase in CO_2 production – mainly from burning fossil fuels. This increase in CO_2 has had far reaching effects including ocean acidification. Ocean acidification also has far reaching effects. For example, fish can lose their ability to smell and thus cannot detect predators or find food in acidic oceans. Visit the A-Z list of topics on the Environmental Protection Agency website and read about ocean acidification. What the effects of ocean acidification? (Mark all that apply.) a. Coral reefs are damaged b. Sea urchin and oyster larvae exhibit developmental problems c. Fish larvae lose their ability to smell and avoid predators d. Mussels, sea urchins, and crabs start to dissolve their protective shells e. Pteropod, or "sea butterfly", start to dissolve their shells f. Food sources for salmon (and larger predators) decrease g. Seafood prices increase h. Fishermen have decreased harvests

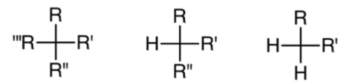
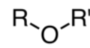
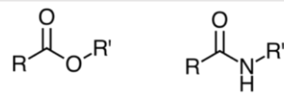
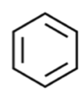
Experiment	Placement	Question
Acids in the Environment Part 2	Prelab	As you saw last week, ocean acidification impacts many different systems including fisheries. Fisheries are critical to many coastal towns and indigenous populations. For example, in the Puget Sound shellfish and salmon are cornerstones of the Suquamish Tribe's economy and culture. In light of the changes that ocean acidification is having on these fisheries, who should be responsible for making decisions about how to manage the salmon fisheries in the Puget sound? The people who live there? Scientists who study the fisheries? The government? People/companies who create possible solutions or technologies? Someone else? Explain your choice.
Acids in the Environment Part 2	Postlab	Two-thirds of all SO_x produced come from electric power plants. Many power plants use coal as a fuel source. Coal is not a pure carbon – when it is burned the sulfur in it combines with oxygen to produce SO_2. As you've learned this week, this emitted SO_2 can eventually produce acid rain. However, SO_2 can be removed or 'scrubbed' from the exhaust of coal power plants by spraying a wet slurry of limestone (calcium carbonate, $CaCO_3$) into a large chamber that contains the SO_2 exhaust: $$2\ CaCO_3\ (s) + 2\ SO_2\ (g) + O_2\ (g) \rightarrow 2\ CaSO_4\ (s) + 2\ CO_2\ (g)$$ One of the byproducts of this reaction, calcium sulfate ($CaSO_4$), can be used to make wallboard and cement and has a role in agricultural and construction applications.
Acids in the Environment Part 2	Postlab	The pH meter in the scrubber for a coal-burning electric power plant records a pH drop for the calcium carbonate slurry from 10 to 8. The pH meter in the scrubber for a methane-burning power plant records a drop from 10 to 9.8. Which plant (coal or methane) produced more SO_2 exhaust? Explain your reasoning.
Acids in the Environment Part 2	Postlab	When used, limestone scrubbers prevent the release of approximately 95% of the SO_2 produced from power plants. However, this reaction produces other byproducts. What is one potential disadvantage of this particular type of scrubber? Explain your choice.
Acids in the Environment Part 2	Postlab	Scrubbers are a way to remediate (remove) pollution after it has already been formed. With what green chemistry principle does this not align?

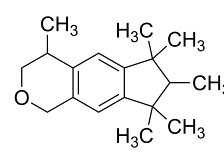
General Chemistry Green Curriculum Version 2 (GC^2 v2), Fall 2019

Table A VIII. Revised and added green chemistry prelab and postlab questions and in-lab observation prompts for the Chem 1AL General Chemistry Green Curriculum version 2 (Fall 2019). Only new or revised questions are shown; all other questions remained the same as seen in GC^2 version 1b.

Experiment	Placement	Question
Designing a Model Airbag	In-lab prompt	Typically, modern airbags are inflated using sodium azide. Why are you using NaHCO3 (sodium bicarbonate or baking soda) instead of sodium azide in this experiment?
Designing a Model Airbag	Postlab	The reaction you used to create your model airbag is shown below. Reaction: NaHCO3 (s) + CH3COOH (aq) → CH3COONa (aq) + CO2 (g) + H2O (l) M.W. (g/mol) 84.01 60.05 82.034 44.01 18.02 a) What is the desired product of this reaction? b) What are the undesired products (byproducts) of this reaction? c) Assuming this reaction goes all the way to completion, what is the % atom economy? What does this tell you about the reaction? (See the Atom Economy section of this experiment's introduction for an example of how to calculate atom economy.) d) How does the atom economy for your reaction compare to the atom economy for the sodium azide (NaN3) reaction typically used to inflate commercial airbags? e) How do the hazards of your reaction compare to the sodium azide (NaN3) airbag? f) Atom economy is one metric for measuring the efficiency of a reaction. What other factor would want to use to judge the efficiency of a reaction? Why? g) Considering all of the physical and chemical evidence you have observed and calculated for your model airbag reaction, would you recommend using this reaction for inflating an airbag? Why or why not?
How the Nose Knows	In-lab prompt	The fragrance molecules you're wafting introduce you to the rich chemistry found in nature and are examples of Renewable Feedstocks. What is the difference between renewable and natural compound? Is a natural compound always safe? What about a renewable compound?

Experiment	Placement	Question
How the Nose Knows	Postlab	In this experiment you learned about the idea of functional groups. Functional groups have many uses including helping predict if a molecule is going to biodegrade or persist in the environment under different conditions (pH, water, oxygen, temperature, microorganisms). Below are some general rules[1] for understanding how the structure of a molecule will biodegrade under aerobic (oxygen present) conditions.

Functional groups that decrease biodegradation (increase persistence)	Structure
Halogens (**fluorine, chlorine,** bromine, iodine)	R−X
Branching carbon chains (carbon atoms with multiple carbons attached especially four carbons)	
Ethers	
Functional groups that increase biodegradation	**Structure**
Esters, amides (the bonds in these functional groups can be broken by enzymes)	
Oxygen atoms (hydroxyls, aldehydes, carboxylic acids, ketones)	
Linear carbon-carbon chains (especially with more than three carbons)	
Phenyl rings	

Experiment	Placement	Question
How the Nose Knows	Postlab	Galaxolide is a synthetic musk used in perfumes and other personal care products. Galaxolide survives treatment at wastewater plants which means that it ends up in many different water sources including the Great Lakes.[2] It also has been found fish tissues in the US and Germany and even in detectable levels in humans.[3]  Circle the functional groups (using a solid line) in Galaxolide that would increase persistence. Circle the functional groups (using a dashed line) Galaxolide that would increase biodegradability.

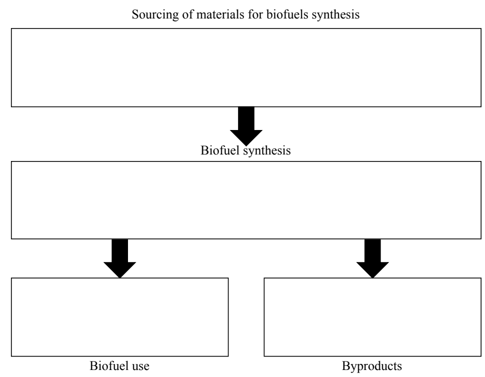
[1] Boethling, R.S., Sommer, E., and DiFiore, D., Chem. Reviews, 2007, Vol. 107, No. 6, 2207-2227

[2] Baldwin AK, Corsi SR, DeCicco LA, Lenaker PL, Lutz MA, Sullivan DJ and Richards KD. (2016) Organic contaminants in Great Lakes tributaries: Prevalence and potential aquatic toxicity. Science of the Total Environment. 554-555, 42-52. 2016.

[3] Hutter H. et.al. (2009) Synthetic musks in blood of healthy young adults: Relationship to cosmetics use. Science of the Total Environment. Vol. 47, pp: 4821-4825. 2009.

Experiment	Placement	Question
How the Nose Knows	Postlab	Based on the structure, would you expect the Galaxolide to biodegrade in aerobic conditions? Use the functional groups present in Galaxolide to support your answer.
How the Nose Knows	Postlab	Why does persistence matter? Just because a molecule is persistent, it doesn't necessarily mean it will be toxic to humans or the environment. Can you think of applications of chemicals in which persistence would be an issue? Provide an example
Polymers: Cross-Linking and Toy Design Part 1	Postlab	Polymers are ubiquitous in our daily lives – plastics are probably the most well-known application. Plastics can take on many different forms (flexible, brittle, clear, opaque, rigid, etc.) and are very durable. All the properties that make plastics excellent products also make them very difficult to use sustainably. Their resistance to degradation means that plastic waste stays in our environment for hundreds to thousands of years. Additionally, plastics are traditionally synthesized from non-renewable sources like fossil fuels. A recent National Geographic article (2018) stated "approximately nine million tons of plastic end up in the ocean each year—the equivalent of five plastic grocery bags stuffed with plastic trash on every foot of coastline around the world. Plastic pollution in the ocean has dire implications for all marine life as well as humans, indeed our entire planet." There are many proposed solutions to the problem of plastic waste such as: A. Create and use biodegradable plastics that decompose under normal environmental conditions. B. Develop chemical additives to help biodegrade any plastic (plant- or fossil fuel-based) more quickly. C. Move towards a "circular economy" model, in which all plastics are reused or recycled – eliminating waste and environmental pollution. D. Create better infrastructure to collect plastic waste – catch the waste before it reaches the ocean. E. Move towards a "zero waste" model – no disposable plastic is used. a) Choose one of these five options that you think is the most promising solution to reduce plastic waste in the ocean and explain why this target is the most promising. Make sure to define the criteria you're using for your choice (e.g. cost, ease of implementation, short-term/long- term solutions, public perception). You can find some good sources of information in the footnote below. b) Suppose your lab partner disagree with your choice for reducing plastic waste. What might be some objections they could raise? c) How would you respond to these criticisms? Would you still consider your choice the best option?
Biofuels Part 1	Postlab	What additional metrics, besides LD50, are used to describe hazards/toxicity? In your LD50 worksheet you saw that Tylenol has a very high LD50 (1944 mg/kg). Based on this information would you classify Tylenol as safe to humans? Why or why not?

Experiment	Placement	Question
Biofuels Part 1	Postlab	Toxicity, especially with consumer products or pharmaceuticals, often revolves around humans. However, chemicals don't just harm humans – they also can harm the environment. What would you say to a friend that wanted to get rid of expired Tylenol by dumping it down the sink?
Biofuels Part 2	In-lab prompt	If you calculated the atom economy for synthesizing biofuel, would the NaCl solution you just added be part of that calculation? (Think about the formula for calculating atom economy – what parts of a reaction process does atom economy include? What parts does it not account for?)
Biofuels Part 2	In-lab prompt	What chemical properties can be used to model environmental harm? Based on structure/polarity, rank methanol, ethanol, 2-butanol, and methyl linoleate from highest to lowest logKow value.
Biofuels Part 2	Postlab	Use ChemSpider to look up the logKow for the following fuels: methanol, ethanol, 2-butanol, biodiesel (methyl linoleate). How to use ChemSpider: Search for your compound in ChemSpider (http://www.chemspider.com/) and then navigate to the Properties à Experimental data to find the Experimental logP (logP = logKow). If no experimental logP is listed you can find predicted logP values in the Predicted – ACD/Labs or Predicted – EPISuite tabs. These predicted values are generated from the structures of the molecules. How does your ranking of the logKow values for methanol, ethanol, 2-butanol, and methyl linoleate compare to the actual logKow values? Explain how the actual values allow you to refine or provide more detail to your ranking.
Biofuels Part 2	Postlab	Why does bioaccumulation matter? From your ecotoxicity data you saw that these fuels have varying toxicity – some fuels aren't toxic until they reach very high concentrations. Can you think of why bioaccumulation, even of a low toxicity fuel, would be an issue?
Biofuels Part 2	Postlab	Based on your collected and calculated data, can you select a "best" biofuel? Make an argument supporting your choice based only on your toxicity data. (Remember, a good argument will address ALL the data.)
Biofuels Part 3	Postlab	In lab this semester, you synthesized biofuel by manually mixing the NaOH catalyst and vegetable oil together and letting the reaction progress over one week. It is also possible to synthesize biofuel much more quickly using heat. Students used to synthesize biofuel by heating 20-mL of vegetable oil to between 40-50oC while rapidly stirring with a stir bar. They then turned off the heat, added 5 mL of the 0.4 M NaOH in methanol to the warm oil, and continued to stir the reaction for 45 minutes. a) Describe the advantages and disadvantages for each biofuel synthesis. b) From a green chemistry perspective, which method is preferable? c) Would your answer change if you were doing a large scale industrial reaction? Why or why not?

<table>
<tr><th>Experiment</th><th>Placement</th><th>Question</th></tr>
<tr><td>Biofuels Part 3</td><td>Postlab</td><td>What does it mean for a reaction to be green? What are the green components of your biofuels synthesis? Think about all the components of a reaction (the sourcing of the reactants, the reaction itself, the waste produced, and the hazards associated with each step of the reaction). It may be useful to review the 12 Principles listed in the introduction of this lab manual.

</td></tr>
<tr><td>Acids in the Environment Part 1</td><td>In-lab prompt</td><td>What benefits are there to using serial dilutions to make solutions? What are the drawbacks?</td></tr>
<tr><td>Acids in the Environment Part 1</td><td>In-lab prompt</td><td>Why is it important to dispose of waste in the proper containers?</td></tr>
<tr><td>Acids in the Environment Part 1</td><td>In-lab prompt</td><td>What happens to this waste once your lab section is finished?</td></tr>
<tr><td>Acids in the Environment Part 1</td><td>In-lab prompt</td><td>What could you have done during this lab to reduce the amount of waste you generated?</td></tr>
<tr><td>Acids in the Environment Part 3</td><td>Postlab</td><td>How can real-time analysis be used to reduce pollution?

Last week you explored the strengths and limitations of indicator titrations for measuring the acidity of ocean water and determining if a lake or stream is affected by acid rain. Could potentiometric titrations determine if a lake or stream is affected by acid rain? For example, would this technique allow you to say if the lake or stream was acidified from local industrial facility runoff versus acid rain?</td></tr>
<tr><td>Extraction and spectroscopy</td><td>Postlab</td><td>Extractions are used for a variety of purposes – from extracting essential oils to decaffeinating coffee. Coffee is one of the most popular beverages in the world and is naturally caffeinated. A cup of coffee contains 70-40 mg of caffeine depending on its size. However, for a variety of reasons, people might want to enjoy a cup of coffee without dealing with the effects of caffeine. Since the early 1900s people have been extracting caffeine from coffee to provide a decaffeinated version of the drink. There are several different ways to decaffeinate coffee as shown below.
<table>
<tr><th>Method</th><th>Solvent</th><th>Solubility of caffeine</th><th>High pressures, temperature</th><th>Selectivity for caffeine</th><th>Safety of solvent</th></tr>
<tr><td rowspan="2">Direct organic solvent extraction</td><td>Methylene chloride</td><td>Soluble</td><td>Heated to 100°C</td><td>Mid</td><td>?</td></tr>
<tr><td>Ethyl acetate</td><td>Soluble</td><td>Heated to 27°C</td><td>Mid</td><td>?</td></tr>
<tr><td>Supercritical carbon dioxide extraction</td><td>Solventless</td><td>--</td><td>High pressure, high temperature</td><td>High</td><td>?</td></tr>
</table>
Rank these three options from the best to worst extraction and explain your choice. Make sure to define the criteria you're using for your choice (e.g., cost, energy, waste, ability to recycle solvents).</td></tr>
</table>

<table>
<tr><th>Experiment</th><th>Placement</th><th>Question</th></tr>
<tr><td>Extraction and spectroscopy</td><td>Postlab</td><td>There are also specific
<table>
<tr><th>Solvent</th><th>Human Health Effects</th><th>Persistent in the Environment</th><th>Predicted No-Effect Concentration[5]</th><th>$\log K_{ow}$</th></tr>
<tr><td>Methylene chloride</td><td>Suspected carcinogen and mutagen, may cause damage to organs; causes serious eye irritation, skin irritation, and drowsiness or dizziness; repeated exposure and may cause respiratory irritation</td><td>Readily biodegradable</td><td>130 - 310 µg/L (freshwater)
31 – 130 µg/L (marine)</td><td>1.19</td></tr>
<tr><td>Ethyl acetate</td><td>Highly flammable liquid and vapor; causes serious eye irritation and drowsiness or dizziness; skin sensitizer</td><td>Readily biodegradable</td><td>240 µg/L (freshwater)
24 µg/L (marine)</td><td>0.71</td></tr>
<tr><td>Super-critical CO_2</td><td>May cause cold burns or frostbite, dry ice sublimes to carbon dioxide vapor at -78°c), vapor may displace oxygen and cause rapid suffocation, can contribute to greenhouse effect when realized in large quantities</td><td>Readily biodegradable</td><td>No ecological effects</td><td>0.83</td></tr>
</table>
environmental and human health effects for each potential solvent.

How does this environmental and human health data influence your choice of extraction solvent? Is your ranking the same? Different? Why?</td></tr>
<tr><td>Extraction and spectroscopy</td><td>Postlab</td><td>Suppose your lab partner disagree with your ranking for caffeine extraction. What might be some objections they could raise? How would you respond to these criticisms?</td></tr>
</table>

Appendix VII. Coding Schemes (Chapter 2 – 5)

Table A IX. Coding scheme for post-survey item “What would you want to change about the green chemistry portion of this course?” (Chapter 3)

Category	Sub-category	Definition	Examples
Blank, off topic		Empty or unclear/irrelevant content	"More focus on practice and exposure to chemistry beyond prelab. "
No Change		Students is happy with the current green chemistry content, and do not want any changes.	"nothing, it was good." "It was ok."
More real-life application		Students want more see more applications or examples of green chemistry in real life	"I would make it more approachable and down to earth and raise more examples that affect us directly." "maybe more discussions about making these things applicable to our lives outside of chem."
More emphasis in course	General	General statement about wanting the courses to have more green chemistry emphasis/explanations/focus/discussion, less vague	"add more emphasis on green chemistry concepts and include them on the exam" "More explanation"
	GSI lab lecture/ discussion	More green chemistry discussed in GSI prelab lecture or other discussions within laboratory	"I believe it should be more a part of the lab lecture part of lab, when the GSI is first talking about the lab for that day"
	Instructor lab lecture	More discussion in lab lecture led by the course instructor	"More discussion about it in lecture " "Put in more lecture material about it because it comes off as a side note."
Postlab green chemistry questions	Increase connections to in-lab procedures	Make green chemistry relevant to actual procedures	"Integrate it more into the physical experiments and relate the questions more to what we did in lab….."
	General negative feedback	Expressed general dislike (e.g., tedious, confusing, long, passive) of postlab green chemistry questions	"…..It is definitely an interesting concept but I felt is was mostly passively addressed in the report sheet questions. "
Prelab green chemistry questions	More GC	Students want more green chemistry incorporated in the prelab	"it should be incorporated more into prelabs and lab discussions"
	Less GC	Students want less green chemistry incorporated in the prelab	"I didn't like having it in my pre-labs. I didn't find it useful or beneficial at all to write the info from my pre-labs in my lab notebook."
	Other	Students want to change green chemistry portion in the prelab, unsure of direction	"I would like to change the amount of green chemistry questions asked in the pre-lab."
Remove/ reduce green chemistry content/focus		Remove or reduce the amount of green chemistry in the course	"Although I liked learning about green chemistry I wouldn't center the entire course around it."

Category	Sub-category	Definition	Examples
Revise green chemistry introductory material		Add more green chemistry content/examples/explanations to introduction of lab manual and/or each experiment	"Make the green chemistry of each experiment more clear in the lab introduction. Ex. 2 paragraphs isn't enough in my opinion. "
Better green chemistry integration into course/ experiment		More integration of green chemistry into experiment/lab procedure and/or more connection of green chemistry to rest of course material	"Sometimes the green chemistry sections of each lab felt oblique to what we were discussing. If possible it should be integrated more fluidly into the course." "Instead of separating the sections between green chemistry and the lab, I would recommend integrating as a vital part of the lab." "I would want the experiments to be more obviously related to green chemistry. It is definitely an interesting concept but I felt is was mostly passively addressed in the report sheet questions. " "Have it be relevant to actually doing the experiment. "
Other			"We should focus on how to reduce plastic waste in the lab. I've used a ton of plastic pipettes this semester!" "add more emphasis on green chemistry concepts and include them on the exam" "Green Chemistry would have been more relevant in this course if there was a large assignment on it in addition to a few questions on each report sheet."

Table A X. Coding scheme for green chemistry definition item administered on the in-class green chemistry quiz (Fall 2018, Fall 2019, Chapter 4). This coding scheme was developed for a previous dataset for the exact same item (Fall 2016, Chapter 2).

Code	Score	Definition	Common Themes	Examples	Notes
Research and Develop-ment	0	Answer shows no evidence that green chemistry is a research process	1. Green chemistry is a field 2. Green chemistry is used, applied, practiced 3. Green chemistry is static 4. Finding reactions (static)	• *chemistry working towards environmental issues* • *Practicing chemistry in a way that is sustainable for the environment.* • *Using resources that are better for the environment.*	Innovations not just applications (e.g. practice of chemistry does not count for a point) Create new product [sustainable way] Note: using an application is not the same as innovation
	1	Answer indicates understanding of green chemistry as a research process	1. Experiment, research, process, field of study 2. Design, development, create, create product. mindfulness 3. Improve, evaluate alternatives, make alternative options, new technologies, make choices 4. Find ways, analyzes ways to have, figure out ways, seeks to 5. Creating/designing chemical experiments 6. Solving problems	• *Green chemistry is a form of chemistry where methods and substances are devised/ made to be better for the planet.* • *Chemistry that tries to make the chemicals in a way that they can broken down by the environment or at the very least will not contaminate the environment.* • *Green chemistry is the branch of chemistry focused on creating chemical solutions to sustainability and environmental problems we face, creating a "greener" society* • *Green Chem does this by finding new chemical reactions that produce the desired outcome or by optimizing an already used reaction to make it less..*	

Code	Score	Definition	Common Themes	Examples	Notes
Minimize Hazards	0	No inclusion of minimizing hazards in answer	1. Atom economy 2. Waste	• *Chemistry that explores the properties of eco-friendly materials and seeks to apply them in daily life in a sustainable manner.* • *Green chemistry is the substudy of chemistry which focuses on efficient, environmentally friendly ways at generating a product.*	Minimizing 'hazardous waste' should be coded as ***Minimizing Hazards*** *OK if they don't actually say minimize*
	1	Answer includes explicit - mention of minimizing hazards	1. Safety, proper disposal or handling, PPE 2. Hazardous effect on environment 3. Hazardous/harmful materials (chemicals), harmful products 4. Hazardous waste 5. Nontoxic product 6. Pollution, contaminate the environment 7. Greenhouse gasses, carbon footprint 8. Chemical reactions that are safer 9. Minimize Chemical persistence	• *Chemistry that does not introduce or tries not to introduce too many hazardous materials to the environment* • *The practice of chemistry or usage of materials that minimize environmental impact/danger and/or are sustainable.* • *Refined chemistry that seeks to diminish the amount of hazardous byproducts of reactions.* • *Chemical processes that limit hazardous byproducts.*	
Minimize Waste	0	No inclusion of minimizing waste in answer	1. Hazardous waste	• *Chemistry and engineering that discovers ways in which to minimize hazardous waste products*	Minimizing 'hazardous waste' should be coded as ***Minimizing Hazards*** Maximizing yield = minimizing waste *OK if they don't actually say minimize*
	1	Answer includes minimizing waste as a component of green chemistry	1. Eliminate waste, no chemical waste, no production of waste 2. Reduce/minimize waste/waste products 3. Environmental waste 4. Recycle waste 5. Minimizing byproducts	• *Chemistry that leads to less chemical waste and pollution resulting from chemical reactions to produce goods.* • *Sustainable design of chemical products that eliminate waste.*	

Code	Score	Definition	Common Themes	Examples	Notes
Energy	0	No mention of energy in answer	1. Resources 2. Efficient/efficiency 3. Eco-friendly	• *Using resources that are better for the environment.* • *Using chemistry in a way that is eco-friendly, or helpful to the environment.* • *Making chemistry more efficient*	Renewable resources are coded in ***Material Lifecycle***
	1	Answer includes energy component of green chemistry	1. Energy resources, energy consumption 2. Energy efficiency 3. Better/more efficient/eco-friendly fuels 4. catalyst	• *Taking the environment into consideration when doing chemistry: limiting waste, toxicity, energy…* • *production/use of chemicals that have little adverse effect on environment and made with high energy efficiency*	
Material Lifecycle	0	No indication of material lifecycle	1. Resources, replacements 2. Efficient/efficiency 3. Biodegradable 4. Sustainable	• *Finding suitable replacements for chemicals used in daily life* • *minimizing waste and byproducts when conducting experiments and trying to figure out the most efficient way to reach the end result.* • *Green Chemistry is trying to conserve materials in lab*	Efficient (lifecycle) = maximizing yield of a desired product while minimizing inputs Just saying"biodegradable" doesn't count
	1	Answer includes mention of material lifecycle	1. Biodegradable recycling, 2. Renewable resources, sourcing reactants 3. Conserving (resources), efficient/sustainable use of materials, broken down 4. Atom economy (efficient, high atom economy) 5. Maximizing output while reducing waste	• *The study of chemicals for use in "green" applications such as renewable energy, sustainability, and recycling.* • *Reusable materials and little waste* • *As little waste and as much product as possible* • *Products and reactants are used fully and completely*	
12 principles	0	Does not mention 12 principles	1. Does not mention the 12 principles of green chemistry		

Code	Score	Definition	Common Themes	Examples	Notes
	1	Does mention 12 principles	2. Does mention the 12 principles of green chemistry		
Philosophy	0	No indication of systems approach	3. Not the same as research or innovation – systems thinking is viewing green chemistry as a complex interaction between different systems or processes		Indicates thinking across systems or processes, integration between different components Other categories rewards responses that are more specific and narrower responses
	1	Answer includes idea of integration or thinking across systems	1. Green chemistry is a philosophy of doing chemistry 2. Green chemistry is a version of doing chemistry 3. Movement of green chemistry 4. A way of doing chemistry (with green chemistry principles in mind) 5. Talk about green chemistry being a way to practice all chemistry. NOT just focused on how green chemistry is a branch of chemistry that can minimize damage to the environment and then go on to list principles of green chemistry.	• *Green chemistry is the integration of chemical techniques, principles, and concepts into a mindset of awareness of environmental and human health towards improving current chemical and industrial processes in order to achieve improved sustainability and environmental impact.* • *Green chemistry is still chemistry except it's chemistry with a better understanding and caution as to how experiments and certain methods can affect the environment. Green chemistry focuses on creating as little waste as possible, having a minimal effect towards the planet, and being more aware with the consequences from being environmentally ignorant in the lab.*	
Total reaction	0	Answer does not demonstrate that chemical reactions have multiple components	1. Does not indicate that chemistry/chemical reactions have multiple components	• *Products and reactants are used fully and completely*	Must have two of the three. Byproducts, waste, output, products all count as just the end.

Code	Score	Definition	Common Themes	Examples	Notes
	1	Answer includes multiple components of doing chemistry	1. Doing chemistry has multiple components (reaction, reactants, products) 2. Chemical reactions have different pieces, complex 3. Reaction process includes solvents, energy efficiency, safer reaction (i.e. For personnel) 4. Products can include, waste, byproducts, 5. Reactants – sourcing materials, safety of reactants	• *Make byproducts and processes more eco-friendly*	
Harm/good for Environment	0	Answer describes waste or hazards	1. Waste 2. Hazards (materials, compounds, waste, etc.)	• *Chemistry and engineering that discovers ways in which to minimize hazardous waste products* • *Chemistry that leads to less chemical waste and pollution resulting from chemical reactions to produce goods.*	Reduce or remediation of harm to the environment Positive impact on the environment Key word here is environment (something in relation to the environment)
	1	Answer describes negative or positive effect on the environment	1. Harm, impact on environnent, minimal affect on environnent 2. (Reduce) environmental footprint 3. Health of environment, improve environment 4. Environmentally friendly, sustainability, conscious, or responsible 5. Harm/good for earth/planet/world	• *Chemistry that minimizes harm to the environment(?)* • *Green Chemistry is the study of how alternative methods of instigating reactions and building devices can leave a lesser impact on the environment.* • *applying chemistry in the least harmful ways that affect the environment*	

Code	Score	Definition	Common Themes	Examples	Notes
Buzzwords only	0/1	Answer consists of green chemistry buzzwords only – or general statements - no explanation	1. Environmentally friendly/conscious/responsible 2. Sustainable/sustainability 3. Biodegradable 4. Pertaining to the environment 5. Eco-friendly, clean, good for the environment	• *Using chemistry to improve sustainability in daily activities* • *Chemistry that is good for the environment.* • *Chemistry in relation to the environment.*	*Efficiency* is interpreted depending on the content: sometimes it relates to energy (e.g. energy efficiency), sometimes it relates to material lifecycle (e.g. energy cost), sometimes it is coded as a buzzword (e.g. *Chemistry that helps make processes more efficient*). Do not check Buzzword if any of the content components or philosophy or total reaction etc. are checked. Harm/Good for environment and 12 principles may be checked with buzzwords only. Philosophy doesn't count for this category
Irrelevant	0/1	Irrelevant answer or no response	1. Healthy chemistry 2. Chemistry that is green 3. Good definition of some other aspect of chemistry	• *The chemistry of organic compounds* • *Learning about the plants and more biology type of studies involving chemicals*	

Table A XI. Coding scheme for two methods choice item administered on the in-class green chemistry quiz (Fall 2019, Chapter 4). The first draft of this coding scheme was developed from the administration of the initial version item during the Fall 2018 semester.

<table>
<tr><th rowspan="2">Main Category</th><th rowspan="2">Sub-category</th><th colspan="2">Definition</th><th rowspan="2">Common words/ Phrases</th><th rowspan="2">Examples</th></tr>
<tr><th>Chooses Method</th><th>Doesn't choose method</th></tr>
<tr><td rowspan="2">Specified Method</td><td>Fossil Fuels</td><td>Stated that fossil fuels would be the preferred method</td><td></td><td></td><td>From a green chemistry perspective, the best method of making cinnamaldehyde I guess would be through fossil fuels because the cost of the product would be less and trees would not be needed to be cut down</td></tr>
<tr><td>Tree Bark</td><td>Stated that tree bark would be the preferred method</td><td></td><td></td><td>Using cinnamon tree bark and steam distillation is the best way.</td></tr>
<tr><td>General: buzzwords</td><td></td><td>States very generic language that is relating to green chemistry principles, but with very little purpose or showing no deeper understanding</td><td>States very generic language that is relating to green chemistry principles, but with very little purpose or showing no deeper understanding</td><td>- green, sustainable
-safer, environmentally friendly, eco-friendly, best for the environment
- efficient
-natural
-Global Warming
-pollution</td><td>I would want to know which process is the most efficient while also causing the least amount of harm to the environment. For example, the process of using fossil fuels is bad for the environment, so I'd want to know if cinnamon tree bark with steam distillation would be better for the environment

I would decide by assessing these reactions in the context of the 12 green chemistry principles. These 12 principles will inform me of the efficiency, toxicity, and environmental effects of the reaction (along with many other characteristics). This would then allow me to choose the best reaction.</td></tr>
</table>

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Renewability	**Unsupported**	Specifies that _____ in the reaction or process is renewable / non-renewable without explaining why or defining what renewable means OR Stating that one process is more renewable/non-renewable than the other without explaining why or defining what renewable means.	States that you should consider renewability in your reaction but does not explain what renewability means or why it is important.	- the reaction/process is renewable - you should consider renewable feedstocks in your reaction -fossil fuels are renewable	*… We would have to look at things like atom economy, renewability, safety, toxicity… If I were to choose, I'd choose the steam distillation because it's renewable, there's less energy consumption and it's non-hazardous for the environment.* *The best way would be via cinnamon tree barks as it is a renewable method.* *I would first see which source causes the most harm to the environment when depleted and whether is renewable*
	Supported	Specifies that something in the reaction or process is renewable (i.e., chooses fossil fuels or cinnamon tree bark) is renewable / non-renewable AND explaining why it is renewable. Demonstrates understanding of renewability and/or its importance.	States that you should consider renewability in your reaction and explains what renewability it or why it is important	- fossil fuels are non-renewable - tree bark is a renewable resource - Using renewable resources is important because ... - *depletion of fossil fuels in an issue*	*The method which uses renewable sources would be preferable. Methods that use fossil fuels are not eco-friendly because fossil fuels are not a renewable source. Tree bark is more renewable.* *I would make it using cinnamon tree bark because this resource can be easily replenished/regrown* *I would use the method with the cinnamon tree bark because it would be done using a renewable feedstock. Whereas the other method uses fossil fuels which are not renewable and are hence at the risk of depleting which is why it would not be sustainable (we are meeting the needs of the current generation by compromising the needs of the future generations*

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Economic	**Unsupported**	Economic category is relating to monetary cost and/or the cost of production. This does not mean environmental cost. States that one reaction has a greater monetary cost or economic cost than the other without any explanation or evidence. Note: Making incorrect or far-fetched assumptions about the scenario will also be placed in this category	Economic category is relating to monetary cost and/or the cost of production. This does not mean environmental cost. States that one reaction has a greater monetary cost than the other without any evidence or support. Note: Making incorrect or far-fetched assumptions about the scenario will also be placed in this category	Do not code if: Reponses that consider time but don't relate it to cost; saying a method requires resources without any other statement tying it to economic cost	*I would decide to use the cinnamon tree bark because fossil fuels are potentially dangerous and* ***costly to the environment and the economy.*** *To decide which method is the best, look at the* ***cost of the reactants****...* *Efficiency -- Does it produce a lot of cinnamaldehyde with* ***little cost/resources?*** *Fossil fuels, the other method, is a nonrenewable source that negatively affects the environment through global warming*
	Supported	States that one reaction has a greater economic cost than the other with evidence or support as to how they came to that conclusion while explicitly defining what they mean by economic cost.	States that one should consider the economic implications of a process while specifying why it is important or what specific cost they are talking about (i.e., reactants, machinery, etc.) Provides methodology, baseline questions, or inquiries to how this economic cost can be measured. Must explicitly define what they mean by economic cost		*By getting [cinnamaldehyde] from fossil fuels, it would be synthetic and easier to obtain/use in cooking to keep the flavor consistent...getting it from steam distillation would be more timely and would not provide consistent flavoring.*

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Energy	**Unsupported**	States that one reaction uses more energy than the other without evidence or explanation. Note: Incorrect or far-fetched assumptions about the two reactions regarding energy will be marked in this category	States that one should consider energy consumed in a process without specifying why it is important or what part of the processing they are talking about. Note: Incorrect or far-fetched assumptions about the two reactions regarding energy will be marked in this category	- consider energy consumption in the reaction - processes using fossil fuels uses more energy than distillation Don't code if: Reponses that say time but don't connect it to temperature and pressure; saying a method requires resources without any other statement tying it to energy	*We would look at the 12 chemistry principles and paying attention to human's and the environment's safety we would choose the one that is less hazardous. We would have to look at things like atom economy, renewability, safety, toxicity… If I were to choose, I'd choose the steam distillation because it's renewable, **there's less energy consumption** and it's non-hazardous for the environment.* *steam distillation saves more energy and does not pollute the earth more than fossil fuels which uses lots of energy and coal.*
	Supported	States that one reaction uses more energy than the other with evidence or support that this is true.	States that one should consider energy consumed in a process and specifying why it is important, or in what part of the processing it is important.	- fossil fuels take a lot of energy to process and refine for use	*However, using trees contribute to indirect land use and steam distillation does not occur at ambient temperature and pressure.*
Harmful Byproducts	**Unsupported**	States that one reaction has more/less harmful byproducts than the other without evidence or support that this is true. (i.e., did not specify the compound)	States that one should consider harmful byproducts produced in a process without specifying why it is important. Note: Making incorrect or far-fetched assumptions about harmful byproducts will be placed marked here	- fossil fuel method has more harmful byproducts than the distillation method -fossil fuels contribute to global warming Do not code if: responses that say they want to know the identity of the byproducts without associating it with hazard	*… it is more environmentally friendly and will **contribute less to pollution.*** *I'm **assuming** that it will create less toxic waste than fossil fuels* *Look at the **toxicity** of the byproducts and waste produced* *I would see the amount of waste produced by each method and if the waste is toxic or not. Toxic waste can be extremely harmful to the environment* *...using natural resources to prevent any hazardous waste*

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
	Supported	States that one reaction has more/less harmful byproducts than the other with evidence or support that this is true. For example, stating which compound is the harmful byproduct. - must state specific chemical compound	States that one should consider harmful byproducts produced in a process and specifying why it is important or insight in how to	-'fossil fuels product CO_2 when burned which is harmful to the environment because of its contribution to global warming -steam distillation gives off water vapor which is not harmful to the environment -Polluting the atmosphere	*… I know that the use of **fossil fuels releases CO2 into the environment and is there bad for the environment**. Steam distillation seems less harmful.* *… **the intermediate for the fossil fuel pathway is a derivative of the very toxic benzene**.* *Look at the toxicity of the byproducts….check CO2 emissions for each method* *I would also want to know the toxicity of all products because humans consume this molecule and we don't want harmful effects*
Hazardous Reactants / Intermediates	**Unsupported**	States that one reaction has more/less hazardous reactants than the other without evidence or support that this is true. (i.e., did not specify the compound)	States that one should consider whether the reactants are hazardous without specifying why it is important or what it means for a reactant to be hazardous. Note: Making incorrect or far-fetched assumptions about harmful byproducts in the context of this question will be marked here	Do not code if: responses that say they want to know the identity of the reactants without associating it with hazard; saying a method requires resources without any other statement tying it to hazardous reagents	*Therefore, I would choose to use steam distillation of cinnamon tree bark since bark is a renewable, nontoxic resource.* *I would choose the 2nd method [tree bark] because of the use of natural and safe solvents* *Look at the toxicity of...the leftover reactants* *Cinnamon tree bark...because it uses the technique of steam distillation, which does less harm than adding chemicals such as benzaldehyde* *I want to know the safety of the materials used*
	Supported	States that one reaction uses more/less hazardous reactants than the other with evidence or support that this is true. For example, stating which compound is a hazardous reactant.	States that one should consider hazardous reactants used in a process and specifying why it is important or giving insight into how to define hazardous.	- steam distillation uses water which is a safe solvent	*Water is safe solvent* *Steam distillation most likely uses a safe solvent like water*

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Less Waste/Waste Disposal	Unsupported	Waste is defined as having to do with material waste (as opposed to energy, time, etc.). States that one reaction has more/less waste than the other without evidence or support that this is true.	Waste is defined as having to do with material waste (as opposed to energy, time, etc.). States that one should consider waste without specifying why it is important. Note: Making incorrect or far-fetched assumptions about waste in the context of this problem will be marked here		*-fossil fuels are a limited resource* ***-Benzaldehyde is another added chemical which may leave waste when producing the product*** *…I would consider a number of factors like the 1) price, 2) release of toxic materials into the environment, 3) time, 4)* ***how much material is used/wasted.*** *1) Concentration -* ***which method consumes less resources****, 2) byproducts - which method produces the* ***least waste****/harmful material, 3) sustainability - are the raw materials renewable*
	Supported	States that one reaction uses more/less waste than the other with evidence or support that this is true. States that one reaction has more processible / less hazardous waste than the other.	States that one should consider waste produced and specifying why it is important or specifying what kind of waste.	- the distillation method has less waste because its raw material, tree bark, can be composted.	***The waste of distillation must be biodegradable.*** *There isn't much leftover chemicals, other than tree bark (biodegradable) and water* *The steam distillation with cinnamon tree bark would be the best since … the process to extract the chemical is not that energy intensive and doesn't require auxiliary components* I think the best method to use for making cinnamaldehyde would be the method that creates less trash and pollution to begin with this is important because it is easier to create less trash in the first place, then clean it up after

Main Category	Sub-category	Definition: Chooses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Sustainable Systems	**Unsupported**	States that one reaction has more/less processing damage than the other without evidence or support that this is true. - Very general, doesn't go into detail - Say something interesting but doesn't go into detail	States that one should consider processing damage without specifying why it is important or in what context they are talking about. - Very general, doesn't go into detail - Say something interesting but doesn't go into detail		***fossil fuels greatly negatively affect the environment****, whereas (I believe)* ***bark can be harvested with less overall harm to the environment****.* *I would believer the steam distillation from cinnamon tree bark would be the best method to use for making cinnamaldehyde. This is because it is* ***naturally derived in a way that isn't as bad for the environment.*** *Want to know how* ***disruptive the extraction of these resources will be to the surrounding environment and community***
	Supported	- Acknowledging that processing damage is a very complex system with lots of factors you need to weigh in and going into detail of why/how it is - Choose one method and goes in detail with how the processing damage specific to that method -Identifies who is being affected by the processing damage	- Acknowledging that processing damage is a very complex system with lots of factors you need to weigh in and going into detail of why/how it is - Choose one method and goes in detail with how the processing damage specific to that method -Mentions the impacts of sourcing precursors / reactants -Identifies who is being affected by the processing damage	-use of land resources -	*…* ***Are cinnamon trees endangered?*** *How much damage do fossil fuels have on the environment?* ***Will using cinnamon tree bark harm the tree itself or lower its lifespan?*** *The steam distillation would be ideal if the cinnamon* ***trees are not severely damaged as a result for the production.*** *1) which method is more hazardous to its surroundings.* ***2) is steam distillation more toxic to the environment than the extraction of fossil fuels? How much so? 3) does the extraction of cinnamon tree bark negatively impact the tree from which it came? I the tree still able to survive and thrive post extraction?***

Main Category	Sub-category	Definition: Choses Method	Definition: Doesn't choose method	Common words/ Phrases	Examples
Yield		Mentions the yield of the process or a comparison of the number of reactants to the amount of product -this specifically refers to the amount of product in relation to the number of reactants		yield Notes: amount of product in relation to amount of resources, economic cost, or byproducts	
Amount of Material		States the physical amount or volume of reactant material (*without tying this amount to increased toxicity or any other consideration*) as a factor to consider or explains how one process may require the use/involvement of more reagents or material. Tying this physical amount to any other category, such as economic, less waste, toxicity, processing damage etc. results in the answer being coded toward those categories only.		number of reactants extra additional Notes: -saying a method requires resources without any other statement tying it to reactant material	*See…the number of reactants needed to perform the reaction(48)* *Steam distillation minimizes the use of external chemicals (45)* *Through steam distillation you are not using extra reagents….the [fossil fuels] reaction requires extra benzaldehyde to run (42)*
Atom Economy		Mentioned atom economy			*Also, **using a minimal number of resources to produce the end product - Atom Economy** - is important.* *…The **atom economy is important, to maximize efficiency.** Long-term effects should be considered as well. The amount of energy needed to move the reaction forward is also important so we can choose the more energy efficient option.*
Incorrect assumptions about reactant (Benzaldehyde)		Specifically mentions use of the chemical benzaldehyde as a consideration against the fossil fuel method, or assumes benzaldehyde is harmful in their response. -Differs from amount of material in the response's direct characterization of benzaldehyde as negative -Claims synthesis with benzaldehyde is bad/unnatural compared to steam distillation		harmful benzaldehyde Notes: Neutral mentions of benzaldehyde, e.g., simply referring to the fossil fuel method as the benzaldehyde method, or mentioning benzaldehyde as an example of an additional reagent (coded into amount of material instead)	*…steam distillation is much **safer for humans** + the plane**t than the chemical benzaldehyde*** *We would rather perform natural processes such as steam distillation rather than artificial synthesis with benzaldehyde*

Main Category	Sub-category	Definition		Common words/ Phrases	Examples
		Chooses Method	Doesn't choose method		
I don't know but my best guess is…		States I don't know but my best guess is… as part of their answer			
Off-topic					*The best way is probably extracting it from fossil fuels because it reduces pollution. If you extract cinnamaldehyde from cinnamon tree bark, you use a lot of land/water, which can affect wildlife. In addition, steam is utilized in the process, which could produce fossil fuels.*

Table A XII. Coding scheme for the green chemistry exam item (Chem 1AL, Chem 3BL) for the Fall 2019 dataset (Chapter 5)

Category		Definition	Examples	SUB-SCORING	Notes
Pro/con reasons for method choice	% yield	Typically method 1 choice		Pro = measure is GOOD reason for choosing method Con = measure is BAD reason for choosing method Acceptable = measure is within acceptable ranges (not the best for their chosen method but not a dealbreaker), often use "Even though... however..." structure Equivalent = variable for two methods seen as essentially the same and thus not a factor in their decision	
	Reaction time	Typically method 1 choice			
	Cost	Typically method 1 choice			
	Purification method	Note any links between extraction + energy use/recrystallisation + solvent use to determine correctness			
	Atom economy	Typically method 2 choice			
	# of byproducts	Typically method 2 choice			
	Persistence of reactants	Typically method 2 choice			
	Acute toxicity of **reactants**	Typically method 2 choice			
	General Hazards	Toxicity w/o mentioning reactants; general safety			
Mentions GC		States that the chosen measures align with green chemistry principles or that the chosen method is 'greener'	*X and Y mean it is a good green chemistry reaction.*		

Category	Definition	Examples	SUB-SCORING	Notes
Supports measure choices	Explains why a measure is 'good' or 'bad' - does not simply assert that it is good or bad	*0: Method 2 has higher atom economy compared to method 1. "The toxicity of reactants in #2 is low, while the tox of #1 is high."* *1: Method 2 has a high % yield which means that few byproducts are produced which means reduced waste; method 1 has a higher percent yield which means more moles of reactant go into making the product* *2: method 2 is preferable because it has high atom economy meaning that it utilizes resources well, a small amount of byproducts which reduces it by product impact on the environment, uses a simpler method of purification-extraction which requires no energy, and the reactants are low toxicity meaning safer reaction* *3: Fewer byproducts mean waste is avoided instead of cleaned up afterward; Atom economy of method 2 is greater than method 1 which means that less wasteful byproducts are formed; the reactants are far less toxic which helps prevent disasters should an accident happen; the reactants maybe more toxic than method 2 but the persistence is very low meaning it wouldn't last long in the environment*	0 = no attempt 1 = attempt to justify but incorrect link between ideas/justification (commonly confuses % yield and AE) 2 = tries to support choice (but reliance on buzzwords or tautological) 3 = good reasoning (not just buzzwords, e.g. AE leads to reduced waste/pollution, contextualizes reason/measure)	If answer has multiple supported measures code based on BEST supported measure

Category	Definition	Examples	SUB-SCORING	Notes
Mentions tradeoffs between variables	Essentially states both pros and cons but in comparison (e.g. atom economy is lower for method 1 but a high yield makes up for it)	*The atom economy for method 2 is greater than for method 2 and although it is not as time efficient the amount of yield and atom economy make the reaction efficient overall.*		has to balance two ideas that are related, i.e. AE+%yield, cost and efficient use of materials (i.e. AE, # byproducts), acute toxicity versus persistence make it clear that the two tradeoffs are linked in a logical way
Measure is more/less important than others	States that a chosen measure (or set of measures) is more/less important/valuable compared to other measures; privileges a set of measures; not all measures are equal	*Perhaps most importantly, method 2's reactant toxicity is much lower than method 2....* *Importantly, from a green chemistry perspective, the reactants are far less toxic...*		uses superlative language - "extremely important" or "most"
Off topic/ incorrect / extrapolates	Part of whole answer is incorrect or off-topic. If part of the answer is incorrect/off-topic, continue coding. If entire answer is incorrect/off-topic, DO NOT continue coding.	...and the waste generated is less toxic and persistent than method 1. ...method 2 is more energy efficient than method 1. [example of extrapolating too much from given info]		Often talk about toxicity of byproducts (confuse reactants and byproducts) or confuse the metrics for one reaction with the other

Appendix VIII. Scoring for Fixed Response Items (Chapter 4)

Table A XIII. Correct and incorrect choices for multiple choice (select all that apply) survey items administered during the Fall 2019 semester on the online survey (Chapter 4)

<table>
<tr><th>Item</th><th>Correct Choices</th><th>Incorrect Choices</th></tr>
<tr>
<td>[Select All #1: Atom Economy] The reaction below can be used to fill an automobile airbag.
<table>
<tr><td></td><td>$2NH_4NO_3(s)$
(ammonium nitrate)</td><td>→</td><td>$4\ H_2O(l)$
(water)</td><td>+</td><td>$2\ N_2(g)$
(nitrogen)</td><td>+</td><td>$O_2(g)$
(oxygen)</td></tr>
<tr><td>M.W.
(g/mol)</td><td>80.04</td><td></td><td>18.02</td><td></td><td>28.01</td><td></td><td>32.00</td></tr>
<tr><td>LD_{50}
(mg/kg in rats)</td><td>2217</td><td></td><td>>90,000</td><td></td><td>none available</td><td></td><td>none available</td></tr>
</table>
The atom economy for this reaction is 55%. This means that: (Select all that are accurate.)</td>
<td>☐ 45% of the starting material ends up as waste in the form of water
☐ 55% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag</td>
<td>☐ 55% of the starting material ends up as waste in the form of water
☐ 45% of the starting material is incorporated into the desired products (nitrogen and oxygen gas) that can be used to inflate the airbag
☐ The theoretical yield of the reaction is 55%.
☐ The theoretical yield of the reaction is 45%.</td>
</tr>
<tr>
<td>[Select All #2: LD_{50}] The reaction below can be used to fill an automobile airbag.
<table>
<tr><td></td><td>$2NH_4NO_3(s)$
(ammonium nitrate)</td><td>→</td><td>$4\ H_2O(l)$
(water)</td><td>+</td><td>$2\ N_2(g)$
(nitrogen)</td><td>+</td><td>$O_2(g)$
(oxygen)</td></tr>
<tr><td>M.W.
(g/mol)</td><td>80.04</td><td></td><td>18.02</td><td></td><td>28.01</td><td></td><td>32.00</td></tr>
<tr><td>LD_{50}
(mg/kg in rats)</td><td>2217</td><td></td><td>>90,000</td><td></td><td>none available</td><td></td><td>none available</td></tr>
</table>
The LD50 for the starting material, ammonium nitrate, is shown above. LD50 tells you:
(Select all statements that are accurate.)</td>
<td>☐ The amount of a chemical that it takes to cause death in half the members of a test population</td>
<td>☐ The amount of a chemical that it takes to cause mutations in an entire test population
☐ The amount of a chemical that it takes to cause bioaccumulation in half the members of a test population
☐ The amount of a chemical that it takes to cause endocrine disruption in an entire test population
☐ The amount of a chemical that it takes to cause birth defects in half the members of a test population
☐ The amount of a chemical that it takes to cause cancer in an entire test population</td>
</tr>
<tr>
<td>[Select All #3: Natural vs Renewable] Over the last few years, there has been an increased demand for natural and/or renewable resources. Please select all of the following statements that are true.</td>
<td>☐ Renewable products are sustainable.</td>
<td>☐ Natural products are sustainable.
☐ The terms “natural” and “renewable” are interchangeable.
☐ Natural products are likely to be safe for humans and the environment.
☐ Renewable products are likely to be safe for humans and the environment.
☐ Natural products or processes are always preferable to synthetic ones.
☐ Renewable products or processes are always preferable to synthetic ones.
☐ I don't know.</td>
</tr>
</table>

Table A XIV. Explicitly and implicitly correct principles for each 12 Principles ranking items administered during the Fall 2019 semester on the online survey (Chapter 4)

Item Prompt [Item Name]	Explicitly correct principles[a]	Implicitly correct principles[b]
[12 Principles #1] Traditionally, paper has been bleached with chlorine to give it a white appearance. Chlorine and its derivatives (such as chlorine dioxide) are very dangerous for humans and toxic to aquatic organisms. Eliminating the use of chlorine in paper production is an example of which green chemistry principle(s)?	▢ Less Hazardous Chemical Syntheses ▢ Inherently Safer Chemistry for Accident Prevention	▢ Designing Safer Chemicals
[12 Principles #2] BASF (the largest chemical producer in the world) is currently developing plastic bags made partly from cassava starch and calcium carbonate. These bags completely disintegrate into water, CO2, and biomass in industrial and city composting systems. These bags are examples of which green chemistry principle(s)?	▢ Waste Prevention ▢ Designing Safer Chemicals	▢ Use of Renewable Feedstocks
[12 Principles #3] Oil-based "alkyd" paints emit high levels of volatile organic compounds (VOCs). As the name suggests, VOCs evaporate from drying paint and can produce many harmful health effects (ranging from eye irritation to liver damage to cancer). Sherwin-Williams won the 2011 Presidential Green Chemistry Challenge Award for the development of low-VOC, water-based paints that are made from recycled plastic bottles and soybean oil. This new paint formulation is an example of which green chemistry principle(s)?	▢ Less Hazardous Chemical Syntheses ▢ Safer Solvents and Auxiliaries	▢ Waste Prevention ▢ Designing Safer Chemicals ▢ Use of Renewable Feedstocks ▢ Design for Degradation ▢ Inherently Safer Chemistry for Accident Prevention

[a]Explicitly correct principles were identified as the most relevant principles that clearly applied to the given green chemistry scenario.
[b]Implicitly correct principles were tangentially related to the given scenario and/or would only apply if certain preconditions or assumptions were met.

Appendix IX. Regression Analysis (Chapter 4 and 5)

Chapter 4 Regression Analysis

Regression Variables

Response variables

Green chemistry definition total score (pretest): A continuous variable measuring the student's total pretest score on the Green Chemistry Definition item.

This variable reports student scores for the item "In my own words, green chemistry means:" A total item score was assigned for each responses by summing the individual coding categories. A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 point plus 1 point for each specific green chemistry category present in the response. This variable had a minimum score of 0 and a maximum score of 9 with only whole number intervals possible.

Green chemistry definition total score change (posttest score – pretest score): A continuous variable measuring the student's change in total score from the pretest to the posttest on the Green Chemistry Definition item described above. This variable had a minimum score of -9 and a maximum score of 9 with only whole number intervals possible.

Two methods choice total score (pretest): A continuous variable measuring the student's total pretest score on the Two Methods Choice item.

This variable reports student scores for the item In my own words, green chemistry means: A total item score was assigned to each responses by summing the individual coding categories. A blank or off-topic/irrelevant response received a score of 0. All other responses received a score of 1 point plus 1 point for each unsupported green chemistry category and plus 2 points for each supported green chemistry category present in the response. This variable had a minimum score of 0 and a maximum score of 18 with only whole number intervals possible.

Two methods choice total score change (posttest score – pretest score): A continuous variable measuring the student's change in total score from the pretest to the posttest on the Two Methods Choice item described above. This variable had a minimum score of -18 and a maximum score of 18 with only whole number intervals possible.

Explanatory variables

Gender (Female): A categorical variable indicating a student's gender, where ***Male*** is the reference group. Students who did not provide their gender or declined to state their gender were dropped from the data set.

First-generation college status (first-generation college student): A categorical variable indicating the level of education for a student's parents, where ***not a first-generation college student*** is the reference group. If neither of the student's guardians had completed college-level degree or higher than the student was coded as a first-generation college student.

URM status (URM student): A categorical variable indicating if a student self-identified as an underrepresented minority, where ***non-URM student*** is the reference group. If students reported that their ethnicity was black, hispanic, indigenous and/or pacific islander they were coded as an URM student. Students who did not provide their ethnicity or declined to state were dropped from the data set.

Prior green chemistry experience (no prior green chemistry experience): A categorical variable indicating if students had heard of green chemistry before 1AL, where ***prior green chemistry experience*** is the reference group. Students were asked on the pretest survey Had you heard of green chemistry before you entered this course (1AL)? – if they responded positively, they were coded as having prior green chemistry experience and if they responded negatively, they were coded as not having prior green chemistry experience.

Prior college credit bearing chemistry experience (no prior college credit bearing chemistry experience): A categorical variable indicating if students had taken college credit bearing chemistry courses before 1AL, where ***prior experience*** is the reference group. Students were asked on the pretest survey to note how many semesters of various chemistry classes they had previously completed (chemistry, honors chemistry, AP chemistry, IB chemistry, etc.). If students noted that had taken at least on semester of AP/IB chemistry, chemistry at a community college, or chemistry at a university there were coded as having prior college credit bearing chemistry experience.

Regression Assumption Checks

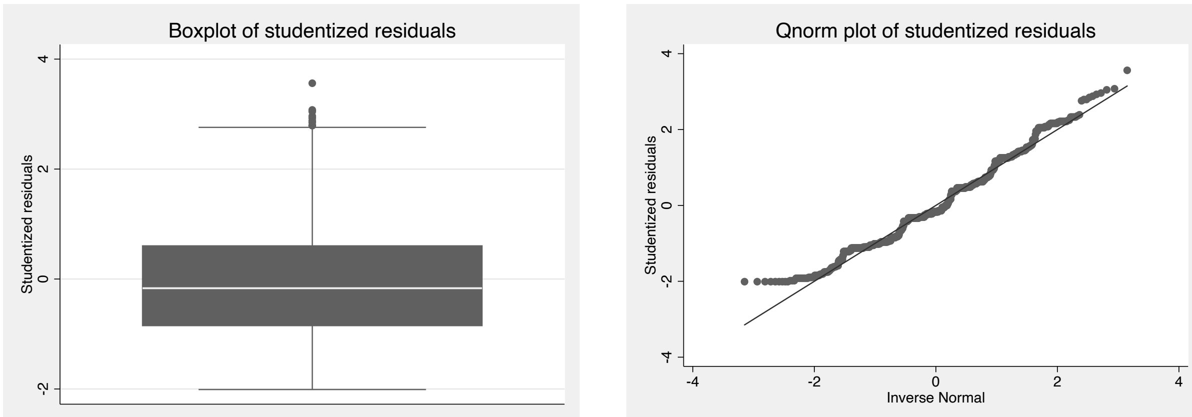
Check for collinearity

Table A XV. Check for collinearity between explanatory variables for Green Chemistry Definition item and Two Methods Choice Item

Variable	Green Chemistry Definition Models 1 and 2		Two Methods Choice Models 1 and 2	
	VIF	1/VIF	VIF	1/VIF
URM status	1.09	0.91	1.08	0.93
First-generation college status	1.08	0.92	1.07	0.93
No prior green chemistry experience	1.02	0.98	1.01	0.99
No prior college credit bearing chemistry experience	1.01	0.99	1.01	0.99
Female	1.01	0.99	1.00	1.00
Mean VIF	**1.04**		**1.04**	

Check assumption of normality

Green Chemistry Definition: Pretest Score (Model 1)



Green Chemistry Definition: Gain Score (Model 2)

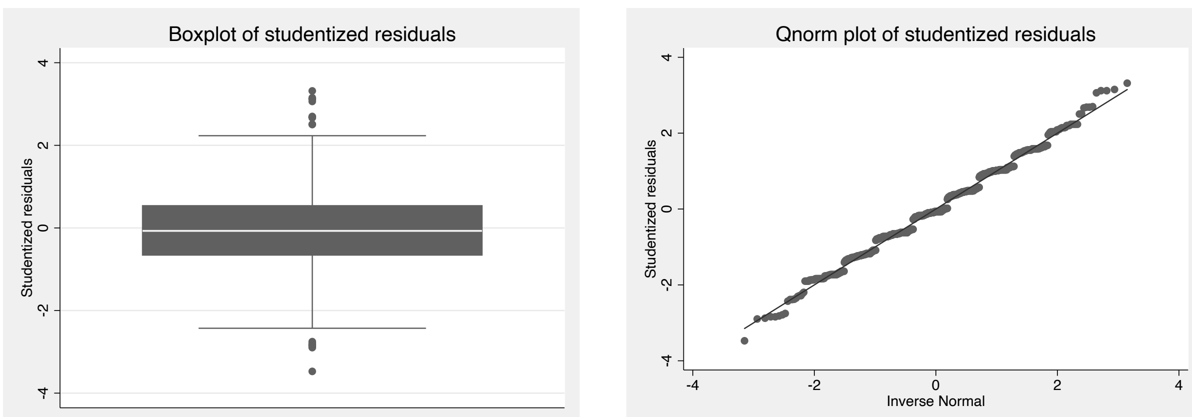
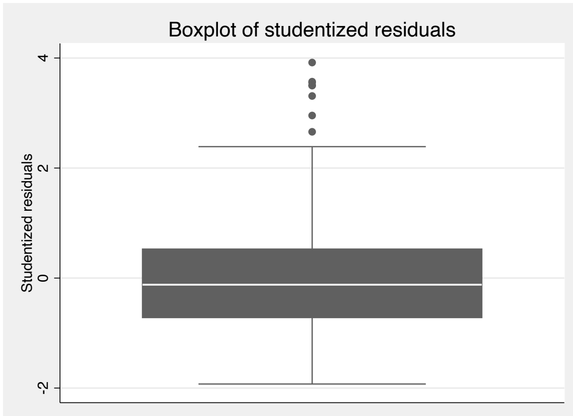
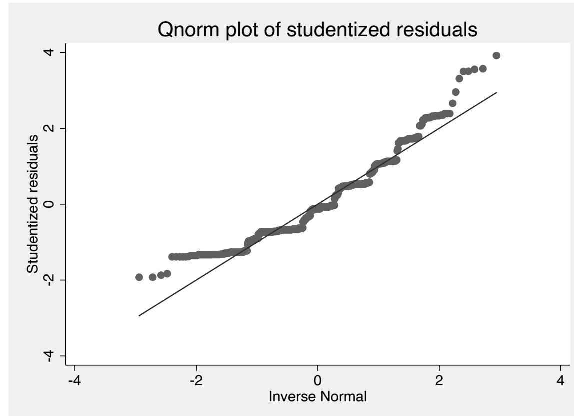


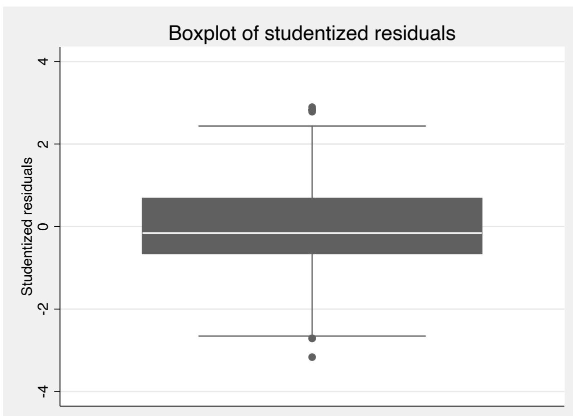
Figure A IV. Qnorm and boxplot of deleted studentized residuals to check assumption of normality of the residuals for Green Chemistry Definition Model 1 (pretest) and Model 2 (gains); studentized deleted residuals have several potential outliers and evidence of non-normal distribution

Two Methods Choice: Pretest Score (Model 1)





Two Methods Choice: Gain Score (Model 2)



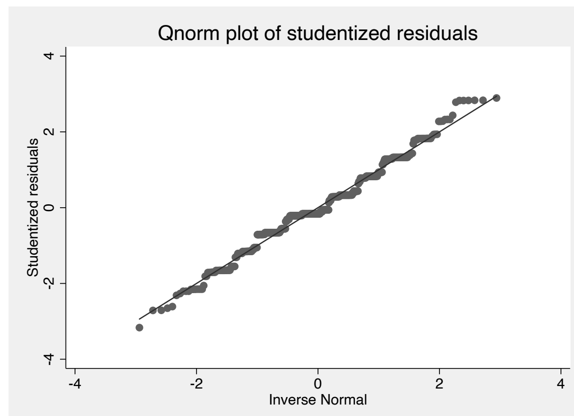
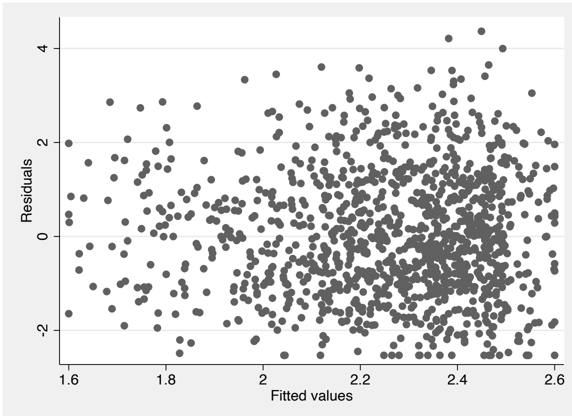
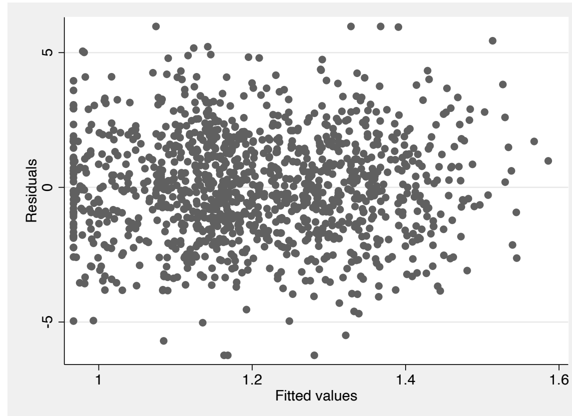


Figure A V. Qnorm and boxplot of deleted studentized residuals to check assumption of normality of the residuals for Two Methods Choice Model 1 (pretest) and Model 2 (gains); studentized deleted residuals have several potential outliers and evidence of non-normal distribution

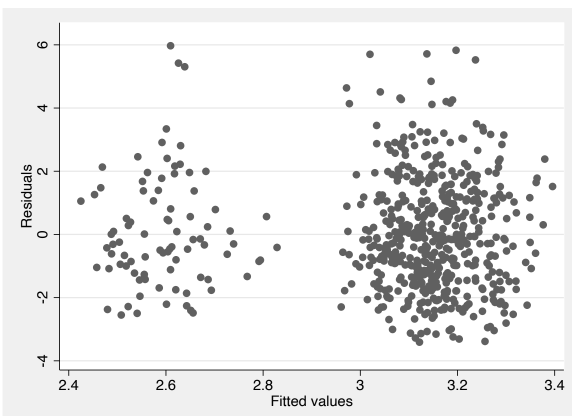
Check assumption of constant variance of residuals



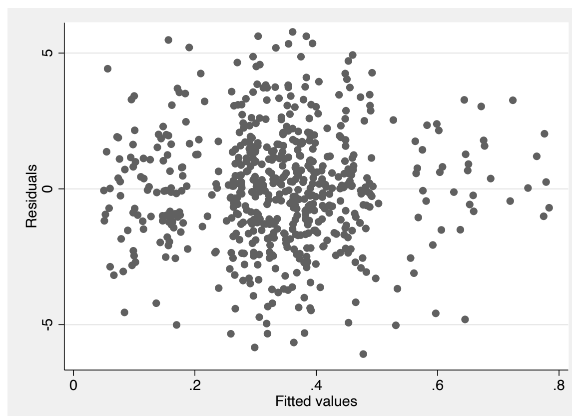
Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals (**Green Chemistry Definition, pretest score**)



Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals (**Green Chemistry Definition, gain score**)



Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals (**Two Methods Choice, pretest score**)



Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals (**Two Methods Choice, gain score**)

Figure A VI. Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals

Chapter 5 Regression Analysis

Regression Variables

Response variables

Method Choice Total Score: A continuous variable measuring the student's total exam score on the green chemistry item (described in detail in a prior appendix). The total score was assigned to each response by summing the number of correct measures used for the chosen method (0.5 points per correct measure) along with the support score (0-3 points) and mentions of tradeoffs (1 point) and prioritization of measures (1 point). Points were subtracted from the total score if a response incorrectly applied a measure (0.5 points per incorrect measurer) or if a portion of the response was off topic/incorrect (1 point).

Explanatory variables

Course (Chem 3BL): A categorical variable indicating the chemistry course the student was enrolled in, where ***Chem 1AL*** is the reference group.

Method (Method 2): A categorical variable indicating which method the student chose for the green chemistry exam item, where ***Method 1*** is the reference group.

Total Lab Exam Score: A continuous variable indicating the student's overall grade on their laboratory exam. To make the exam scores comparable for both courses the raw percentage grade (0-100%) was standardized using z-scores.

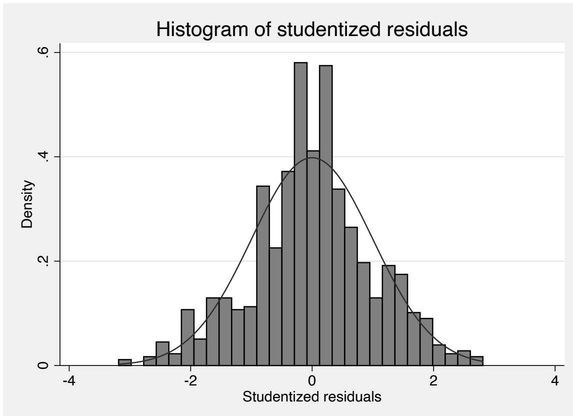
Regression Assumption Checks

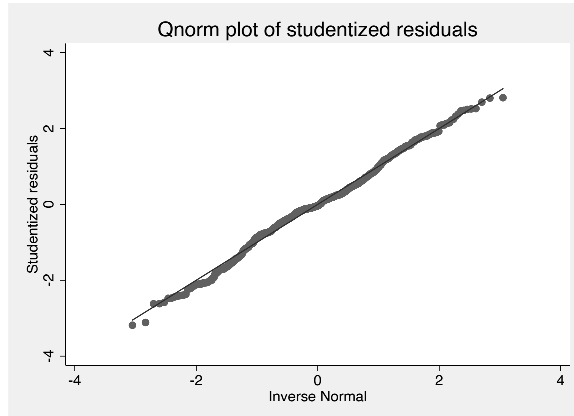
Check for collinearity

Table A XVI. Check for collinearity between explanatory variables

Variable	Green Chemistry Exam Item Model	
	VIF	1/VIF
Chemistry course	1.08	0.92
Method choice	1.08	0.93
Lab exam score (z-score)	1.01	0.99
Mean VIF	**1.06**	

Assumption check of normality





Assumption check of constant variance of residuals

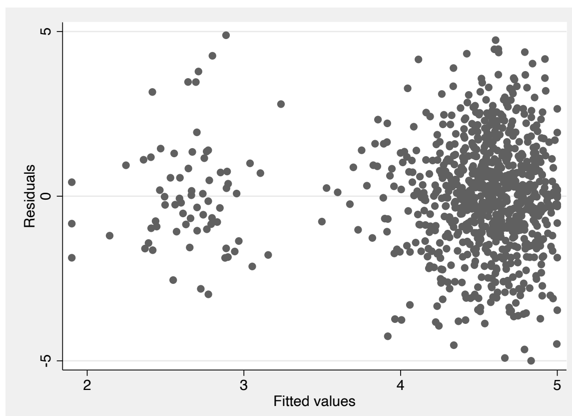


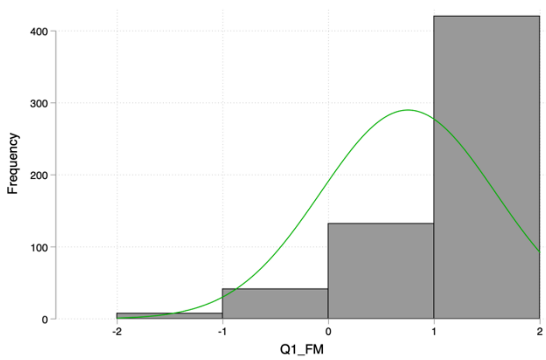
Figure A VII. (Top) Histogram and qnorm plots for deleted studentized residuals to check assumption of normality of the residuals; studentized deleted residuals have several potential outliers though a normal distribution. (Bottom) Scatterplot of deleted studentized residuals versus fitted to check constant variance of residuals; spread of the residuals was not constant suggesting some heteroscedasticity.

Appendix X. Additional Results (Chapter 4 – 5)

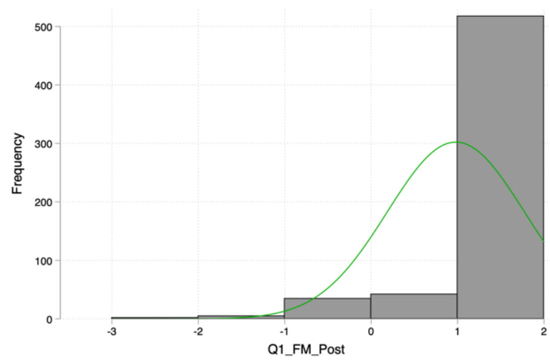
Chapter 4 Additional Results

Select All Items

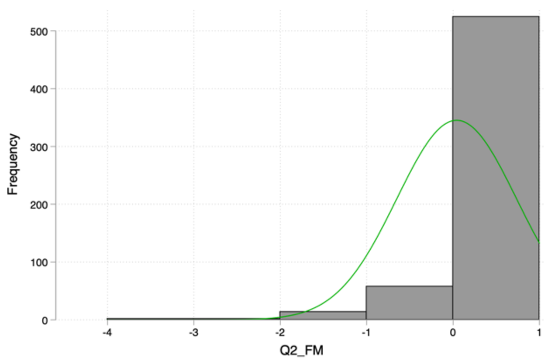
Select All #1: Pretest



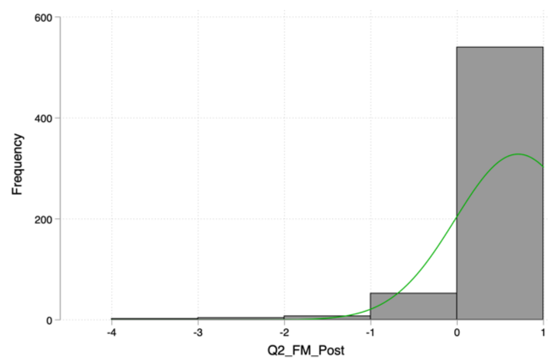
Select All #1: Posttest



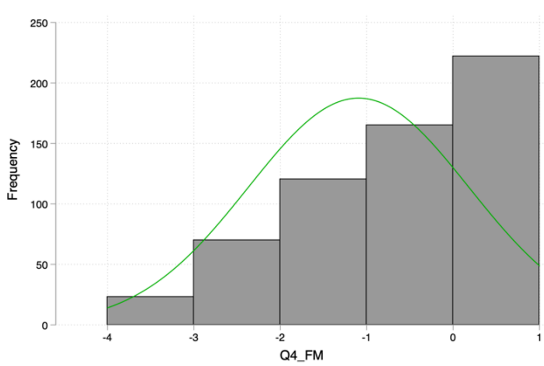
Select All #2: Pretest



Select All #2: Posttest



Select All #3: Pretest



Select All #3: Posttest

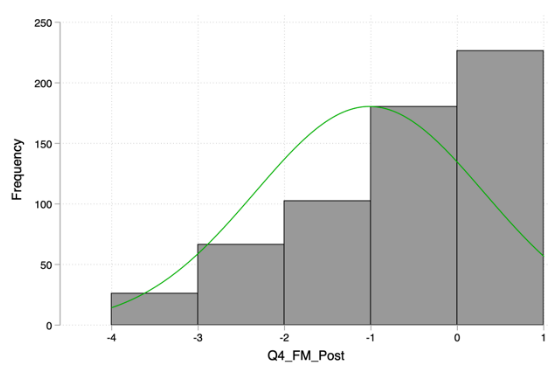


Figure A VIII. Histograms for pre and posttest select all items using formula scores (Fall 2019)

12 Principles Ranking Items

Table 12. Descriptive statistics and Wilcoxon rank sum tests for each variable using the "number right" scores. Students who placed all incorrect principles in the top three or said "I don't know" for this item were given a score of zero.

Variable	N	Pretest				Posttest				p-value (z-value)
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	
12 Prin. #1	522	1.50	0.86	0.00	522	1.73	0.84	0.00	3.00	$p < 0.001$ (-4.59)
12 Prin. #2	522	1.54	0.81	0.00	522	1.84	0.86	0.00	3.00	$p < 0.001$ (-6.20)
12 Prin. #3	522	2.28	1.01	0.00	522	2.47	0.78	0.00	3.00	$p = 0.002$ (-3.03)

Table 13. Descriptive statistics and paired t-tests for each variable using the "modified" formula scores

Variable	N	Pretest				Posttest				p-value (t-value)
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	
12 Prin. #1	522	2.31	2.41	-3.00	522	2.76	2.66	-3.00	7.00	$p = 0.019$ (-3.13)
12 Prin. #2	522	2.89	2.49	-3.00	522	3.29	2.70	-3.00	7.00	$p = 0.004$ (-2.89)
12 Prin. #3	522	3.57	2.22	-3.00	522	3.61	1.93	-3.00	7.00	$p = 0.75$ (-0.31)

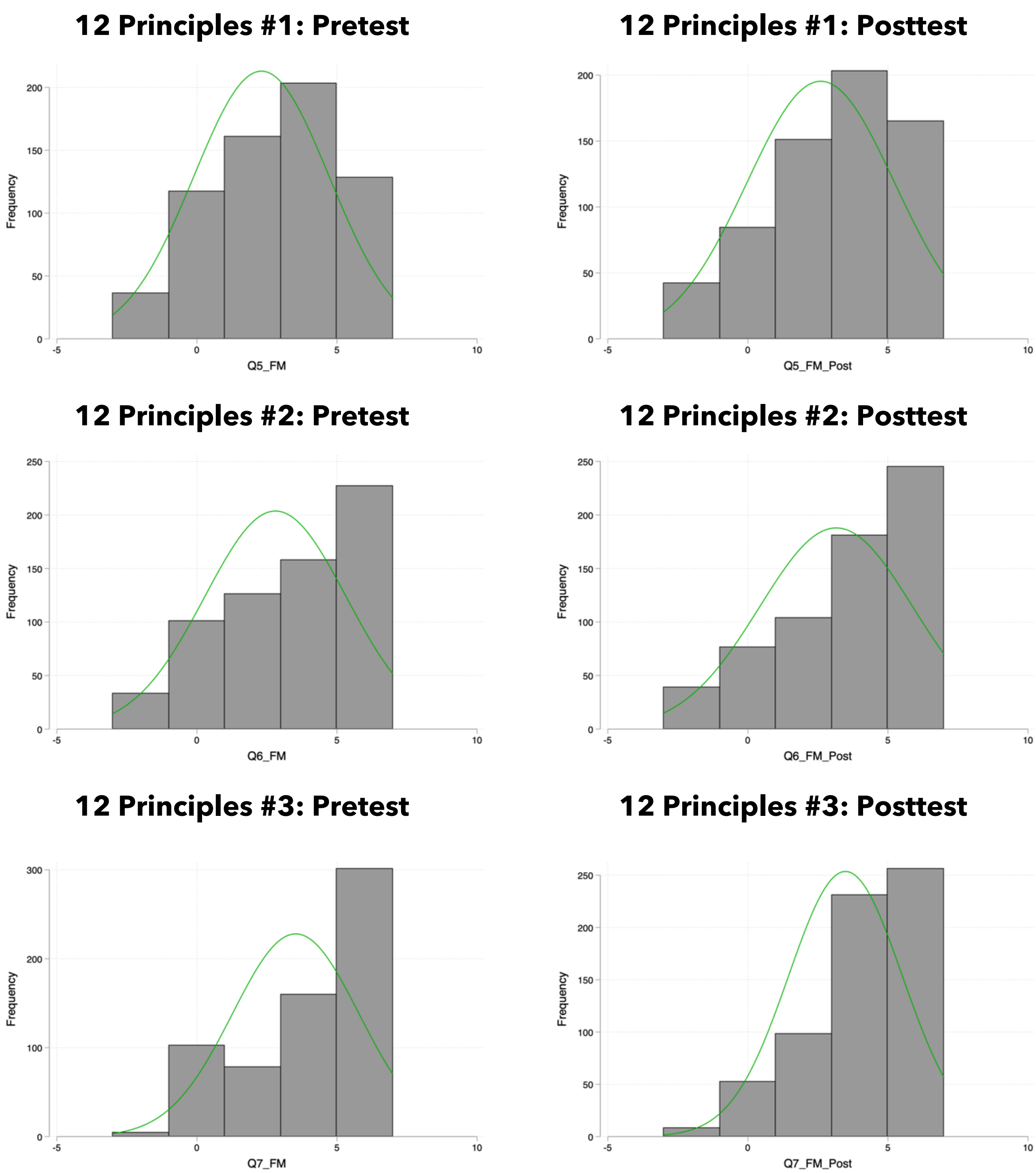
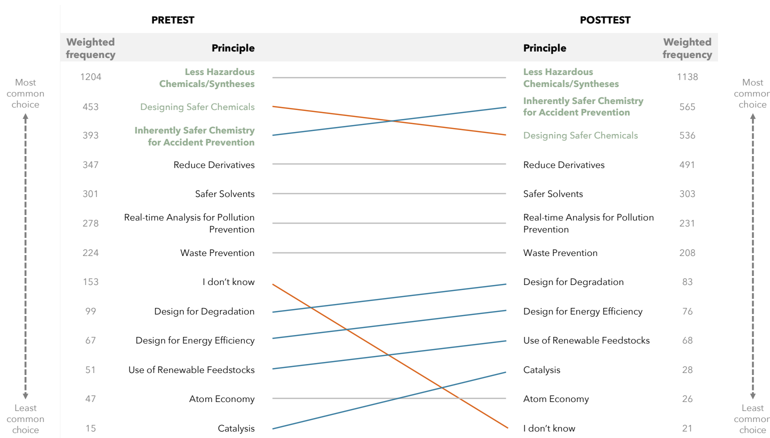
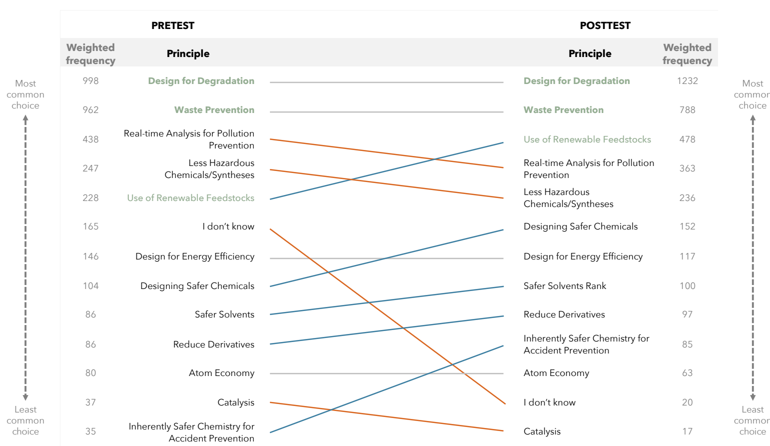


Figure A IX. Histograms for pre and posttest ***12 Principles*** **ranking** items using formula scores (Fall 2019)

Q: Traditionally, paper has been bleached with chlorine to give it a white appearance. Chlorine and its derivatives (such as chlorine dioxide) are **very dangerous for humans and toxic to aquatic organisms**. **Eliminating the use of chlorine** in paper production is an example of which green chemistry principle(s)?



Q: BASF (the largest chemical producer in the world) is currently developing **plastic bags** made partly from **cassava starch and calcium carbonate**. These bags completely **disintegrate into water, CO_2, and biomass** in industrial and city composting systems. These bags are examples of which green chemistry principle(s)?



Q: Oil-based "alkyd" paints emit high levels of volatile organic compounds (VOCs). As the name suggests, VOCs evaporate from drying paint and can produce many **harmful health effects** (ranging from eye irritation to liver damage to cancer). Sherwin-Williams won the 2011 Presidential Green Chemistry Challenge Award for the development of **low-VOC, water-based paints** that are made from **recycled plastic bottles and soybean oil**. This new paint formulation is an example of which green chemistry principle(s)?

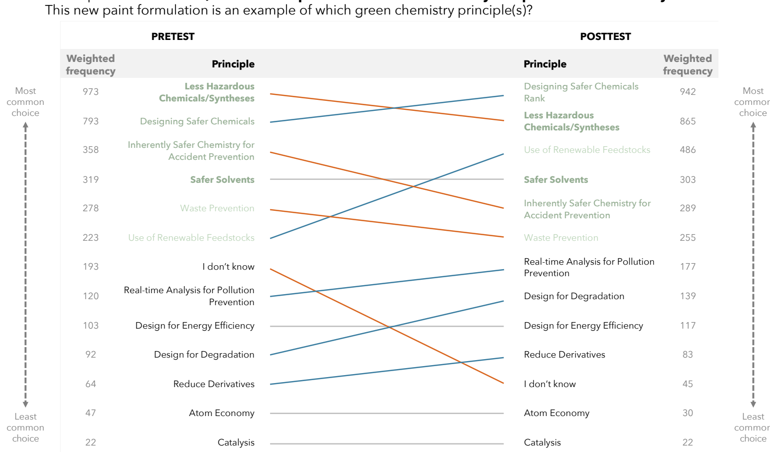


Figure A X. Weighted frequencies for each 12 Principle Ranking item. The weighted frequency for each principle was based on ranking; the top position (#1) resulted in the highest "weight" of 3 while the lowest position (#3) resulted in a "weight" of 1

Chapter 5 Additional Results

Chem 1AL students who chose method 1 did not have significantly different scores on the qualitative ($t = -0.32$, d.f. = 612, $p = 0.74$) or quantitative ($t = 0.23$, d.f. = 612 $p = 0.82$) exam items compared to those that chose method 2. Quantitative exam items were defined as any item that required a mathematical calculation and required a numeric response. Qualitative items were defined as items that required a non-numeric response (short answer, multiple choice, true-false, fill in the blank) and did not require any calculation to obtain the answer.

Table A XVII. Exam scores for students who chose method 1 or method 2 for Chem 1AL and Chem 3BL

Course	N	Quantitative Exam Score (SD)	Qualitative Exam Score (SD)
1AL	**614**	**86.5 (15.0)**	**79.9 (10.7)**
Method 1 (traditional)	22	87.3 (17.4)	79.2 (10.8)
Method 2 (green)	592	86.5 (15.0)	79.9 (10.7)

Student method choices were also analyzed for potential differential response choices by certain student characteristics (first generation status, gender, underrepresented minority (URM) status). There were no major differences in the percentage of students who chose method 1 compared to method 2 for both courses combined (similar patterns were seen for Chem 1AL and Chem 3BL separately as well).

Table A XVIII. Demographic breakdown of students who chose method 1 versus method 2 for both courses (Chem 1AL and 3BL combined). Percentages represent row totals (i.e., of the total number of students who chose *method x*, what percentages of those were *demographic y*?)

Method	% First-generation students (N = 218)	% Female students (N = 563)	% URM students (N = 113)
Method 1 (traditional)	28% (N = 18)	69% (N = 44)	17% (N = 11)
Method 2 (green)	27% (N = 200)	69% (N = 519)	14% (N = 102)