Investigations into Student Outcomes in Organic Chemistry Courses and Online Laboratory Environments, and Progress Toward the Synthesis of Asnovolin E

By

Katherine A. Blackford

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Chemistry

in the

Graduate Division

of the

University of California, Berkeley

Committee in Charge:

Professor Anne M. Baranger, Chair
Professor Richmond Sarpong
Professor Nicholas T. Ingolia

Summer 2022

Abstract

Investigations into Student Outcomes in Organic Chemistry Courses and Online Laboratory Environments, and Progress Toward the Synthesis of Asnovolin E

by

Katherine A. Blackford

Doctor of Philosophy in Chemistry

University of California, Berkeley

Professor Anne M. Baranger, Chair

Organic Chemistry: Progress toward a total synthesis of the spiromeroterpenoid natural product asnovolin E is presented in **Chapter 1** of this dissertation. Key features of our synthetic strategy include a Ti(III)-mediated cyclization of an epoxide, rhodium-catalyzed C−C bond cleavage of the resulting cyclobutanol, and the coupling of two carvone-derived cyclic fragments. This synthesis aims to provide efficient access to this biologically active natural product in a convergent fashion from an inexpensive chiral pool starting material, (*R*)-(−)-carvone. The synthesis and attempted coupling of several possible northern and southern fragments is described. In addition, the development of an acid-catalyzed Prins/semipinacol rearrangement cascade reaction of hydroxylated pinene derivatives which affords tricyclic fenchone-type scaffolds is reported. Quantum chemical analysis suggests that a post-transition state bifurcation exists following the Prins transition state, and the unusual selectivity for the fenchone-type scaffold is determined by nonstatistical dynamic effects.

Chemical Education: The remaining chapters of this dissertation focus on various student outcomes in two settings: organic chemistry courses and online laboratory environments. In **Chapter 2**, our investigation into how and why students make use of strategies related to metacognitive regulation during the process of solving organic chemistry problems is described. Student usage of planning, monitoring, and evaluation strategies in the specific context of completing complex predict-the-product problems was measured using think-aloud interviews and self-report instruments. Student usage of the same strategies in the more general context of completing assignments for their organic chemistry courses was also assessed using a similar self-report instrument. Results were compared between students with different levels of experience and between more and less successful problem solvers. In both contexts, a positive relationship was observed between metacognitive regulation and problem-solving performance or course performance. The results of this investigation support the importance of teaching metacognitive problem-solving strategies in organic chemistry courses and suggest several methods for the assessment and instruction of metacognition. In **Chapter 3**, the design and evaluation of choose-your-own-adventure-style video-based online experiments developed for use in 11 different courses across UC Berkeley and UC Santa Cruz is discussed. Students' and instructors' impressions of the online experiments and student learning outcomes in online and traditional laboratory courses were assessed using surveys, focus groups, and interviews. Though most respondents did not agree that online laboratory instruction was as effective as in-person instruction, the majority agreed that the online experiments were clear and easy to follow, interesting and engaging, and helpful for learning about laboratory techniques. Many also mentioned several benefits of online laboratory instruction, including greater flexibility in scheduling and an increased focus on conceptual learning. Assessments of student learning suggested that students who took the course online learned as much conceptually as students who had previously completed the course in person. These results highlight the positive and negative aspects of different modes of laboratory instruction, which could help inform the design of future laboratory experiences.

For my Mom and Dad

Table of Contents

Acknowledgements

I am incredibly grateful to every one of the advisors, mentors, colleagues, friends, and family members who helped make my graduate school experience special. Over these past five years, I've gained so much – knowledge, experience, confidence, the ability to finally see myself as a *scientist* – that would not have been possible without the guidance, support, and cheerleading of so many others. I'm thrilled to be able to take these next few pages to acknowledge and thank those who contributed, directly or indirectly, to this dissertation.

I'll start by thanking my primary research advisor, Anne Baranger. Thank you for warmly welcoming me into your research group and for being a steadfast advocate and mentor through my transition from chemistry to chemical education research. Over the past three years, you have inspired and encouraged me to pursue new goals, interests, and opportunities that I previously wouldn't have even considered. You have supported my research and career aspirations every step of the way, from helping me flesh out nascent ideas into research questions to guiding me through the final stages of writing papers and applying for jobs. Thanks to the positive and supportive environment you created, I was empowered to grow as a researcher, educator, and colleague. For all of these reasons and more, I am very grateful to have had the chance to get to know you and work with you.

I've had two other research mentors who played a major role in my journey towards earning this degree. Richmond Sarpong, thank you for your mentorship, encouragement, and advice during my time in your group. Working in your lab as an Amgen Scholar taught me an incredible amount and cemented my decision to apply to Berkeley for graduate school so I'd have the chance to return to your lab. I look back on the years I spent in your group fondly, and I really appreciate your support in helping me learn and develop as a researcher and chemist. Also, thanks again for the bird statue! I'd also like to acknowledge Kevin Shea, my undergraduate research advisor, for the huge impact he had on my decision to study chemistry in the first place. I entered college with zero interest in the subject, and the only reason I decided to take general chemistry at all was to fulfill a requirement. If I hadn't taken that class and encountered your inspiring and infectious enthusiasm for the subject, I do not think that I would have pursued research in chemistry or gone to graduate school. Thank you so much for introducing me to the wonders of organic synthesis, letting me join your research group despite my lack of laboratory experience, and helping me achieve my goals throughout my college years and beyond.

Many current and former members of the Chem Ed Group and Sarpong Group played an integral role in getting my research projects off the ground. Max Helix, thank you for introducing me to the field of organic chemistry problem-solving research. I learned so much about problem-solving models and think-aloud interviews from our subgroup meetings and other discussions, and I'm so happy that I got to build off of your excellent work as a part of my dissertation. I've also had the opportunity to work closely with seven creative, hardworking, and knowledgeable undergraduate researchers in the Chem Ed Group: Zach Firestein, Katia Gibson, Julia Greenbaum, Nikita Redkar, Nelson Gaillard, Adrienne Calderon, and Alex Zera. I have loved watching each of you grow as researchers as you progress through college and beyond. Thank you for your valuable assistance with transcribing and coding countless interviews and coming up with new ideas for collecting and analyzing data. Working with Jade Fostvedt on teaching and assessment projects has also been amazing. Jade, you are such a talented and passionate teacher, course designer, and scientist, and I am so thankful that we've gotten to become closer friends through working together on Summer Bridge and the Discovery Program over the past year. Finally, to Marcus Blümel, Shota Nagasawa, and Shelby McCowen, working with you on the asnovolin and arcutinidine projects was a pleasure and a great introduction to my first years in graduate school.

So many other people at Berkeley have given me valuable guidance about research, teaching, or career options. Much of what I've learned about chemical education has come from my kind, inspiring, and brilliant colleagues in the Chem Ed Group. I've learned so much about educational theories and effective teaching practices from our group meetings and insightful discussions. I am also grateful to Michelle Douskey, Alexis Shusterman, Pete Marsden, and MaryAnn Robak for their advice and insights into teaching as lecturers at Berkeley, and for letting me distribute countless surveys and research recruitment announcements to their students. I'd like to give a special shout-out to Michelle Douskey for always cheering me on. When I've felt frustrated with my research progress or afraid that I haven't done enough, reading over your relentlessly positive emails and texts has made me feel so much better. Thanks also to my qualifying exam and dissertation committee members (Peter Vollhardt, Tom Maimone, John Hartwig, Nicholas Ingolia, Richmond Sarpong, and Anne Baranger) for your expert advice and feedback.

One of the most positive aspects about my time in graduate school was the close relationship I built with the friends I made along the way. I'll start by thanking Valerie McGraw for being a wonderful friend and a one-half of my "covid bubble." You were the first friend I made at Berkeley. Hanging out on your roof, dancing together at the Missouri Lounge, and getting late night poutine or Au Coquelet were some of my best early memories of graduate school. To Ian Bakanas, Bobby Lusi, and Justin Jurczyk, I'm so glad that, despite our paths diverging since those early days of struggling through Phys Org problem sets and joining a lab together, we've stayed close friends. To Colin Gould, Chris Anderson, and Marianne Sleiman, AKA the Parker Street crew, thanks for welcoming me as that girl Ben was dating who suddenly moved into your apartment. Your companionship, caring attitudes, and humor helped me through stressful parts of my Ph.D. like prepping for my qual, starting in a new research group, and the pandemic. Michael Boreen, it's been great becoming closer friends over the past couple years. There are few better ways to keep sane in graduate school than chilling on the couch with you, Ben, some geoguesser or F1, and a few beers. Last but not least, thank you to my Terrace House/Love Wagon/whatever-reality-show-we're-on-now buddies (Dan Brauer, Alina Buevich, Zaneta Jung, Tyler Detomasi, Ari Turkiewicz, Sandy Frank) for being a reliably bright spot in my week. You all, together with the many other wonderful people I've met in the Sarpong lab, Miller lab, and my chemistry department cohort, have made my graduate school experience so much richer.

I have been very lucky to have the constant support of my family throughout graduate school. My parents, Tim and Juliet Blackford and my brother, Jonathan Blackford, have cheered me on and encouraged me in my personal and educational goals and interests for as long as I can remember. Thank you for always loving me, inspiring me, and being by my side through every achievement, setback, and major decision. I'm also grateful that moving to the Bay Area helped me spend more time with my extended family. To my aunts, uncles, cousins, and especially my grandma, Charlotte Blackford, thank you for welcoming me to the East Bay, inviting me to football games, wine-tastings, and family barbecues, and giving me great advice about graduate school and teaching. And I'd be remiss if I didn't acknowledge the newest member of my family, Noodle. Having a warm, fluffy cat snuggling on my lap when I'm working from home has made writing this dissertation so much sweeter.

Finally, thank you to Ben Raliski for making me laugh, accompanying me on adventures, being the #1 cat dad to Noodle, experimenting in the kitchen with me, and providing me with unyielding love, support, comfort, and hugs through so many important life events. When I felt like I was drowning and wanted to quit, you helped ground me and reassured me through your words and actions that you believed in me completely. Words aren't strong enough to fully express my gratitude and love for you, but I hope to show you how thankful I am for you each and every day. Meeting you at the beginning of graduate school changed my life for the better in immeasurable ways, and I am thrilled to be able to call you my husband in a couple weeks!

Chapter 1.

Progress Towards the Synthesis of Asnovolin E

Portions of this chapter are adapted with permission from:

Blümel, M.; Nagasawa, S.; Blackford, K.; Hare, S. R.; Tantillo, D. J.; Sarpong, R. "Rearrangement of Hydroxylated Pinene Derivatives to Fenchone-Type Frameworks: Computational Evidence for Dynamically-Controlled Selectivity" *J. Am. Chem. Soc.* **2018**, *140*, 9291–9298.

Abstract

Progress toward a total synthesis of the spiromeroterpenoid asnovolin E is presented. Key features of our synthetic strategy include a Ti(III)-mediated cyclization of an epoxide, rhodium-catalyzed C−C bond cleavage of the resulting cyclobutanol, and the coupling of two carvone-derived fragments. This synthesis aims to provide efficient access to this biologically active natural product in a convergent fashion from an inexpensive chiral pool starting material, (*R*)-(−)-carvone. In addition, we report the development of an acid-catalyzed Prins/semipinacol rearrangement cascade reaction of hydroxylated pinene derivatives which affords tricyclic fenchone-type scaffolds. Quantum chemical analysis suggests that a post-transition state bifurcation exists following the Prins transition state, and the unusual selectivity for the fenchone-type scaffold is determined by nonstatistical dynamic effects.

Introduction

Cancer is a leading cause of death worldwide, with about 10 million deaths reported in 2020 alone.[1] Its incidence has risen sharply over the past century, and is projected to increase by approximately 70% over the next two decades.[1] Discovering new anti-cancer targets and corresponding therapies is thus of utmost importance. Historically, the most common source of inspiration for new anti-cancer therapies has been natural products. From 1981 to 2002, nearly three-quarters of newly approved anti-cancer agents were natural products or compounds derived from natural products.[2] The synthesis of natural products with potential anti-cancer properties is therefore crucial for facilitating the development of new drug treatments for this group of diseases. One such natural product that our group has targeted is asnovolin E (**5**, Figure 1.1).[3]

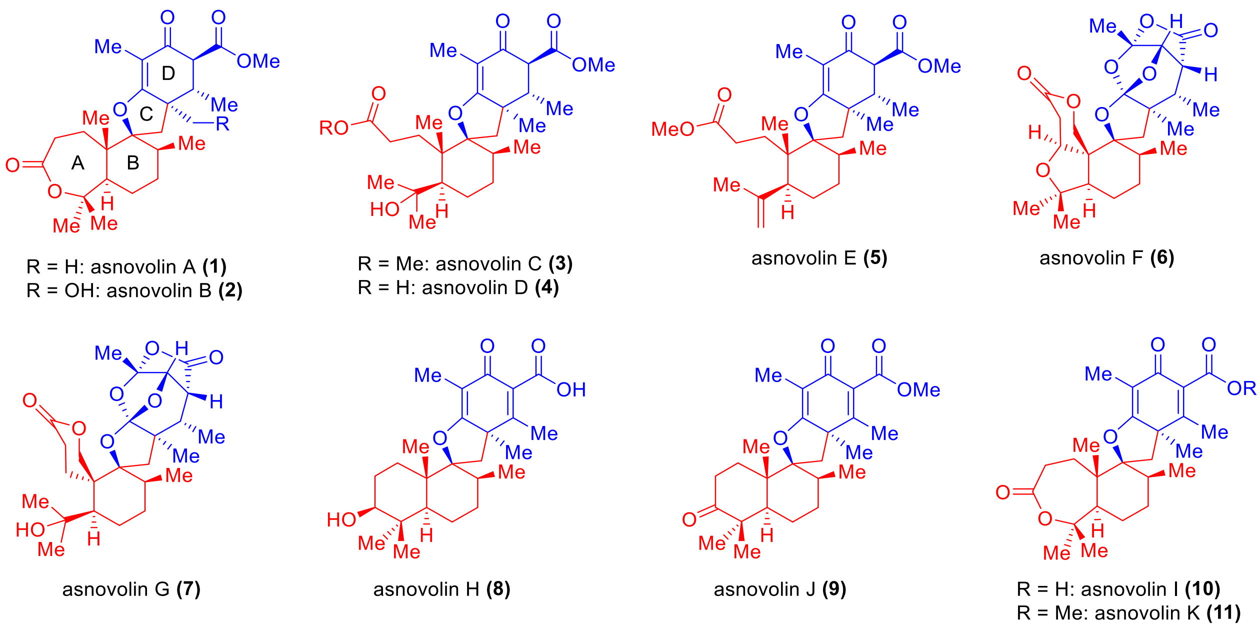
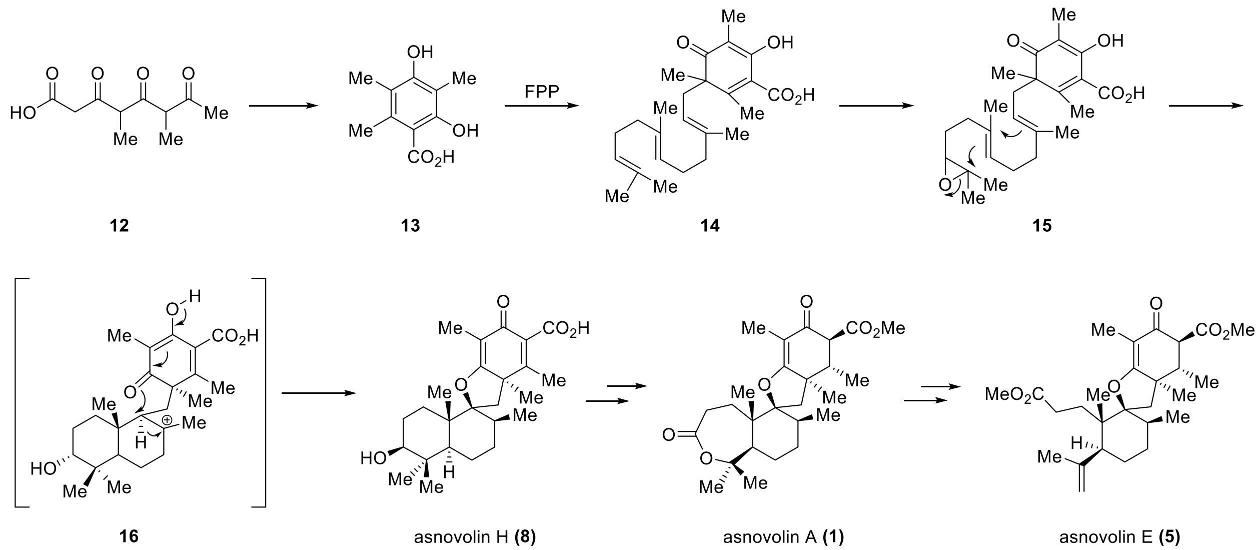


Figure 1.1. Asnovolins A-K. Polyketide-derived moieties are highlighted in blue, while terpene-derived moieties are highlighted in red.

The Asnovolin Family of Natural Products

The asnovolin family of fungal metabolites was first isolated in 2016 by Hosoe and co-workers from *Aspergillus novofumigatus*.[3] Hosoe and co-workers isolated seven members of the family, asnovolins A–G (Figure 1.1, **1**–**7**). Four additional members of the family, asnovolins H-K (Figure 1.1, **8**–**11**) were discovered by the Abe group in 2018; these natural products were identified as biosynthetic intermediates which had not previously been isolated from the fungi.[4] All members of the asnovolin family can be classified as spiromeroterpenoids as they are of mixed polyketide and terpenoid origin. More specifically, each originates from a sesquiterpene precursor and shares a common spirocyclic tetrahydrofuran core.

Biosynthetically (Scheme 1.1), the asnovolins have been found to arise via the following pathway: bis-methyl-tetraketide **12** first cyclizes to form 3,5-dimethylorsellenic acid (**13**), which then reacts with the terpenoid farnesyl pyrophosphate (FPP) to produce **14**. Epoxidation affords intermediate **15**, which undergoes a cationic cyclization cascade to produce the A and B rings of cationic species **16**. A subsequent cyclization terminated by a 1,2-hydride shift forms the characteristic spirocycle and generates asnovolin H (**8**). It is proposed that **8** is then further elaborated to the remaining members of the asnovolin family.[3,4]



Scheme 1.1. Proposed biosynthetic route to the asnovolin family

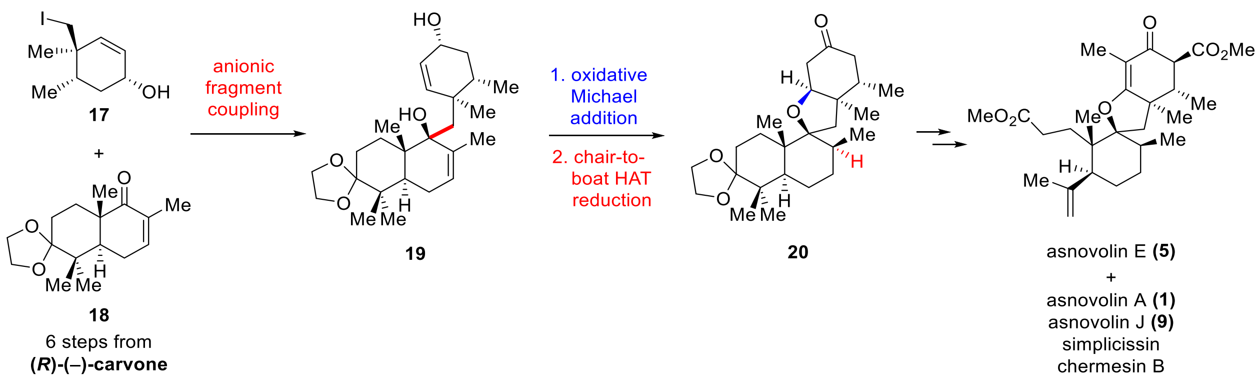
Biological Activity of Asnovolin E

A possible new target for anticancer therapeutics is fibronectin, a matrix glycoprotein. Fibronectin overexpression has been linked to several types of cancers, including those of the lung, breast, and ovaries. In healthy cells, fibronectin is involved in embryonic development, differentiation, migration, cell adhesion, blood coagulation, and wound healing. Fibronectin also participates in multiple stages of tumorigenesis by associating with integrin and syndecan receptors of tumor cells, activating signaling cascades that promote tumor invasion, proliferation, evasion of apoptosis, and metastasis.[5] A study by Mitra et al. showed that the binding of fibronectin to the integrin receptor $\alpha_5\beta_1$ activated signaling pathways associated with tumor growth in human ovarian cancer cells. Consequently, blocking this interaction reduced xenograft tumor weight and proliferation.[6] Overexpression of fibronectin has also been found to convey resistance to traditional chemotherapies and is associated with poor clinical outcomes in cancer patients.[5] Pontiggia and co-workers showed that co-incubating human and mouse breast tumor cells with fibronectin decreased the sensitivity of the cells to tamoxifen, a drug used to treat breast cancer.[7] The relationship between fibronectin expression and the prognosis of breast cancer patients was examined by Ioachim et al.; they observed that higher levels of fibronectin expression were associated with increased mortality risk in the 134 cases studied.[8]

As natural products isolated from *Aspergillus novofumigatus* had previously been found to upregulate the expression of fibronectin, the effect of each of the asnovolins on fibronectin expression was investigated by Hosoe and co-workers.[9] In contrast to this previously observed upregulation, it was observed that asnovolin E was capable of inhibiting fibronectin expression by 87% relative to a DMSO control at a 25 μM concentration in normal human neonatal dermal fibroblast cells.[3] Therefore, it has been hypothesized that asnovolin E could have anti-cancer activity. The mechanism by which asnovolin E inhibits fibronectin expression is currently unknown, but it has been postulated by Hosoe and co-workers that the exomethylene group present only in asnovolin E among the asnovolins may play a crucial role in its activity.

Previous Syntheses of The Asnovolins and Structurally-Related Fungal Spiromeroterpenoids

At the time when our work toward the synthesis of asnovolin E was conducted (2017-2018), no syntheses of the asnovolin family of natural products had been published. However, in July 2022, Porco and co-workers reported a unified, asymmetric total synthesis of asnovolins A, E, and J in addition to two related spiromeroterpenoids, chermesin B and simplicissin (Scheme 1.2).[10] Their synthesis relied upon a bis-neopentyl-type 1,2-addition to couple decalin fragment **18**, prepared in six steps from (*R*)-(–)-carvone, and iodide **17** following lithium-halogen exchange. Subsequent tandem allylic oxidation/oxa-Michael addition of the resulting diol, followed by stereoselective MHAT reduction of the trisubstituted alkene, furnished spirocyclic compound **20**. This structure was then elaborated to each of the spiromeroterpenoids synthesized, with asnovolin E accessible in six additional steps from **20**.



Scheme 1.2. Porco's 2022 synthesis of several spiromeroterpenoids, including asnovolin E.

Several syntheses of structurally-related fungal spiromeroterpenoids have also been published over the past few decades. For example, Corey et al. and McMurry et al. synthesized K-76, a complement inhibitor isolated from *Stachybotrys complementi* in 1982 and 1985, respectively.[11,12] Corallidictyal D, a protein kinase C inhibitor isolated from *Aka coralliphagum*, was synthesized by Dethe and co-workers in 2017, and progress toward the fungal metabolite simplicissin was made by Lockner and Baran in 2011.[13,14] Key steps of these syntheses are summarized in Figure 1.2.

In their syntheses of K-76, summarized in Figure 1.2A/1.2B, Corey and McMurry coupled aryllithium and allylic bromide species to connect the A/B ring system with the aromatic D ring. After treating the resulting tricycle with a THF-ethylene glycol-HCl mixture, Corey obtained the desired spirocyclic furan ring in K-76 as a 3:1 mixture with the undesired fused pyran ring. McMurry used Amberlyst® 15 acidic resin to effect the spirocyclization, yielding a 1.7:1 ratio of the spirocyclic:fused isomers. In his synthesis of corallidictyal D, summarized in Figure 1.2C, Dethe made use of a Friedel-Crafts alkylation reaction between an allylic alcohol and a sesamol derivative. Seeking to improve the selectivity for the desired spirocycle, Dethe employed an NIS-PPh_3-mediated method for the cyclization, which afforded the product in up to a 10:1 ratio of the spirocyclic:fused product. Rather than coupling together two cyclic systems, in his endeavors to synthesize simplicissin, Lockner alkylated the D ring with a geranyl geraniol derivative and then attempted an acid-catalyzed biomimetic cyclization cascade in order to forge the remaining rings in one step. However, he obtained solely the undesired fused pyran ring rather than the spirocycle present in simplicissin.

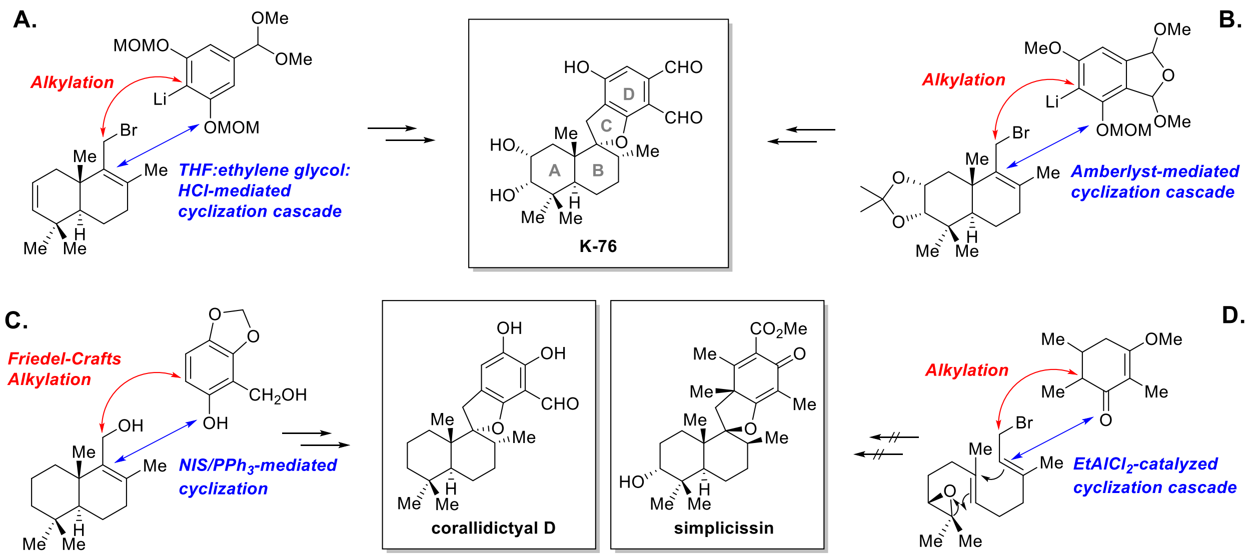
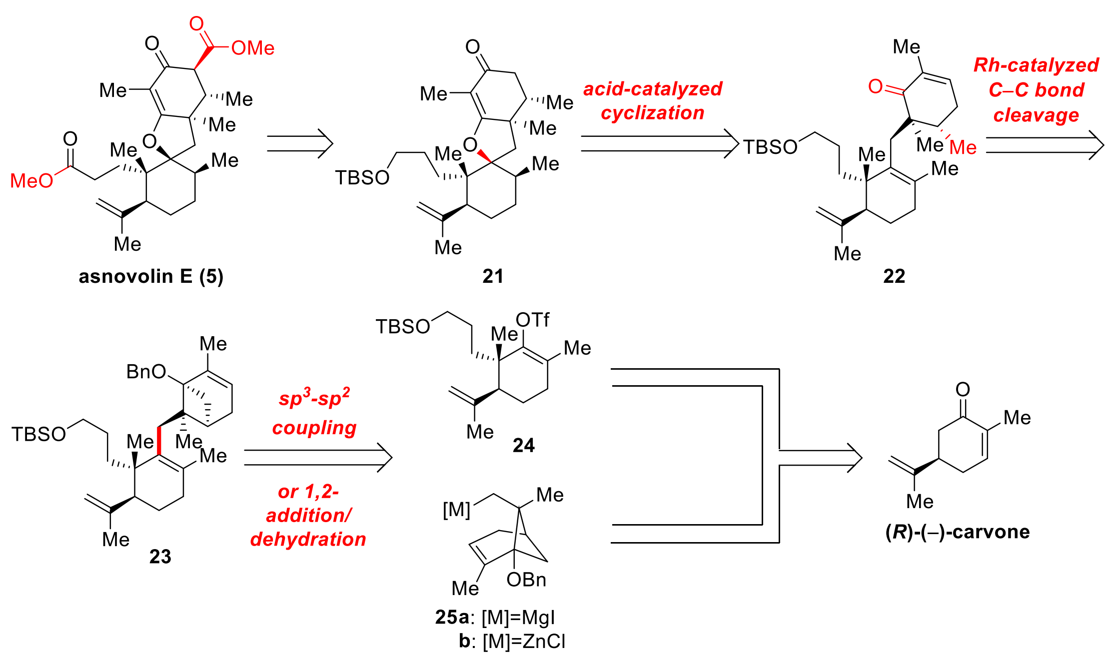


Figure 1.2. Approaches taken by A. Corey, B. McMurry, C. Dethe, D. Lockner and Baran.

Our Synthetic Route to Asnovolin E

Our proposed synthesis of asnovolin E resembles the spiromeroterpenoid syntheses of Corey, McMurry, Dethe, and Porco in that we aimed to couple two cyclic fragments and then perform a spirocyclization to complete the tricyclic core. These two cyclic molecules would be derived from the readily available, inexpensive, chiral pool molecule (*R*)-(–)-carvone.



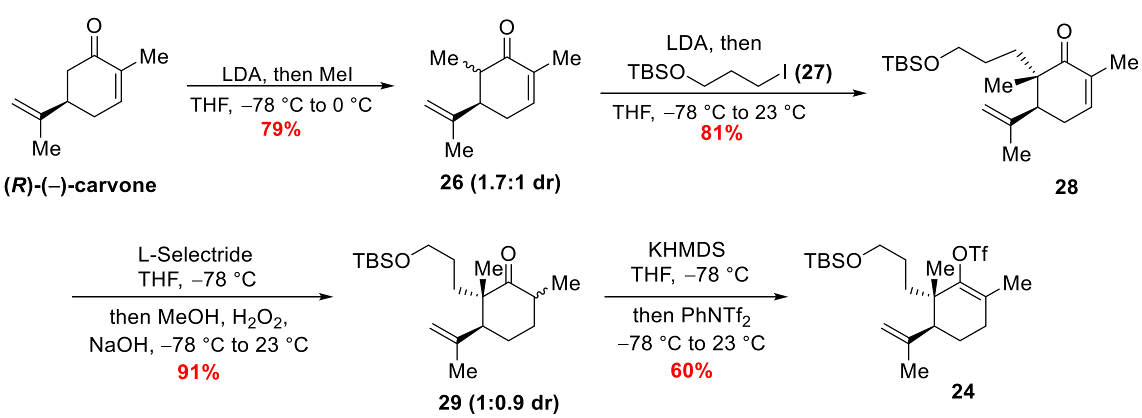
Scheme 1.3. Retrosynthesis of asnovolin E.

As illustrated in Scheme 1.3, we envisioned asnovolin E (**5**) arising from intermediate **21** by manipulation of the side chain and installation of the methyl ester. The spirocycle present in **21** would arise from an acid-catalyzed cyclization of an oxidized version of ketone **22**, which could be obtained following a rhodium-catalyzed C–C bond cleavage of benzylated cyclobutanol **23.** Intermediate **23** would be furnished via either a transition metal catalyzed sp^3-sp^2 coupling or a 1,2-addition/dehydration sequence performed on fragments **24** and **25**, which can both be constructed from (*R*)-(–)-carvone. A vinyl triflate similar to fragment **24** was employed by our lab in a recent synthesis of (–)-crotogoudin,[15] while cyclobutanols related to **25** have been utilized for the synthesis of taxoid and phomactin natural products.[16]

Results and Discussion

*Synthesis of Southern Fragment **24***

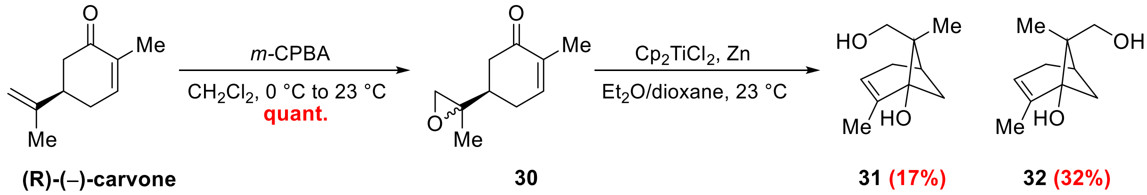
The synthesis of southern fragment **24** commenced with the installation of a methyl group in the α-position of (*R*)-(–)-carvone (Scheme 1.4). Using a protocol developed by Nishimura et al., 6-methyl carvone (**26**) was obtained in 79% yield as a 1.7:1 mixture of diastereomers.[17] This diastereomeric mixture was alkylated a second time using TBS-protected 3-iodo-1-propanol (**27**), prepared in two steps from 3-chloro-1-propanol.[15] This reaction was initially attempted using 1.5 equivalents of iodopropanol **27**, but due to separation issues between enone **28** and excess alkylation reagent during the purification, we lowered the amount of **27** to 1.0 equivalent. We were pleased to see that employing this modification allowed us to obtain enone **28** in 81% yield as a single diastereomer. Subsequently, **28** was converted to ketone **29** in 91% yield (1:0.9 dr) by conjugate reduction with L-Selectride® followed by oxidative workup.[15] Completion of the southern fragment was achieved by deprotonation of **29** with KHMDS and trapping the resulting enolate with $PhNTf_2$. We observed decomposition of **24** when we subjected it to silica column chromatography; however, using silica pre-neutralized with triethylamine and 2% triethylamine in hexanes as eluent, we obtained **24** in 60% yield from ketone **29** and 35% yield from (*R*)-(–)-carvone.



Scheme 1.4. Four-step synthesis of southern fragment **24** from (*R*)-(–)-carvone.

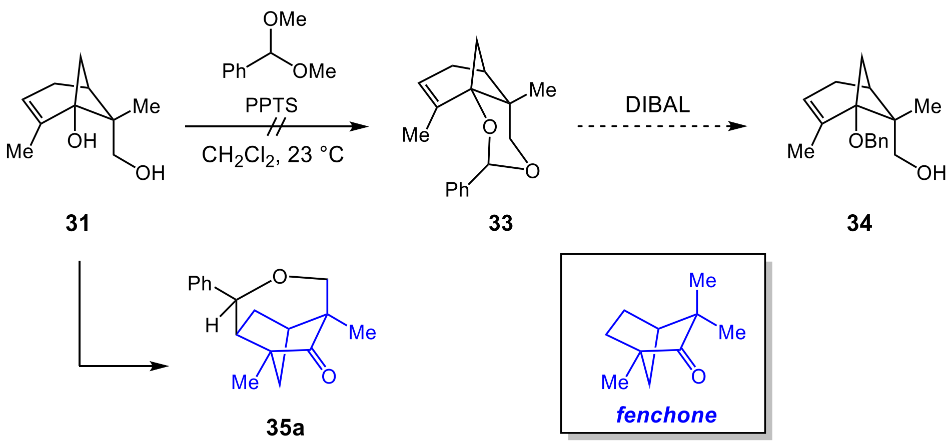
*Initial Attempt to Synthesize Northern Fragment **25***

With the southern coupling partner in hand, we next focused on the synthesis of benzylated cyclobutanol **25**. Employing a sequence developed by Bermejo and co-workers, we first synthesized cyclobutanol **31** by a cyclization of epoxide **30** in the presence of Ti(III), which was obtained in quantitative yield by treating (*R*)-(–)-carvone with *m*-CPBA.[18] The Ti(III)-mediated cyclization afforded the desired diastereomer, **31**, in 17% yield as well as diastereomer **32** in 32% yield (Scheme 1.5).



Scheme 1.5. Generation of cyclobutanols **31** and **32**.

As Appel iodination of **31** yielded only (*R*)-(–)-carvone via a Grob-type fragmentation, our next goal was to protect the tertiary hydroxy group while maintaining the primary hydroxy group. Drawing on precedent from Bermejo and co-workers, we treated cyclobutanol **31** with benzaldehyde dimethyl acetal and pyridinium p-toluenesulfonate (PPTS) with the aim of forming benzylidene acetal **33**, which could be reductively cleaved to afford benzylated diol **34** (Scheme 1.6).[19] Unexpectedly, cyclobutanol **31** was instead converted to fenchone derivative **35a**.



Scheme 1.6. Unexpected formation of fenchone derivative **35a** in the attempted benzylation of **31**.

Previous work in our lab has provided efficient access to hydroxylated camphor derivatives via semipinacol rearrangement or epoxide opening/semipinacol rearrangement,[20] but the corresponding fenchone derivatives had previously been unattainable. For this reason, we sought to thoroughly investigate this rearrangement.

Investigation of Prins/Semipinacol Rearrangement Cascade

We propose that fenchone derivative **35a** is produced by a Prins/semipinacol rearrangement of cyclobutanol **31**. Cyclobutanol **31** likely first condenses with benzaldehyde dimethyl acetal, yielding oxonium ion **36**. A Prins reaction then produces **37**. It can be imagined that either camphor derivative **38** or fenchone derivative **35a** could be produced in the subsequent semipinacol rearrangement depending on which alkyl migration occurs (Figure 1.3).

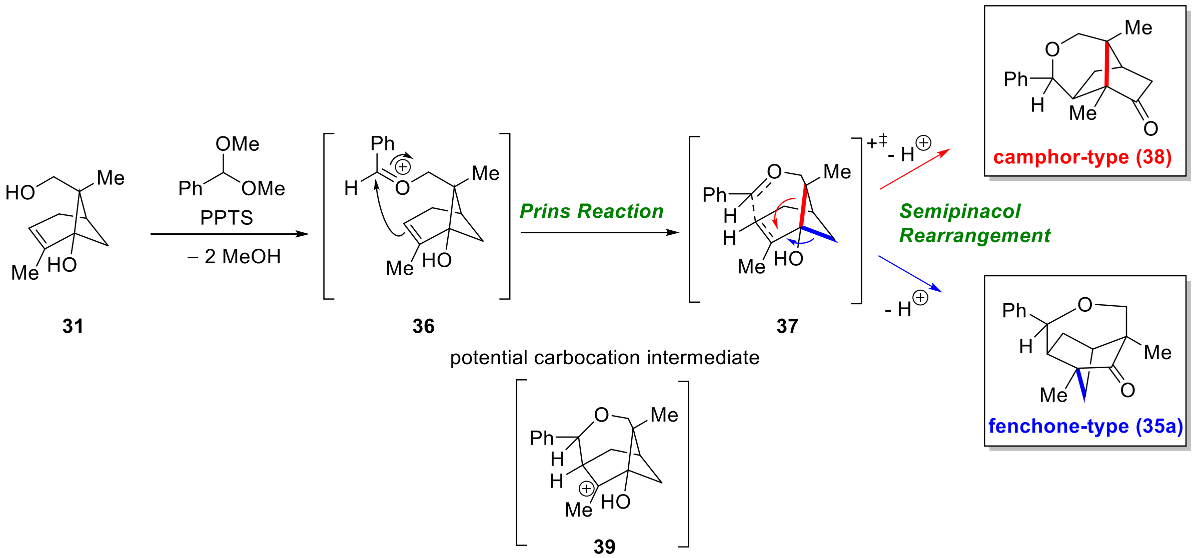


Figure 1.3. Potential products arising from Prins/semipinacol rearrangement of cyclobutanol **31**.

On the basis of relative migratory aptitudes, it would be expected that the tertiary alkyl shift to produce **38** would be favored. However, NOE experiments suggested that the primary alkyl shift occurred, producing **35a**. We unambiguously confirmed that the fenchone derivatives were formed upon obtaining a crystal structure of **35i** (Figure 1.4).

A variety of solvents, acidic additives, acetals, reaction times, and temperatures were explored in order to determine the optimal conditions for this rearrangement. We screened a variety of Lewis and Brønsted acids with pK_as between 4.76 and −6.5[21] and concluded that the use of *p*-toluenesulfonic acid (*p*-TSA), with a moderate pK_a of 0.7, led to the best yields. We additionally examined the effect of various solvents on the reaction time and yield, and determined that CH_2Cl_2 was ideal. Overall, we found that running the reaction with 1.2 equivalents of acetal and 1 mol% *p*-TSA at 23 ˚C overnight gave the highest yield (86%). We also screened several other acetals, including benzaldehyde diethyl, dioxolane, and dioxane acetals, and obtained 81%, 45%, and 34% yields, respectively. This trend may be explained by the lower entropic driving force for the reactions with cyclic acetals.

With these optimized conditions in hand, we launched an investigation into the substrate scope of the Prins/semipinacol rearrangement (Figure 1.4). Myriad electron-deficient and electron-rich aryl dimethyl acetals and aldehydes participate in the reaction. Generally, the use of dimethyl acetals afforded higher yields than the corresponding aldehydes as the release of methanol to form the oxocarbenium ion is preferable over the release of water. Extremely electron-deficient aryl aldehydes, such as that containing a nitro group (**35h**) underwent the reaction with much lower yields, which can be explained by the destabilizing effect of the electron-withdrawing substituent on the incipient oxocarbenium ion. Reactions of electron-rich aromatic acetals and aldehydes initially produced the expected tricyclic fenchone derivatives, but the stabilization of the carbocation in the α-position led to cleavage of the cyclic ether, releasing steric strain. Subsequent deprotonation gave alkene products **40a**–**40h**. Benzylic and aliphatic acetals and aldehydes were also able to participate in the reaction, yielding **35u** and **35q** in relatively low yields, owing to the lesser degree of stabilization of the intermediate carbocation.

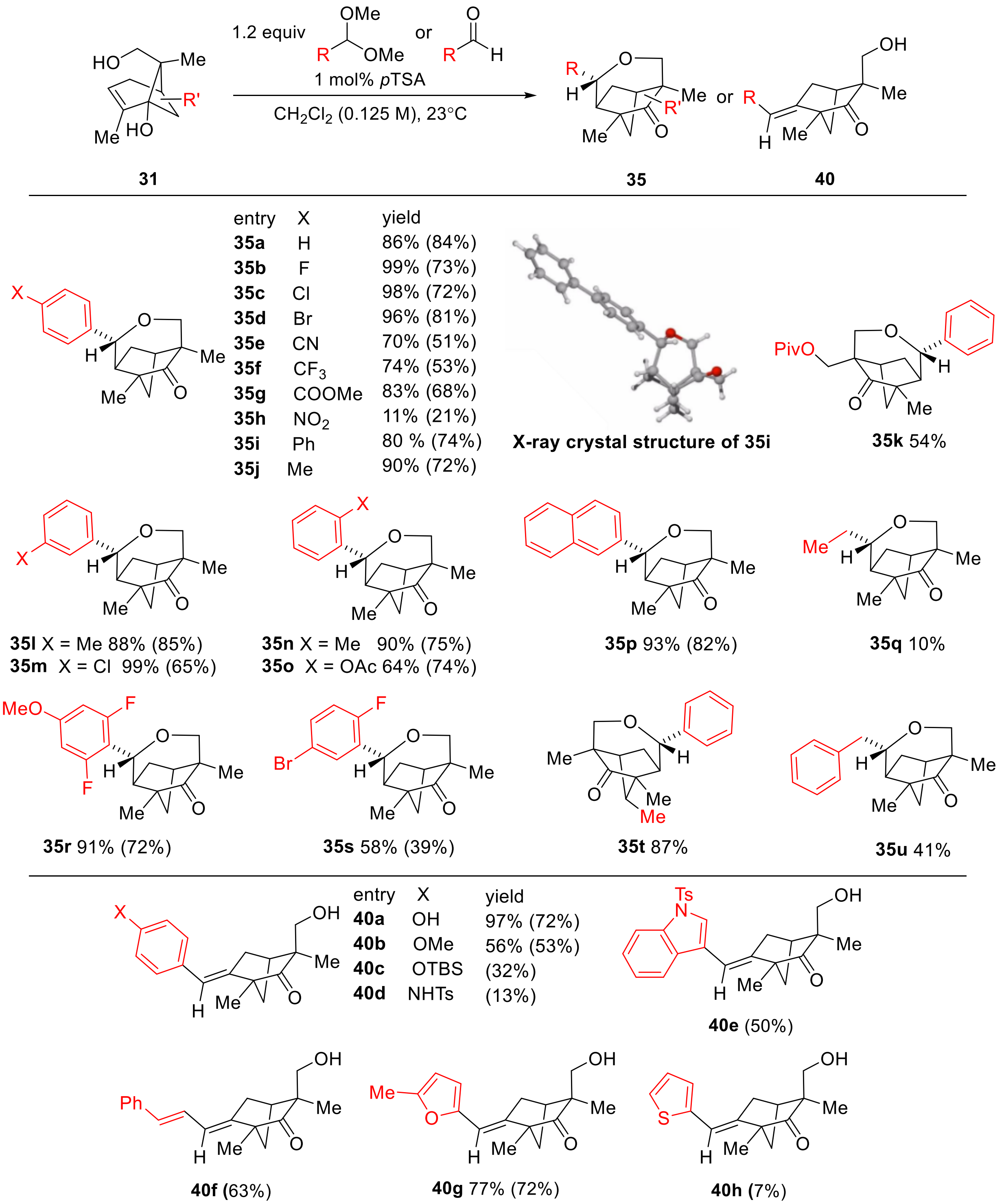


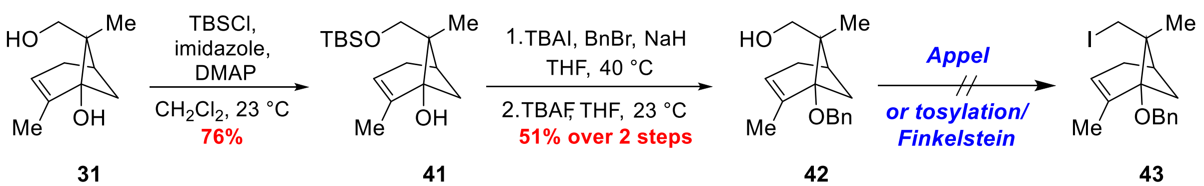
Figure 1.4. Substrate scope of Prins/semipinacol rearrangement. Yields for the reaction with the aldehyde are given in parentheses.

Quantum Chemical Studies

We next sought to understand the unusual selectivity for the primary alkyl shift over the tertiary alkyl shift. Computational studies revealed that there may be a post-transition state bifurcation (PTSB)[22] following Prins cyclization transition state **37** (Figure 1.3), meaning this transition state is ambimodal. Using the wB97X-D[23]/6-31+G(d,p)[24] density functional theory (DFT) method, it was determined that potential carbocation intermediate **39** exists in a shallow potential energy surface (PES) minimum with predicted free energy barriers for the migration of the primary and tertiary alkyl groups of 1.2 and 3.3 kcal/mol, respectively. Considering the shallowness of this minimum, we hypothesize a dynamically-determined kinetic selectivity for this reaction. Dynamic trajectory simulations starting from transition state **37** predicted nearly complete (~99:1) selectivity for the primary alkyl shift, consistent with our experimental results.

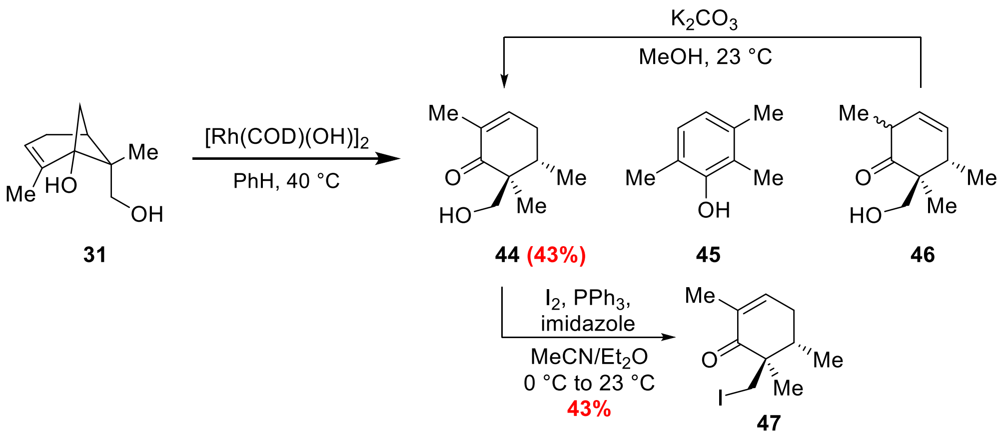
Further Progress toward Asnovolin E

As cyclobutanol **31** was not successfully converted to benzylidene acetal **33** (Scheme 1.6), we instead decided to first protect the primary hydroxy group as a TBS ether, yielding **41** in 76% yield (Scheme 1.7). We then investigated optimal conditions for converting the tertiary hydroxyl group to a benzyl ether and found that a temperature of 40 ˚C and concentration of 0.2 M resulted in complete conversion. Due to difficulties in separating the benzyl ether adduct from excess benzyl bromide, the crude material was directly treated with TBAF to cleave the TBS ether, yielding **42** in 51% yield over two steps. Unfortunately, Appel iodination of **42** led to decomposition, and our attempts to form a mesylate or tosylate followed by iodination using a Finkelstein reaction were also unsuccessful.



Scheme 1.7. Double protection/deprotection strategy for the synthesis of iodide **35**.

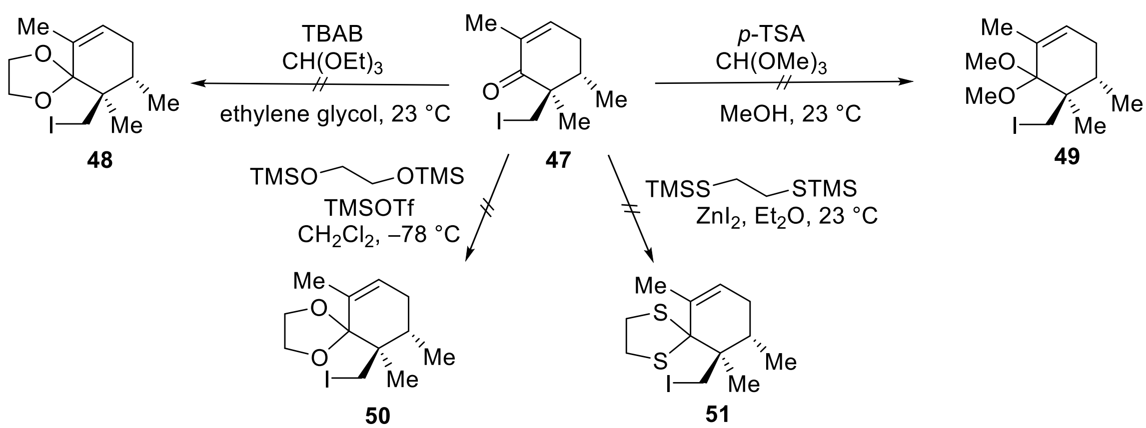
Convinced that the combination of steric hindrance and the close proximity of the primary hydroxy group to the alkene in **42** was leading to the observed problems with reactivity, we next examined whether performing the rhodium-catalyzed ring-opening of the cyclobutanol prior to attempting the coupling of both fragments would allow me to install the desired iodide. Employing a procedure developed by Drs. Ahmad Masarwa and Manuel Weber, we were able to convert cyclobutanol **31** to enone **44** in 43% yield (Scheme 1.8).[20] This low yield is a result of a combination of factors: the product's volatility, the competing retro-aldol reaction leading to phenol **45**, and the challenging separation of **44** from **46**. Increasing the reaction time from 48 h to 140 h led to the isomerization of initially formed **46** to the thermodynamically favored **44**. Alternatively, mixtures of **44**/**46** can be completely isomerized to **44** by treatment with K_2CO_3 in MeOH at 23 ˚C.



Scheme 1.8. Rhodium-catalyzed cyclobutanol opening of **31** and Appel iodination of ketone **44**.

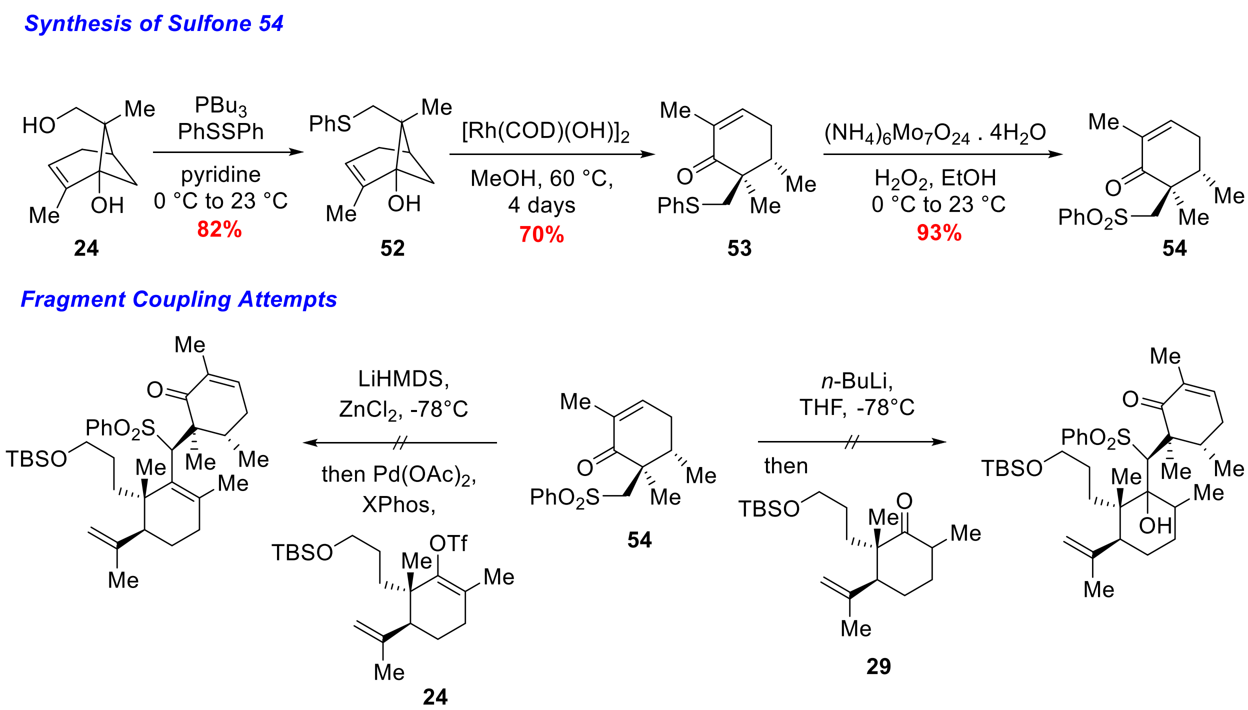
Exposing enone **44** to Appel iodination conditions furnished iodide **47** in typical yields of 40–50%. In order to avoid potential side reactions in the coupling reaction, we tried to protect the carbonyl of **47** as a dioxolane, diothiolane, or dimethyl acetal. Unfortunately, all attempts led to recovered starting material (i.e. **47**), presumably due to steric hindrance (Scheme 1.9).

Noting the lack of reactivity of ketone of **47**, it was postulated that a magnesium or lithium-halogen exchange to convert the northern fragment into a suitable nucleophile may be possible even in the presence of this carbonyl group. However, treatment of **47** with isopropyl magnesium chloride at temperatures between −78 ˚C and 0 ˚C followed by quenching with water yielded recovered starting material, and treatment with *s*-BuLi resulted in its addition to the carbonyl group.



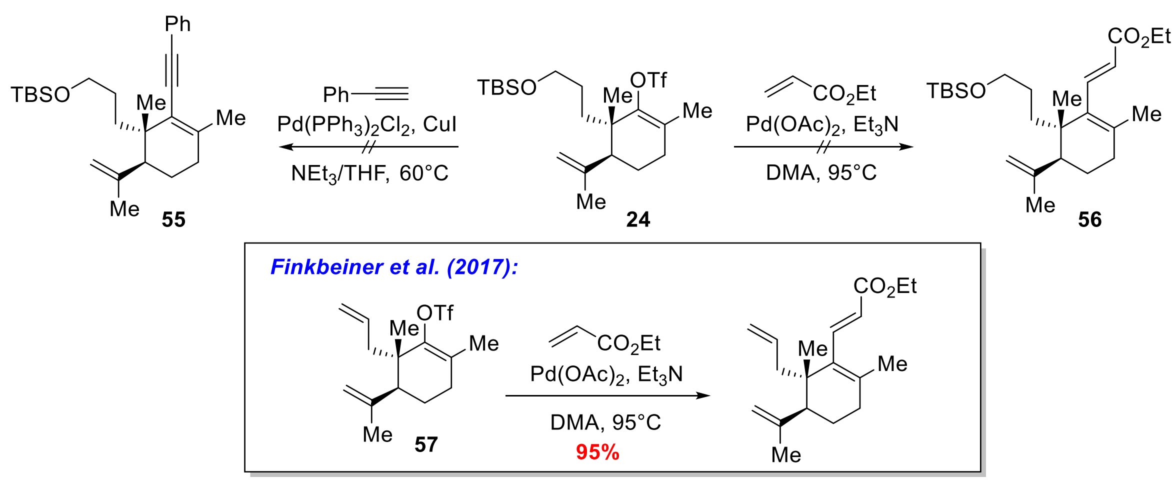
Scheme 1.9. Attempts to install various protecting groups on the ketone of **47**.

Seeking an alternative to the nucleophilic coupling partner we originally proposed would arise from iodide **47**, we synthesized sulfone **54** in three steps from cyclobutanol **31** according to a sequence recently employed by our group in the synthesis of several phomactin natural products (Scheme 1.10). We then attempted to use sulfone **54** in a 1,2 addition to ketone **29** and in a Negishi reaction with triflate **24**; however, neither reaction was successful.[25]



Scheme 1.10. Synthesis of an alternative northern fragment, sulfone **54**, and its application in coupling reactions.

We also studied the reactivity of the southern coupling partner as that could be another reason for the observed issues. We first attempted to reproduce a Heck reaction of triflate **24** with ethyl acrylate that had previously been performed on a similar vinyl triflate by Finkbeiner et al. (Scheme 1.11).[15] Neither this reaction (i.e., **24** → **56**) nor a Sonogashira reaction with phenyl acetylene furnished the expected products, suggesting that the southern fragment (i.e., **24**) is not easily amenable to palladium-catalyzed chemistry, perhaps due to an interaction between palladium and the TBS-protected hydroxy group or added steric encumbrance. This suggests that the use of an alternative southern fragment should be examined.



Scheme 1.11. Probing the reactivity of vinyl triflate **24**.

Conclusions

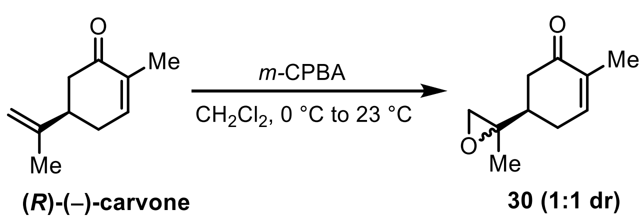
In summary, we synthesized vinyl triflate **24**, which we proposed to employ as the southern fragment in our synthesis of asnovolin E. We also investigated multiple possible northern coupling partners, including sulfone **54** and iodide **47**. In addition, we developed a Prins/semipinacol rearrangement sequence that provides access to various fenchone derivatives in high yields. However, coupling the northern and southern fragments remains a challenge. Further research is needed to determine an appropriate route to couple these fragments. After successfully coupling these fragments, our next task will be to accomplish the selective spirocyclization. Once this challenge is overcome, installation of the two methyl esters will provide asnovolin E.

Experimental Procedures

General Considerations

Unless otherwise stated, reactions were performed in oven-dried glassware under a positive pressure of N_2 using standard Schlenk techniques. Reaction mixtures were stirred using Teflon-coated magnetic stir bars. All commercially purchased reagents were used without further purification. Dry tetrahydrofuran (THF), methanol (MeOH), benzene (PhH), triethylamine (NEt_3), diethyl ether (Et_2O), and acetonitrile (MeCN) was obtained by passage through activated alumina columns under an argon atmosphere. Dichloromethane (CH_2Cl_2) and diisopropylamine were distilled over calcium hydride under an N_2 atmosphere prior to use. Reactions were monitored via thin layer chromatography (TLC) on glass-backed Merck Silica Gel 250 µm thickness, 60 Å porosity F-254 pre-coated plates. TLC Plates were visualized by a combination of UV irradiation (254 nm) and *p*-anisaldehyde stain. Volatile solvents were removed using a rotary evaporator with a dry ice-isopropanol condenser. Manual flash column chromatography was performed using Fisher Chemical silica gel (60 Å, 230-400 mesh, 40-63 µm particle size). Automated flash column chromatography was conducted on a Yamazen Smart Flash EPCLC W-Prep 2XY (dual channel) chromatography system using universal premium columns prefilled with silica gel (60 Å, 30 µm particle size). ^{1}H and ^{13}C NMR spectra were acquired in $CDCl_3$ using Bruker spectrometers (AVB-400, AVQ-400, AV-600, AV-700) at the University of California, Berkeley College of Chemistry NMR Facility. Chemical shifts are reported relative to the residual $CHCl_3$ solvent signal (^{1}H NMR: $\delta = 7.26$; ^{13}C NMR: $\delta = 77.16$). NMR data are reported as follows: chemical shift (multiplicity, coupling constants where applicable, integration). Splitting is reported using the following abbreviations: s = singlet, bs = broad singlet, d = doublet, t = triplet, dd = doublet of doublets, ddd = doublet of doublet of doublets, dt = doublet of triplets, ddtd = doublet of doublets of triplets of doublets, m = multiplet. IR spectra were recorded on a Bruker Alpha FT-IR spectrophotometer with a diamond ATR accessory, and selected transmission signals are reported in frequency of absorption (cm^{-1}). Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Melting points were measured on a Laboratory Devices Mel-Temp II instrument. High-resolution mass spectral data were obtained at the UCB Mass Spectral Facility, on a Perkin-Elmer AxIon 2 UHPLC-TOF instrument using an AxIon DSA APCI or ESI source.

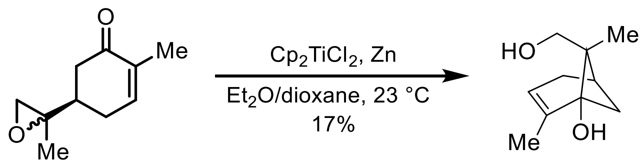
Epoxycarvone 30



Epoxycarvone **30** was synthesized according to a procedure adapted from Nishimura et al.[17] To a stirred solution of (*R*)-(−)-carvone (10.4 mL, 66.4 mmol, 1.0 equiv) in ACS-grade CH_2Cl_2 (350 mL) at 0 ˚C was added *m*-CPBA (70%, 19.7 g, 79.9 mmol, 1.2 equiv) portionwise over 5 min. The reaction mixture was warmed to 23 ˚C and was stirred for 22 h. The milky suspension was then filtered through Celite®, eluting with CH_2Cl_2. The filtrate was quenched with sat. aq. $Na_2S_2O_3$

(100 mL) and sat. aq. $NaHCO_3$ (100 mL). After separating the organic and aqueous layers, the aqueous layer was CH_2Cl_2 (2 x 100 mL), and the combined organic layers were washed with sat. aq. $NaHCO_3$ (100 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo* to yield **30** as a light brown oil (10.31 g, 1:1 dr). The crude material was deemed sufficiently pure by ^{1}H NMR analysis and was carried forward without further purification. ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.76 – 6.69 (m, 2H), 2.70 (d, *J* = 4.4 Hz, 1H), 2.66 (d, *J* = 4.4 Hz, 1H), 2.60 (d, *J* = 4.5 Hz, 1H), 2.58 (d, *J* = 4.5 Hz, 1H), 2.56 – 2.50 (m, 2H), 2.32 – 2.13 (m, 5H), 2.10– 2.00 (m, 1H), 1.77 (m, 6H), 1.32 (s, 3H), 1.30 (s, 3H). Full characterization has been reported by Nishimura et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[17]

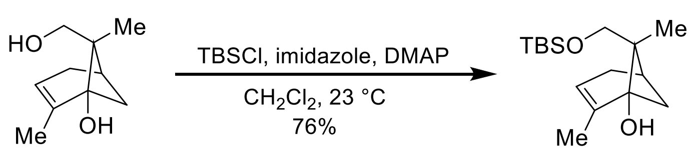
Cyclobutanol 31



30 31

Cyclobutanol **31** was synthesized according to a procedure adapted from Bermejo et al.[18] To a 1 L three-neck flask under an N_2 atmosphere was added Et_2O (120 mL) and 1,4-dioxane (100 mL). After sparging with N_2 for 35 min, Cp_2TiCl_2 (16.52 g, 66.36 mmol, 2.2 equiv) and Zn (13.03 g, 199.3 mmol, 6.6 equiv) were added to the flask. The dark green reaction mixture was stirred at 23 ˚C for 2.5 h. The flask was equipped with a 250 mL addition funnel, which was charged with 5.20 g of epoxycarvone **30** (31.3 mmol, 1.0 equiv), Et_2O (90 mL), and 1,4-dioxane (110 mL). The resulting solution was sparged with N_2 for 20 min and added to the flask over 2 h, and the reaction mixture was stirred at 23 ˚C for 18 h. The mixture was then quenched with sat. aq. NaH_2PO_4 (250 mL) and brine (50 mL) and diluted with EtOAc (50 mL). After being stirred open to air at 23 ˚C for 46 h, the resulting orange and gray suspension was filtered through Celite®. The aqueous layer was extracted with EtOAc (2 x 60 mL) and the combined organic layers were washed with brine (100 mL), dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude viscous orange oil was purified using the Yamazen automated flash chromatography system (gradient: 20% EtOAc in hexanes to 60% EtOAc in hexanes), yielding **41** as a light yellow solid (0.915 g, 5.44 mmol, 17% yield). ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.28 (m, 1H), 3.75 (d, *J* = 10.3 Hz, 1H), 3.41 (d, *J* = 10.3 Hz, 1H), 2.26 (ddd, *J* = 8.4, 6.8, 2.0 Hz, 1H), 2.18 – 2.09 (m, 2H), 2.09 – 2.00 (m, 1H), 1.79 (m, 3H), 1.60 (d, *J* = 8.4 Hz, 1H), 1.32 (s, 3H). Full characterization has been reported by Bermejo et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[18]

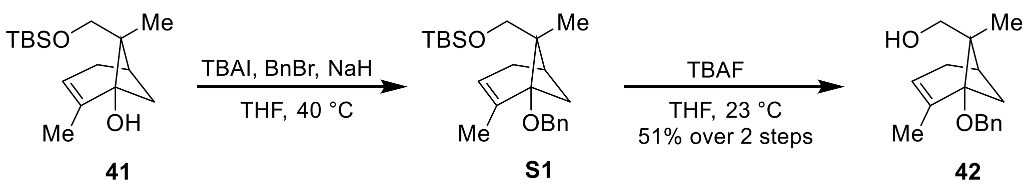
TBS-protected cyclobutanol 41



31 41

TBS-protected cyclobutanol **41** was synthesized according to a procedure adapted from Molawi et al.[26] To a solution of cyclobutanol **31** (84 mg, 0.50 mmol, 1.0 equiv) in CH_2Cl_2 (5.0 mL) was added imidazole (0.103 g, 1.51 mmol, 3.0 equiv) and 4-dimethylaminopyridine (DMAP) (6.9 mg, 0.056 mmol, 0.11 equiv). Tert-butyldimethylsilyl chloride (TBSCl) (0.104 g, 0.69 mmol, 1.4 equiv) was added and the reaction mixture was stirred at 23 ˚C for 17 h. The solution was washed with 1 M aq. HCl (20 mL), and the aqueous layer was extracted twice with Et_2O (10 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. Flash column chromatography on silica (hexanes – 5:1 hexanes:Et_2O) afforded **41** as a colorless oil (0.107 g, 0.38 mmol, 76%). ^{1}H NMR (600 MHz, $CDCl_3$) δ 5.22 (tq, *J* = 3.0, 1.6 Hz, 1H), 3.69 (d, *J* = 9.1 Hz, 1H), 3.26 (d, *J* = 9.1 Hz, 1H), 2.26 (dd, *J* = 8.2, 6.8 Hz, 1H), 2.12 (dtd, *J* = 16.5, 5.1, 2.6 Hz, 2H), 2.03 (ddt, *J* = 16.5, 4.0, 2.0 Hz, 1H), 1.78 (q, *J* = 2.0 Hz, 3H), 1.57 (d, *J* = 8.2 Hz, 1H), 1.28 (s, 3H), 0.87 (s, 9H), 0.00 (s, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 146.13, 116.80, 77.62, 65.78, 45.96, 38.70, 34.49, 30.94, 25.89, 18.17, 17.42, 17.29, -5.68. IR (ATR, thin film): ν_{max} = 3436, 2928, 2856, 1471, 1252, 1070, 1001, 832, 772 cm^{-1}. HRMS (ESI): calc'd for $[C_{16}H_{30}NaO_2Si]^+$ *m/z* = 305.1914 found 305.1913.

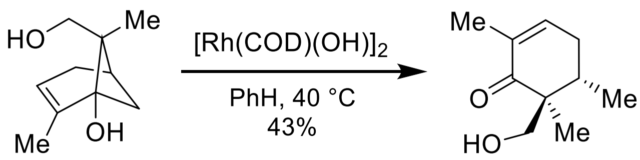
Benzylated cyclobutanol 42



Benzylated cyclobutanol **42** was synthesized according to a procedure adapted from Müller et al.[27] TBS-protected cyclobutanol **41** (29 mg, 0.010 mmol, 1.0 equiv) and tetrabutylammonium tribromide (TBAI) (3.7 mg, 0.011 mmol, 0.11 equiv) were added to a 1 dram vial with a septum cap. THF (0.5 mL) and NaH (60% in mineral oil, 20.3 mg, 0.051 mmol, 5.0 equiv) were added after evacuating and backfilling with N_2. Upon addition of NaH, the yellow solution turned milky tan and bubbled. Benzyl bromide (25 µL, 0.21 mmol, 2.1 equiv) was added using a microsyringe, and the reaction mixture was stirred at 40 ˚C for 64 h. The reaction mixture was then quenched with MeOH (1 mL) and sat. aq. $NaHCO_3$ (4 mL). The aqueous layer was extracted twice with Et_2O (10 mL) and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated to yield a dark yellow oil. As excess benzyl bromide could not be removed by flash column chromatography, the crude material was carried on without further purification. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41-7.18 (m, 5H), 5.31 (m, 1H), 4.49 (s, 2H), 3.52 (s, 2H), 2.45 (t, *J* = 7.6 Hz, 1H), 2.17 – 2.09 (m, 3H), 1.82 (m, 3H), 1.56 (d, *J* = 8.1 Hz, 1H), 1.32 (s, 3H), 0.87 (s, 9H), 0.00 (s, 6H).

Tetrabutylammonium fluoride (TBAF) (1 M in THF, 7.1 mL, 0.71 mmol, 10.0 equiv based on **41**) was added dropwise to the crude mixture in 4 mL of THF. The resulting orange solution was stirred at 23 ˚C for 18 h before it was quenched with H_2O (10 mL). The aqueous layer was extracted twice with Et_2O (20 mL) and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated. Flash column chromatography on silica (3:1 – 1:1 hexanes:Et_2O) afforded **42** (93 mg, 0.36 mmol, 51% over two steps) as a yellow oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 7.39 – 7.32 (m, 3H), 7.28 (d, *J* = 1.6 Hz, 2H), 5.36 (dt, *J* = 4.1, 1.8 Hz, 1H), 4.50 (s, 2H), 3.71 (d, *J* = 10.6 Hz, 1H), 3.46 (d, *J* = 10.6 Hz, 1H), 2.50 – 2.45 (m, 1H), 2.22 – 2.16 (m, 2H), 2.14 – 2.07 (m, 1H), 1.86 (t, *J* = 2.0 Hz, 3H), 1.62 (d, *J* = 8.2 Hz, 1H), 1.38 (s, 3H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 145.44, 139.11, 128.26, 127.26, 127.16, 119.25, 83.14, 67.87, 65.54, 46.38, 35.20, 34.17, 30.96, 17.93, 17.59. IR (ATR, thin film): ν_{max} = 3383, 3026, 2939, 1453, 1234, 1161, 1026, 731, 697 cm^{-1}. HRMS (ESI): calc'd for $[C_{17}H_{22}O_2Na]^+$ *m/z* = 281.1512, found 281.1525.

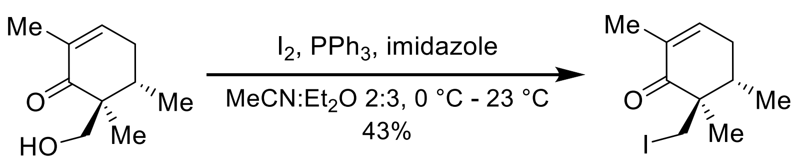
Hydroxyketone 44



31 **44**

Hydroxyketone **44** was synthesized according to a procedure adapted from Masarwa et al.[20] Cyclobutanol **31** (30.0 mg, 0.178 mmol, 1.0 equiv) was dissolved in benzene (2 mL) in a glovebox. $[Rh(COD)(OH)]_2$ (6.7 mg, 0.015 mmol, 8.3 mol%) was added to the solution, and the resulting bright yellow solution was stirred at 40 ˚C in the glovebox for 6 days. The resulting opaque black solution was allowed to cool to 23 ˚C and was concentrated *in vacuo*. Flash column chromatography on silica (10:1 – 3:1 pentanes:Et_2O) yielded **44** (13.0 mg, 0.077 mmol, 43%) as a yellow oil (volatile). ^1H NMR (400 MHz, $CDCl_3$) δ 6.70 (m, 1H), 3.91 (d, *J* = 11.4 Hz, 1H), 3.55 (d, *J* = 11.5 Hz, 1H) 2.67 (br s, 1H), 2.44-2.27 (m, 2H), 2.27 – 2.16 (m, 1H), 1.80 (m, 3H), 1.01 (d, *J* = 6.7 Hz, 3H), 0.97 (s, 3H). Full characterization has been reported by Masarwa et al. The ^1H NMR spectrum is consistent with that reported in the literature.[20]

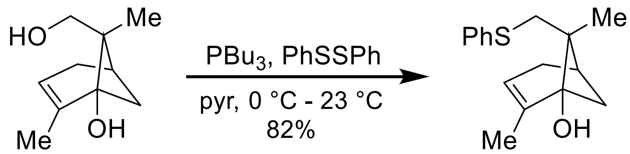
Iodide 47



44 **47**

Iodide **47** was synthesized according to a procedure adapted from Liu et al.[28] To a solution of hydroxyketone **44** (0.113 g, 0.672 mmol, 1.0 equiv) in MeCN (4 mL) and Et_2O (6 mL) at 0 ˚C was added PPh_3 (0.221 g, 0.869 mmol, 1.3 equiv), I_2 (0.246 g, 0.938 mmol, 1.4 equiv), and imidazole (68.3 mg, 1.00 mmol, 1.5 equiv). The resulting reddish-brown solution was stirred at 0 ˚C for 20 min, quickly forming a white precipitate, and was then warmed to 23 ˚C and stirred for 16 h. The reaction mixture was diluted with Et_2O (50 mL), vigorously shaken with sat. aq. $Na_2S_2O_3$ (50 mL), and washed once with water (50 mL) and once with brine (50 mL). The organic layer was dried over $MgSO_4$, filtered, and concentrated *in vacuo*. Flash column chromatography on silica (50:1 – 25:1 pentanes:Et_2O) afforded **47** (79.5 mg, 0.286 mmol, 43%) as a yellow oil. ^1H NMR (600 MHz, $CDCl_3$) δ 6.64 (ddq, *J* = 5.7, 2.9, 1.5 Hz, 1H), 3.85 (d, *J* = 9.8 Hz, 1H), 3.02 (d, *J* = 9.8 Hz, 1H), 2.47 (dqd, *J* = 13.7, 6.8, 4.8 Hz, 1H), 2.36 – 2.28 (m, 1H), 2.09 (ddq, *J* = 19.2, 10.2, 2.5 Hz, 1H), 1.79 – 1.76 (m, 3H), 1.06 (s, 3H), 0.92 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 200.66, 143.30, 133.73, 48.11, 35.95, 31.33, 16.45, 16.33, 14.55, 13.14. IR (ATR, thin film): ν_{max} = 2951, 2929, 2858, 1663, 1449, 1363, 1213, 1018, 918, 837, 649, 563, 501, 453 cm^{-1}. HRMS (ESI): calc'd for $[C_{10}H_{16}IO]^+$ *m/z* = 279.0247, found 279.0242.[14]

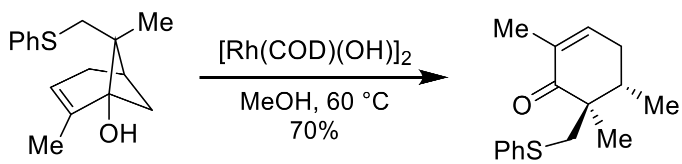
Phenyl sulfide 52



31 **52**

Phenyl sulfide **52** was synthesized according to a procedure by Kuroda et al.[16] Cyclobutanol **31** (0.301 g, 1.78 mmol, 1.0 equiv) and phenyl disulfide (0.93 mL, 3.7 mmol, 2.1 equiv) were dissolved in 3 mL of pyridine. Tri-*n*-butylphosphine (0.778 g, 3.56 mmol, 2.0 equiv) was added to the resulting solution at 0 ˚C and the reaction mixture was stirred, slowly warming to 23 ˚C, for 16 h. The pyridine was removed *in vacuo* and the residue was purified by flash column chromatography on silica (hexanes – 10:1 hexanes:EtOAc), yielding **52** (0.378 g, 1.45 mmol, 82%) as a light yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, *J* = 7.6 Hz, 2H), 7.27 (t, *J* = 7.6 Hz, 2H), 7.14 (t, *J* = 7.6 Hz, 1H), 5.28 (br s, 1H), 3.18 (d, *J* = 11.1 Hz, 1H), 2.94 (d, *J* = 11.1 Hz, 1H), 2.29 (dd, *J* = 8.3, 6.8 Hz, 1H), 2.26-2.21 (m, 1H), 2.20-2.15 (m, 2H), 2.00 (br s, 1H), 1.82 (s, 3H), 1.63 (d, *J* = 8.1 Hz, 3H), 1.39 (s, 3H). Full characterization has been reported by Kuroda et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[16]

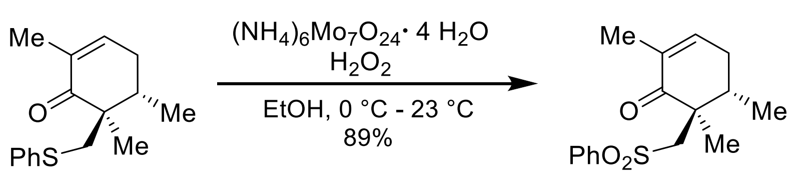
Cyclohexenone 53



52 **53**

Cyclohexenone **53** was synthesized according to a procedure by Kuroda et al.[16] In a glovebox, phenyl sulfide **52** (0.378 g, 1.45 mmol, 1.0 equiv) and $[Rh(COD)(OH)]_2$ (33 mg, 0.072 mmol, 5 mol%) were dissolved in MeOH (8 mL, degassed via freeze-pump-thaw). The resulting orange solution was stirred at 60 ˚C for 4 days. The reaction mixture was then cooled to 23 ˚C, filtered through Celite®, and concentrated. The golden-brown oil was purified by flash column chromatography on silica (hexanes – 4:1 hexanes:EtOAc), affording **53** (0.265 g, 1.02 mmol, 70%) as a light yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 – 7.43 (m, 1H), 7.34 – 7.28 (m, 3H), 7.24 – 7.17 (m, 1H), 6.67 (ddd, *J* = 5.7, 3.0, 1.6 Hz, 1H), 3.66 (d, *J* = 12.2 Hz, 1H), 2.97 (d, *J* = 12.1 Hz, 1H), 2.66 – 2.47 (m, 1H), 2.43 – 2.30 (m, 1H), 2.24 – 2.06 (m, 1H), 1.82 (d, *J* = 1.2 Hz, 2H), 1.08 (s, 3H), 0.95 (d, *J* = 6.8 Hz, 3H). Full characterization has been reported by Kuroda et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[16]

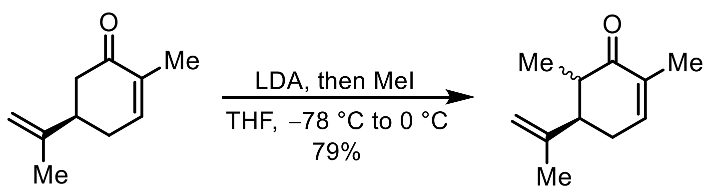
Sulfone 54



53 **54**

Sulfone **54** was synthesized according to a procedure by Kuroda et al.[16] Hydrogen peroxide (35 wt% in H_2O, 1.8 mL, 21 mmol, 21 equiv) was added to ammonium molybdate tetrahydrate (0.261 g, 0.212 mmol, 0.21 equiv) at 0 ˚C. The resulting yellow solution was stirred open to air at 0 ˚C for 15 min and was then added dropwise to a 0 ˚C solution of sulfide **53** (0.265 g, 1.02 mmol, 1.0 equiv) in EtOH (6 mL) in a separate flask. The reaction mixture was stirred for 3.5 h, slowly warming to 23 ˚C, and was subsequently quenched at 0 ˚C by the addition of sat. aq. Na_2SO_3 (10 mL). The resulting mixture was stirred at 23 ˚C for 5 min. The aqueous layer was extracted three times with EtOAc (30 mL) and the combined organic layers washed with brine (30 mL), dried over $MgSO_4$, filtered, and concentrated under reduced pressure to yield **54** (0.287 g, 0.912 mmol, 89%) as a white crystalline solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 7.5 Hz, 2H), 7.62 (t, *J* =7.5 Hz, 1H), 7.55 (t, *J* = 7.5 Hz, 2H), 6.71 (d, *J* = 5.6 Hz, 1H), 4.12 (d, *J* = 14.0 Hz, 1H), 3.19 (d, *J* = 14.0 Hz, 1H), 3.05 (tt, *J* = 11.5, 6.6 Hz, 1H), 2.37 (dt, *J* = 19.0, 5.6 Hz, 1H), 2.16 (ddt, *J* = 18.9, 11.0, 2.5 Hz, 1H), 1.82 (m, 3H), 1.16 (d, *J* = 6.7 Hz, 3H), 0.96 (s, 3H). Full characterization has been reported by Kuroda et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[16]

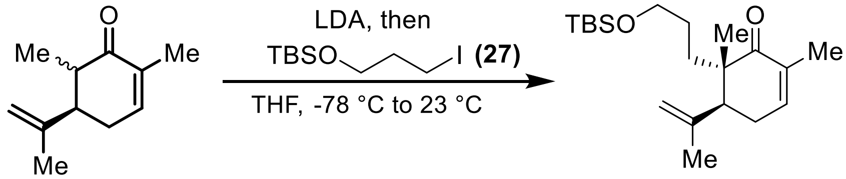
6-methyl carvone (26)



(R)-(–)-carvone **26 (1.7:1 dr)**

6-methyl carvone (**26**) was synthesized according to a procedure by Cory et al.[29] To a solution of diisopropylamine (5.4 mL, 38 mmol, 1.2 equiv) in THF (50 mL) at −78 ˚C was added *n*-BuLi (23.9 mL, 38.3 mmol, 1.2 equiv) over 10 min. The resulting yellow solution was stirred at −78 ˚C for 2 h, then (*R*)-(–)-carvone was added over 10 min. After stirring at −78 ˚C for 2 h, methyl iodide (MeI, 6.0 mL, 95.9 mmol, 3.0 equiv) was added quickly. The yellow reaction mixture was warmed to 0 ˚C and stirred for 1 h. The resulting orange solution was quenched by addition of sat. aq. NH_4Cl (100 mL) and the aqueous layer was extracted with Et_2O (3 x 50 mL). The combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The viscous yellow residue was purified by flash column chromatography on silica (hexanes – 20:1 hexanes:EtOAc), yielding **26** (4.13 g, 25.1 mmol, 79%, 1:1.7 mixture of diastereomers) as a yellow oil. ^{1}H NMR (600 MHz, $CDCl_3$, mixture of diastereomers): δ 6.73 – 6.65 (m, 1H), 4.95 – 4.71 (m, 2H), 2.79 – 2.20 (m, 4H), 1.86 – 1.74 (m, 3H), 1.07-0.89 (m, 3H). Full characterization has been reported by Cory et al. The ^{1}H NMR spectrum is consistent with that reported in the literature.[29]

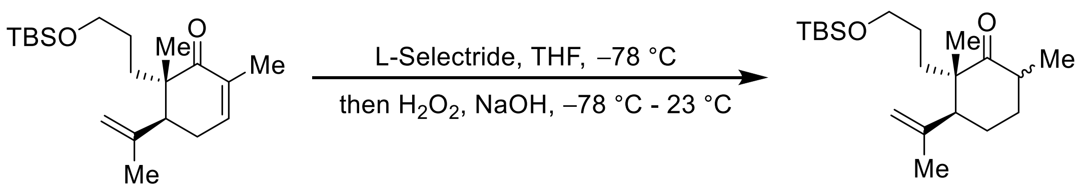
TBS-protected alcohol 28



26 **28**

TBS-protected alcohol **28** was synthesized according to a procedure adapted from Finkbeiner et al.[15] To a solution of diisopropylamine (0.60 mL, 4.1 mmol, 1.4 equiv) in THF (5 mL) at −78 ˚C was added *n*-BuLi (1.6 M in hexanes, 2.1 mL, 3.4 mmol, 1.1 equiv) dropwise. The resulting pale yellow solution was stirred at −78 ˚C for 20 min and 0 ˚C for an additional 20 min. The reaction mixture was cooled to −78 ˚C and a solution of 6-methyl carvone (**26**, 0.50g, 3.0 mmol, 1.0 equiv) in THF (1 mL) was added dropwise. The reaction mixture was stirred at −78 ˚C for 1.5 h and at 0 ˚C for an additional 1 h, cooled to −78 ˚C, then iodopropanol **27** (0.92 g, 3.0 mmol, 1.0 equiv) in THF (1 mL) was added rapidly. The solution was stirred 18 h, slowly warming to 23 ˚C, and was then quenched by the addition of sat. aq. NH_4Cl (10 mL). The aqueous layer was extracted with Et_2O (3 x 30 mL) and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The viscous yellow residue was purified by flash column chromatography on silica (hexanes – 50:1 hexanes:EtOAc), yielding **28** (0.82 g, 2.4 mmol, 81 %) as a clear, colorless oil. ^1H NMR (600 MHz, $CDCl_3$) δ 1H NMR (600 MHz, Chloroform-d) δ 6.53 (qd, J = 2.9, 1.3 Hz, 1H), 4.76 (q, J = 1.6 Hz, 1H), 4.72 – 4.68 (m, 1H), 3.60 – 3.48 (m, 2H), 2.70 (t, J = 5.4 Hz, 1H), 2.66 – 2.54 (m, 1H), 2.27 (dtd, J = 18.9, 4.3, 2.1 Hz, 1H), 1.75 (qd, J = 2.2, 1.5 Hz, 3H), 1.62 (d, J = 1.5 Hz, 3H), 1.58 (dd, J = 9.5, 7.1 Hz, 2H), 1.52 – 1.43 (m, 1H), 1.41 – 1.30 (m, 1H), 1.00 (s, 3H), 0.86 (s, 9H), 0.01 (d, J = 3.7, 6H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 204.14, 146.47, 141.37, 134.14, 113.85, 63.34, 50.03, 47.25, 34.09, 28.74, 27.63, 25.88, 22.17, 19.25, 18.25, 16.36, -5.35; IR (ATR, thin film): ν_{max} = 2953, 2927, 2856, 1668, 1640, 1462, 1379, 1255, 1097, 894, 834, 774 cm^{-1}. HRMS (ESI): calc'd for $[C_{20}H_{37}O_2Si]^+$ *m/z* = 337.2564, found 337.2569.

Ketone 29

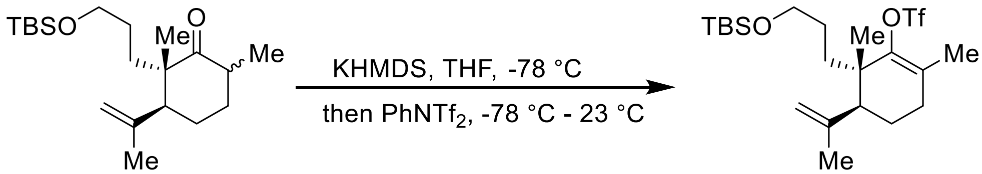


28 **29 (1:0.9 dr)**

Ketone **29** was synthesized according to a procedure adapted from Finkbeiner et al.[15] To a solution of TBS-protected alcohol **28** (1.00 g, 2.97 mmol, 1.0 equiv) in THF (12 mL) at −78 ˚C was added L-Selectride (1.0 M in THF, 3.27 mL, 3.27 mmol, 1.1 equiv) dropwise over 10 min. The resulting pale yellow solution was stirred at −78 ˚C for 5 h, at which point MeOH (1.0 mL), NaOH (3 M in H_2O, 3.0 mL), and H_2O_2 (35 wt % in H_2O, 1.0 mL) were slowly added. The reaction mixture was stirred for an additional 16 h, gradually warming to 23 ˚C, and was then diluted with H_2O (10 mL) and sat. aq. $Na_2S_2O_3$ (10 mL). The aqueous layer was extracted with Et_2O (3 x 10 mL), and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo. The bright yellow residue was purified via flash column chromatography on silica (hexanes – 50:1 hexanes:EtOAc) to afford ketone **29** (0.911 g, 2.69 mmol, 91%, 1:0.9 mixture of diastereomers) as a clear, colorless oil. ^1H NMR (600 MHz, $CDCl_3$, mixture of diastereomers) δ 4.89 (p, *J* = 1.7 Hz, 1H), 4.83 (q, *J* = 1.6 Hz, 1H), 4.74 (d, *J* = 1.8 Hz, 1H), 4.36 (s, 1H), 3.61 – 3.55 (m, 3H), 3.51 (ddd, *J* = 10.0, 7.2, 5.2 Hz, 1H), 2.62 (dp, *J* = 12.9, 6.3 Hz, 2H), 2.49 (dd, *J* = 5.8, 3.0 Hz, 1H), 2.32 – 2.23 (m, 2H), 2.12 – 2.04 (m, 2H), 2.04 – 1.97 (m, 1H), 1.95 – 1.86 (m, 1H), 1.79 – 1.76 (m, 3H), 1.68 – 1.65 (m, 3H), 1.64 – 1.58 (m, 1H), 1.54 – 1.32 (m, 5H), 1.28 – 1.19 (m, 1H), 1.11

(d, J = 1.8 Hz, 4H), 1.02 – 0.93 (m, 9H), 0.87 (d, J = 2.9 Hz, 18H), 0.02 (d, J = 5.3 Hz, 11H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 217.84, 215.79, 145.52, 145.33, 114.00, 112.91, 63.97, 62.91, 54.31, 52.55, 51.73, 50.43, 47.42, 45.02, 40.71, 40.39, 36.38, 34.72, 32.52, 31.44, 27.75, 27.47, 27.20, 25.94, 25.86, 24.65, 24.34, 23.92, 20.33, 19.16, 18.31, 18.22, 15.11, 14.95, -5.33, -5.36, -5.38; IR (ATR, thin film): v_{max} = 2929, 2856, 1703, 1462, 1377, 1254, 1095, 895, 833, 774 cm^{-1}. HRMS (ESI): calc'd for $[C_{20}H_{39}O_2Si]^+$ m/z = 339.2720, found 339.2722.

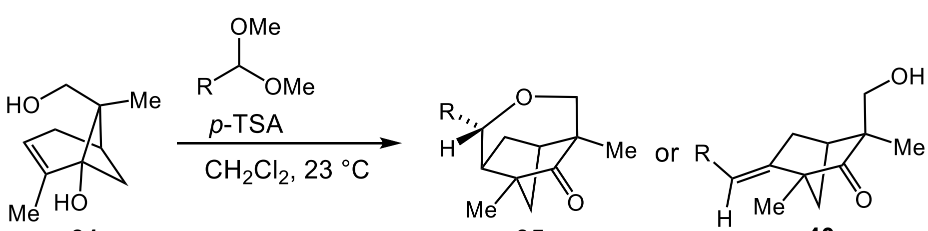
Vinyl triflate 24



29 24

Vinyl triflate **24** was synthesized according to a procedure adapted from Finkbeiner et al.[15] To a solution of ketone **29** (0.179 g, 0.53 mmol, 1.0 equiv) in THF (7 mL) at −78 ˚C was added KHMDS (0.7 M in toluene, 0.90 mL, 0.63 mmol, 1.2 equiv) dropwise. After the resulting solution was stirred at −78 ˚C for 5 h, $PhNTf_2$ (0.214 g, 0.60 mmol, 1.1 equiv) was added rapidly. The reaction mixture was stirred for 40 h, slowly warming to 23 ˚C, and was then quenched by the addition of H_2O (3 mL). The aqueous layer was extracted with Et_2O (2 x 20 mL) and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated. The resulting orange residue was purified by flash column chromatography on silica pre-neutralized with NEt_3 (hexanes – 50:1 hexanes:NEt_3), yielding **24** (0.150 g, 0.32 mmol, 60%) as a pale yellow oil. ^{1}H NMR (600 MHz, $CDCl_3$) δ 4.97 (q, J = 1.6 Hz, 1H), 4.74 (dt, J = 2.1, 0.9 Hz, 1H), 3.60 (ddd, J = 10.2, 7.2, 5.4 Hz, 1H), 3.53 (dt, J = 9.9, 6.9 Hz, 1H), 2.42 (dd, J = 12.8, 2.6 Hz, 1H), 2.18 – 2.13 (m, 2H), 1.77 (d, J = 1.2 Hz, 6H), 1.45 – 1.34 (m, 1H), 1.34 – 1.23 (m, 1H), 1.06 (s, 3H), 0.89 (s, 9H), 0.04 (s, 6H); ^{13}C NMR (151 MHz, $CDCl_3$) δ 148.76, 145.08, 127.91, 115.13, 63.45, 46.98, 43.03, 32.00, 31.45, 27.47, 25.93, 23.60, 22.92, 21.50, 18.38, 17.67, -5.42; ^{19}F NMR (376 MHz, $CDCl_3$) δ -72.40 (s, 3F); IR (ATR, thin film): v_{max} = 2951, 2886, 2858, 1463, 1401, 1206, 1141, 1097, 960, 886, 833, 774, 601 cm^{-1}. HRMS (ESI): calc'd for $[C_{21}H_{38}F_3O_4SSi]^+$ m/z = 471.2213, found: N/A (no ionization).

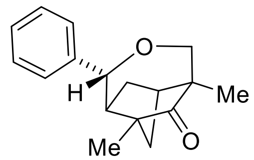
Prins-Semipinacol Rearrangements (Representative Procedure)



31 35 40

To a solution of cyclobutanol **31** (2.1 mg, 0.125 mmol, 1.0 equiv) and acetal (0.150 mmol, 1.2 equiv) in CH_2Cl_2 (1 mL) was added p-TSA (0.2 mg, 0.0125 mmol, 1 mol%). The resulting mixture was stirred at 23 ˚C until TLC showed consumption of all of the starting material. The reaction mixture was quenched with 2 drops of NEt_3, concentrated *in vacuo*, and purified by flash column chromatography on silica or preparative thin layer chromatography using hexanes:Et_2O as eluent.

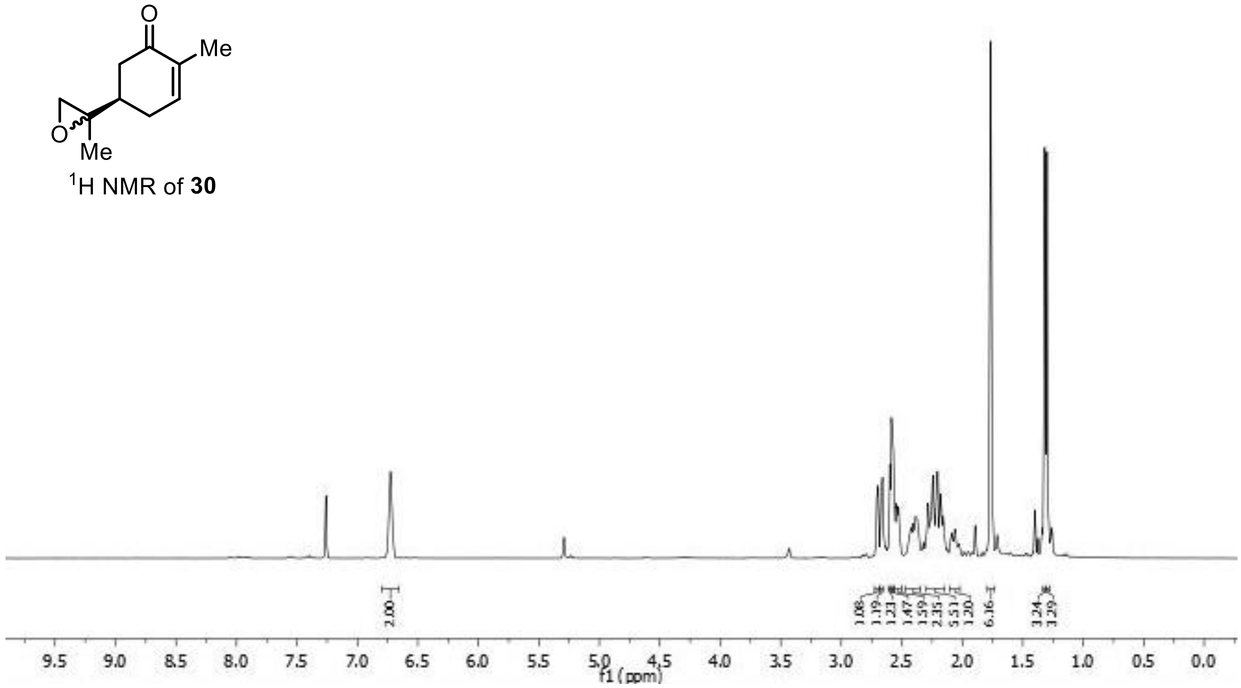
Fenchone-type derivative 35a



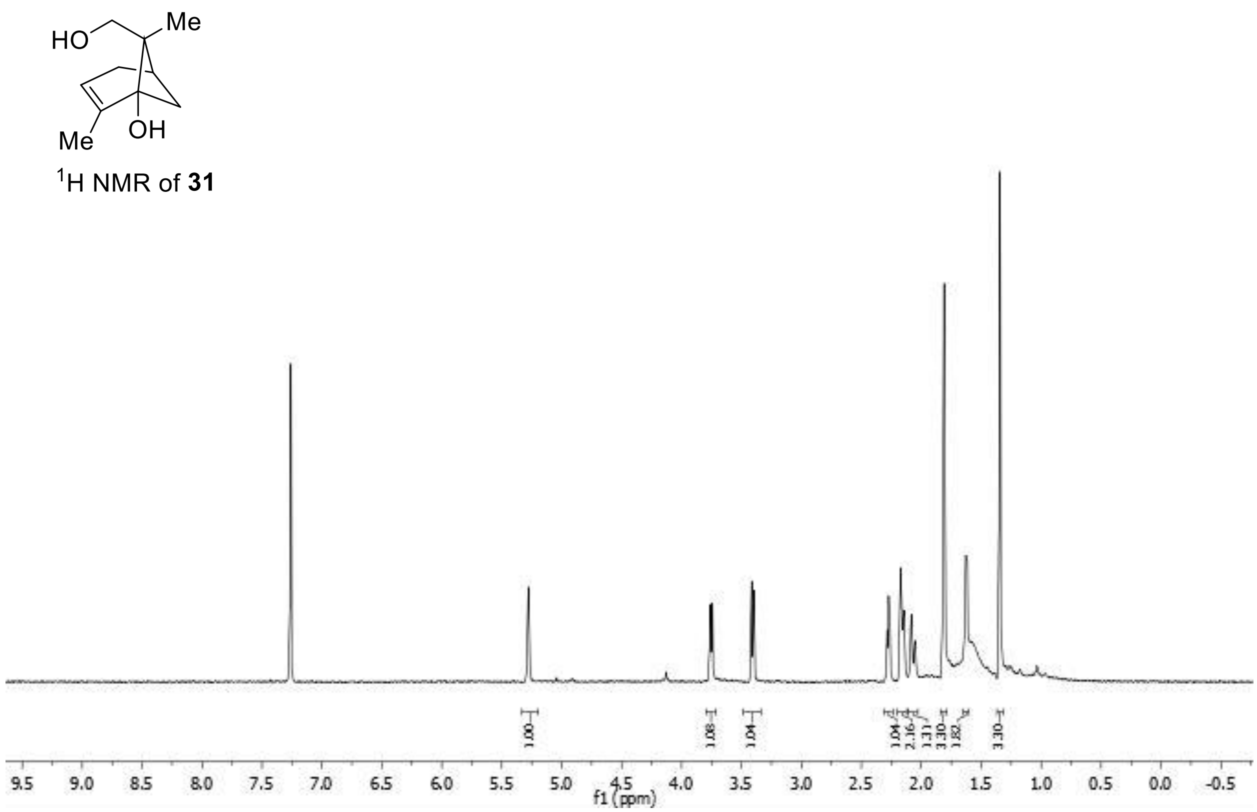
35a

Prepared according to representative procedure described above using either benzaldehyde, benzaldehyde dimethyl acetal, benzaldehyde diethyl acetal, benzaldehyde dioxane acetal, or benzaldehyde dioxolane acetal to afford **35a** as a colorless solid. Yield: 86% (dimethyl acetal), 84% (aldehyde), 81% (diethyl acetal), 45% (dioxolane acetal), 34% (dioxane acetal). ^{1}H NMR (700 MHz, $CDCl_3$): δ 7.31 (t, *J* = 7.6 Hz, 2H), 7.26 – 7.21 (m, 3H), 4.49 (s, 1H), 3.90 (d, *J* = 11.2 Hz, 1H), 3.79 (d, *J* = 11.2 Hz, 1H), 2.65 (d, *J* = 11.7 Hz, 1H), 2.33 (q, *J* = 1.9 Hz, 1H), 2.26 (d, *J* = 9.4 Hz, 1H), 1.67 – 1.62 (m, 3H), 1.27 (s, 3H), 1.03 (s, 3H); ^{13}C NMR (175 MHz, $CDCl_3$): δ 216.65, 144.07, 128.60, 127.34, 125.49, 78.31, 74.15, 57.83, 51.19, 46.73, 43.94, 43.90, 28.78, 17.40, 13.68; IR (ATR, thin film): ν_{max} = 2953, 2925, 2868, 1741, 1450, 1127, 1073, 972, 754, 707 cm^{-1}. $[\boldsymbol{\alpha}]_{\boldsymbol{D}}^{\mathbf{22}}$= −45.0 (c 0.55, $CHCl_3$). T_m = 95-96 °C. HRMS (APCI): calc'd for $[C_{17}H_{21}O_2]^+$ *m/z* = 257.1536, found 257.1536.

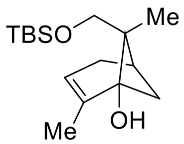
Spectral Data



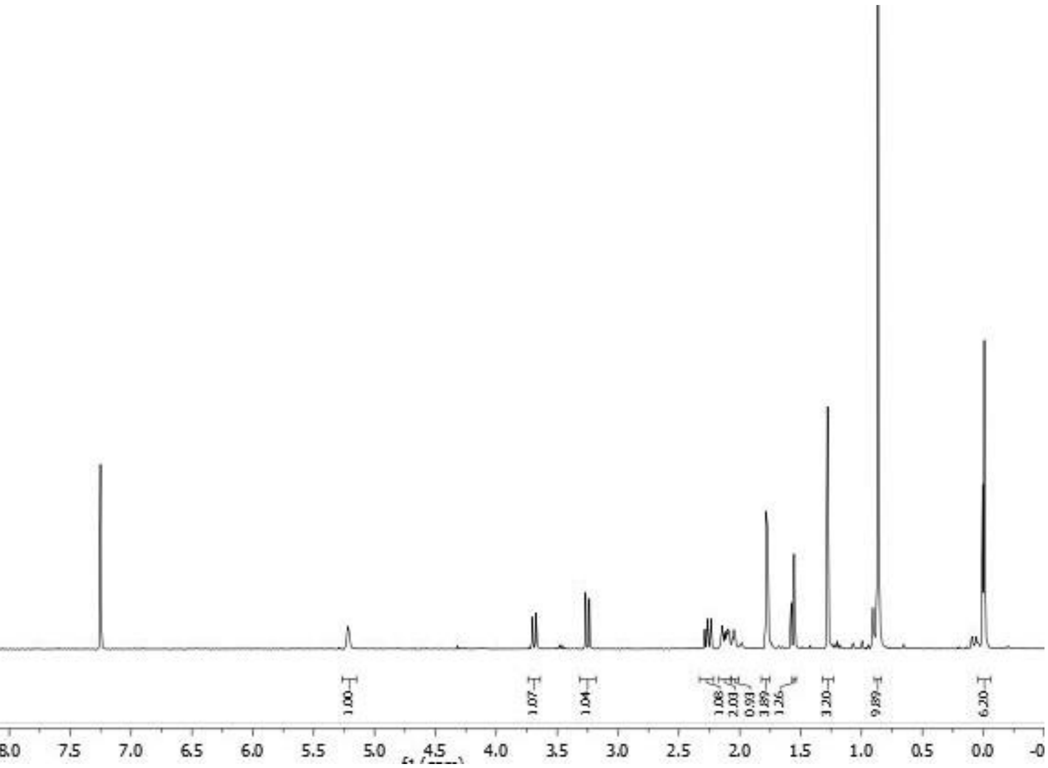
^{1}H NMR of **30**

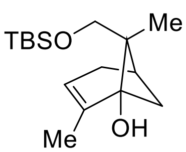


^{1}H NMR of **31**

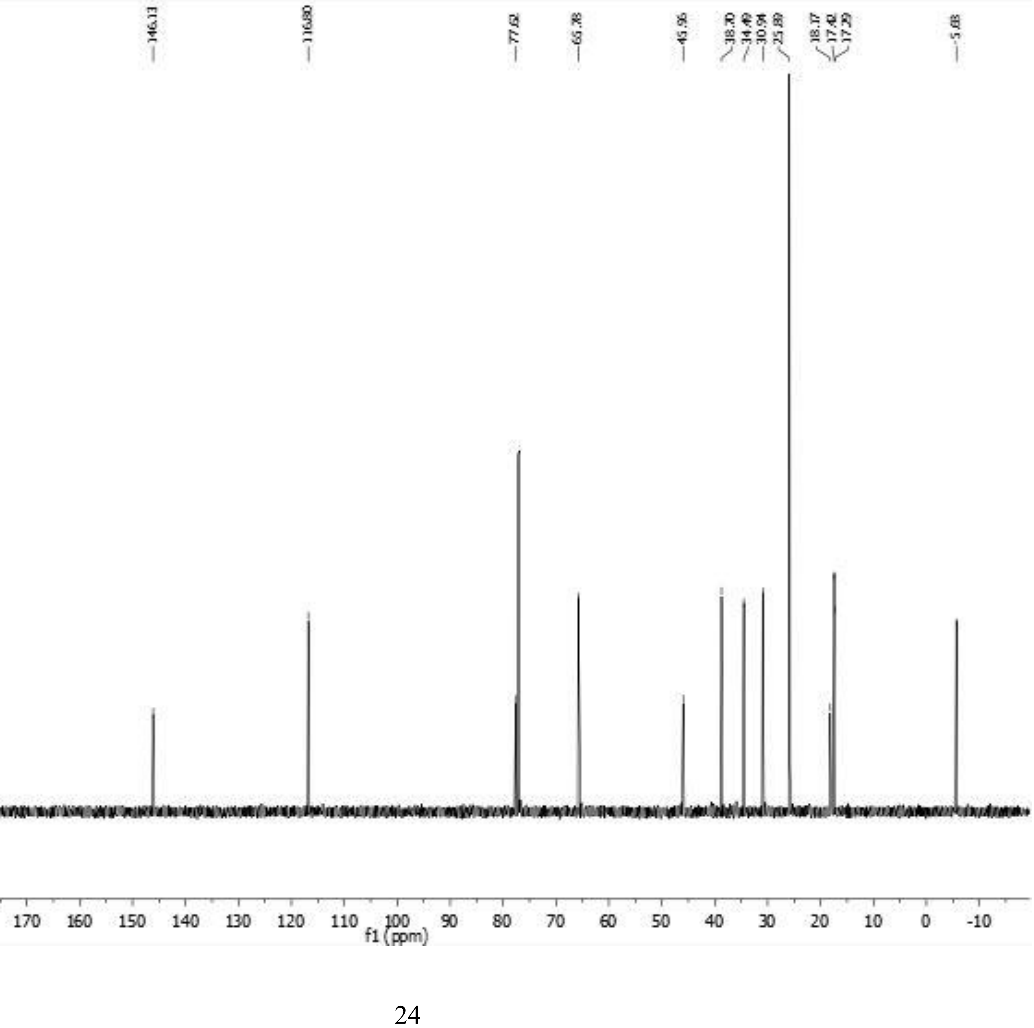


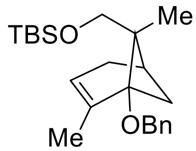
[1]H NMR of **41**



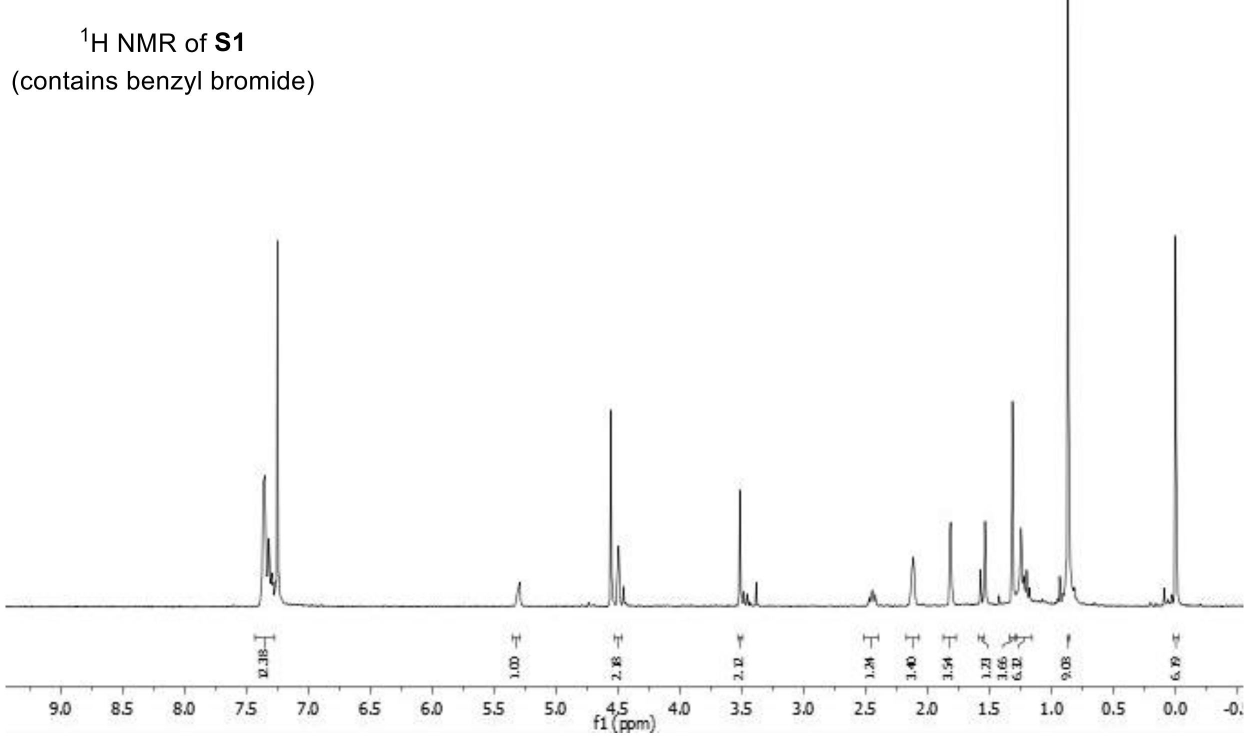


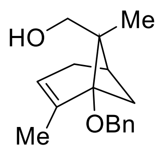
[13]C NMR of **41**



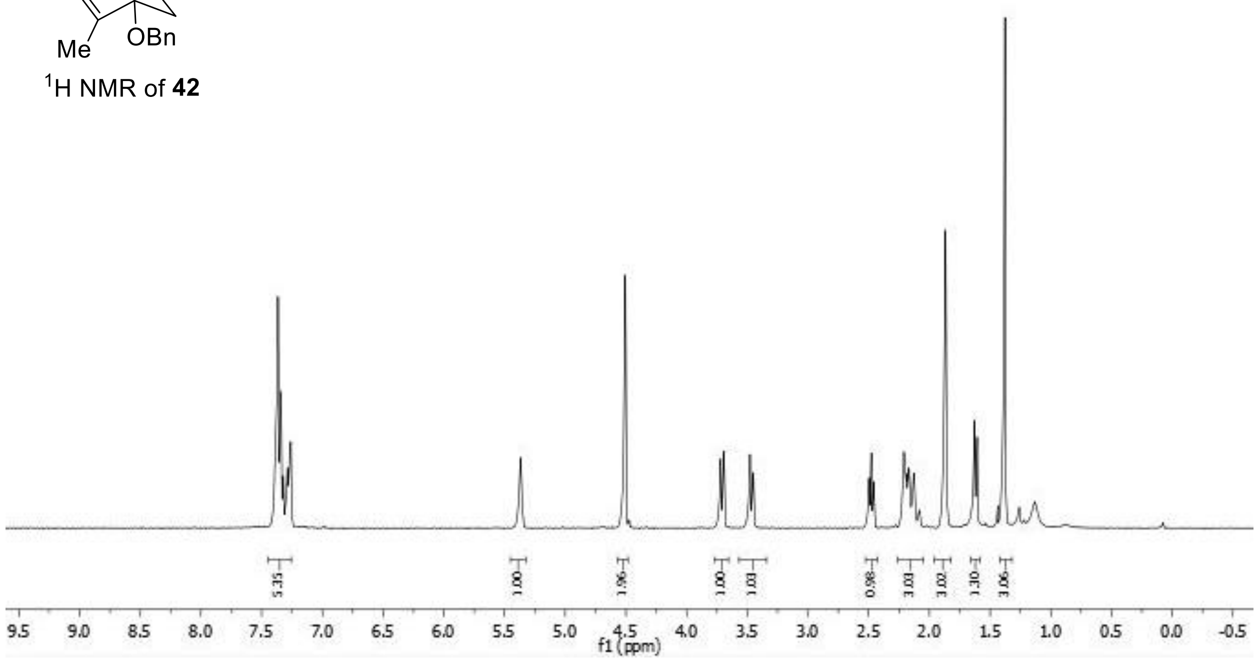


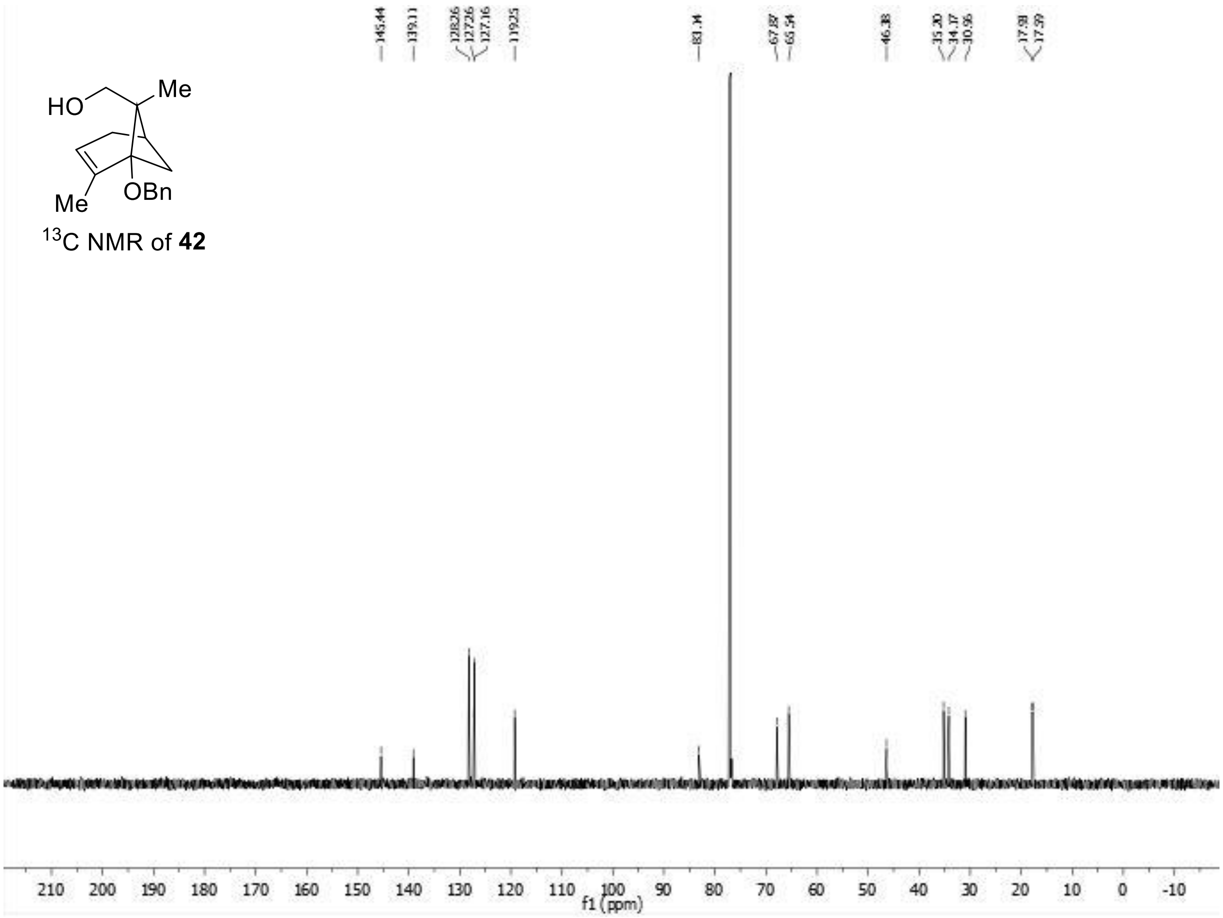
^{1}H NMR of **S1**
(contains benzyl bromide)

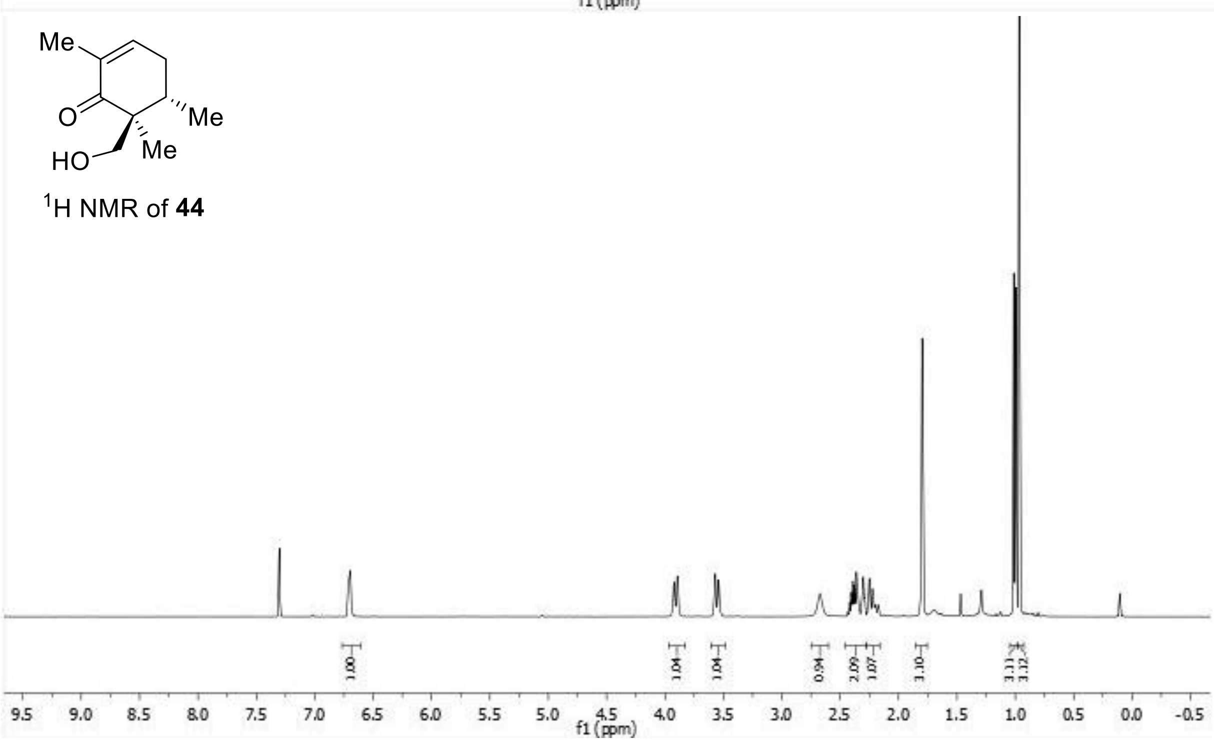


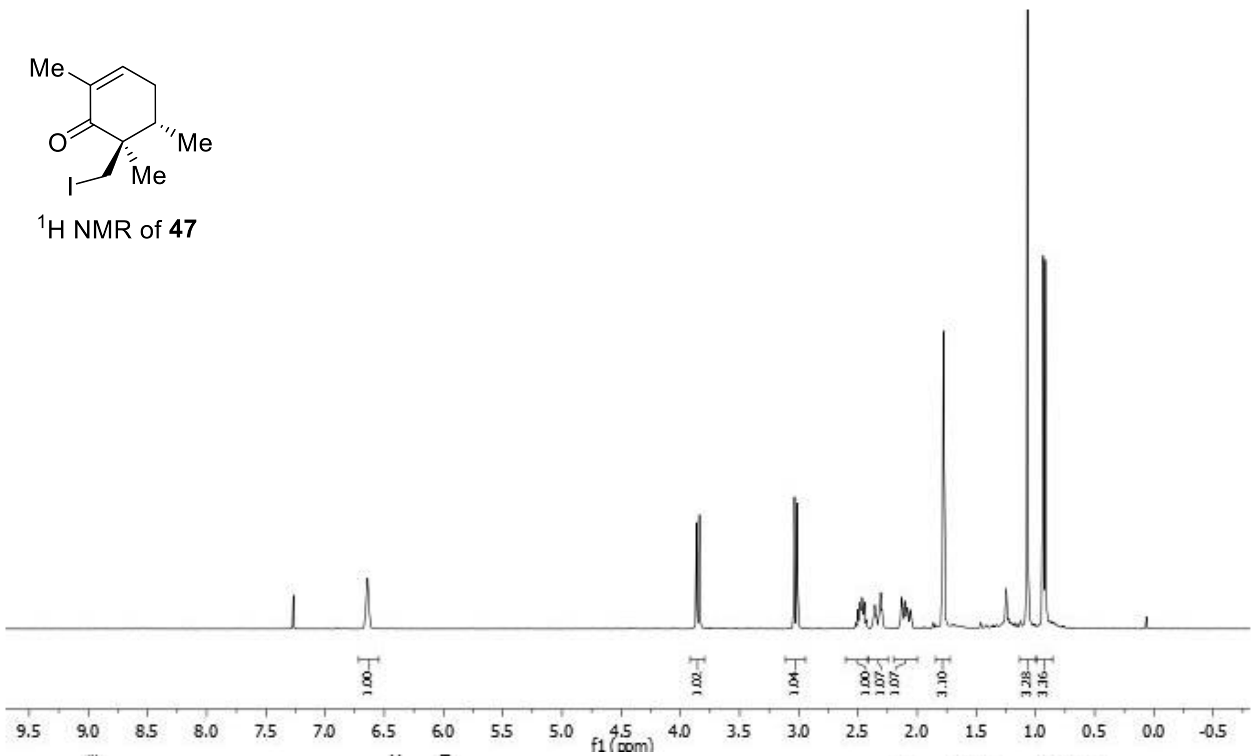


^{1}H NMR of **42**

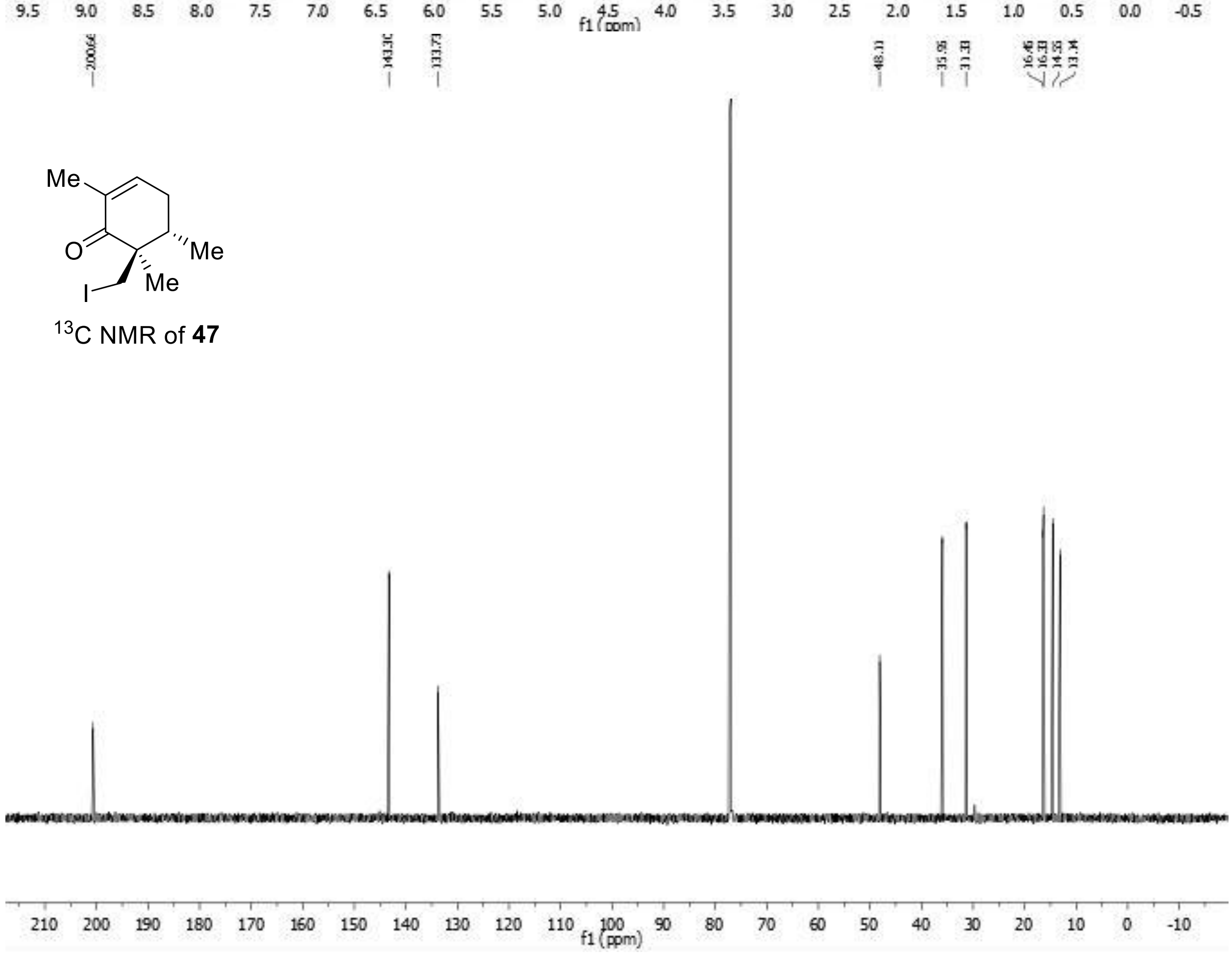



HO
Me
OBn
Me
13C NMR of 42
145.44
139.11
128.26
127.26
127.16
119.25
83.14
67.87
65.54
46.38
35.20
34.17
30.56
17.58
17.39
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
f1 (ppm)

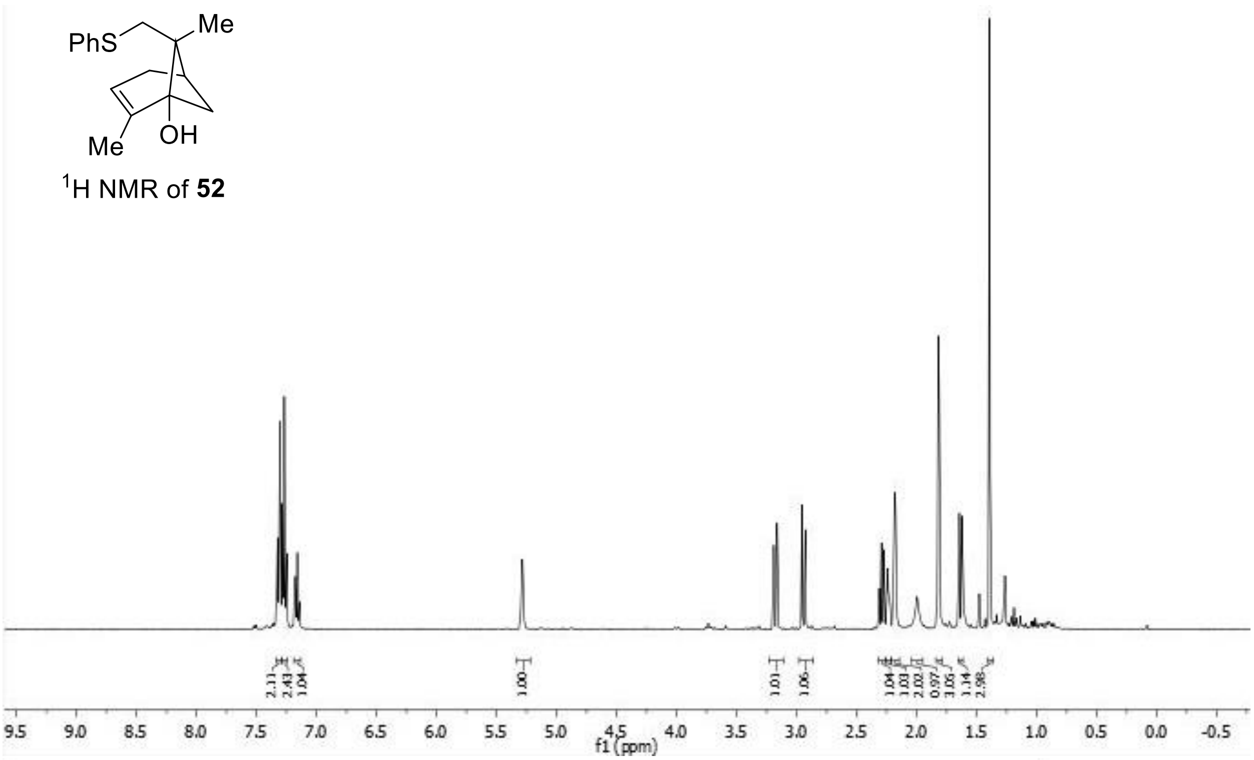

Me
O
Me
HO
Me
1H NMR of 44
1.00
1.04
1.04
0.94
2.09
1.07
3.10
3.11
3.12
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)



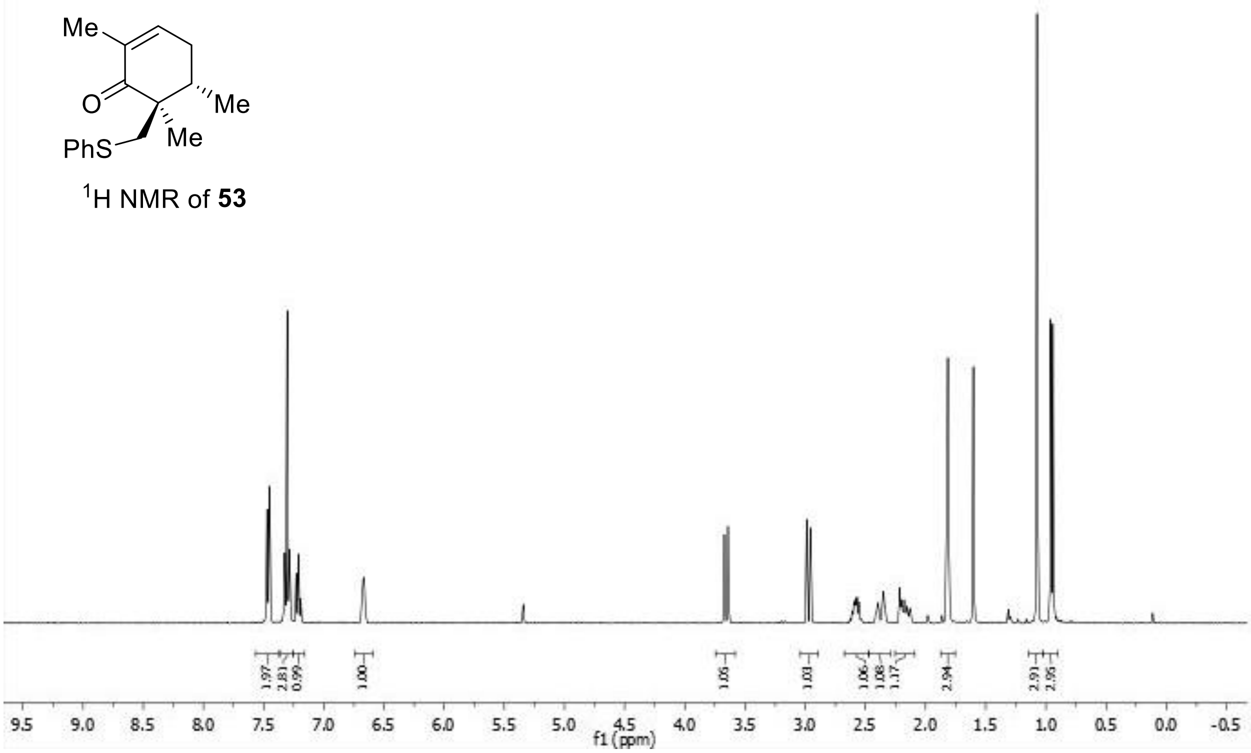
^{1}H NMR of **47**



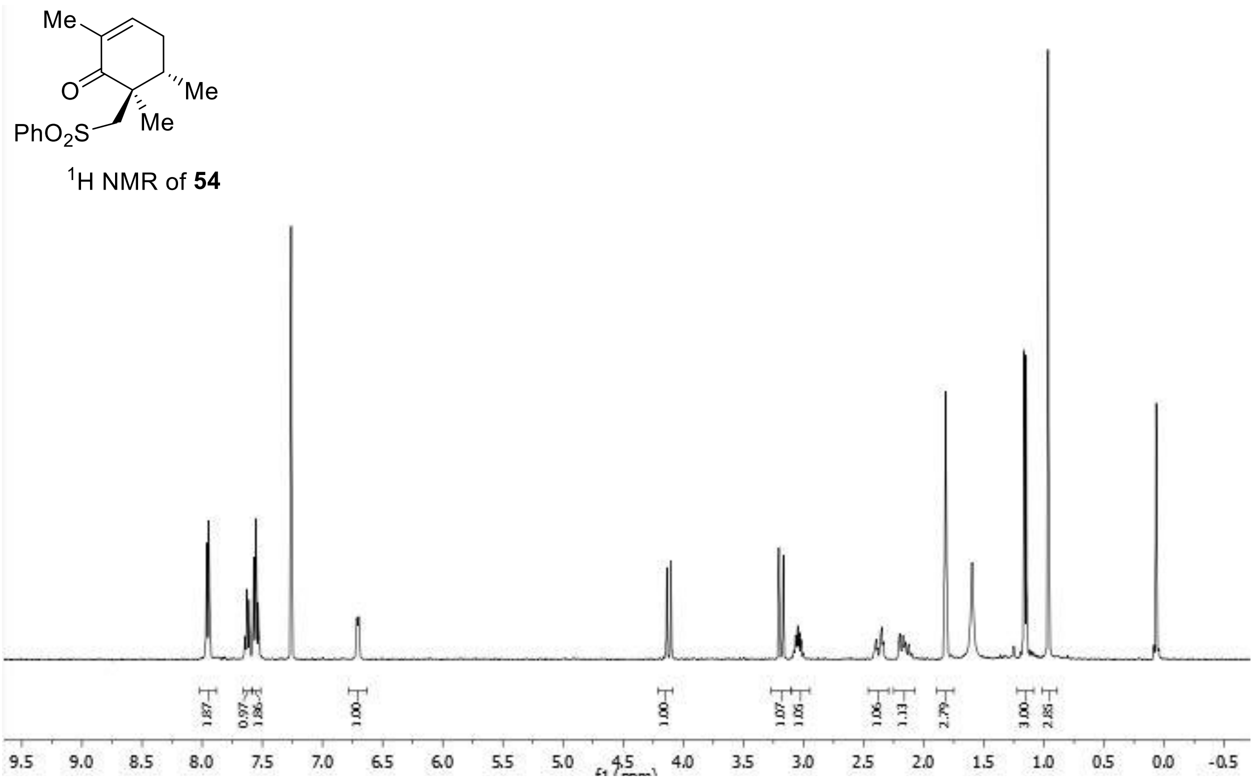
^{13}C NMR of **47**

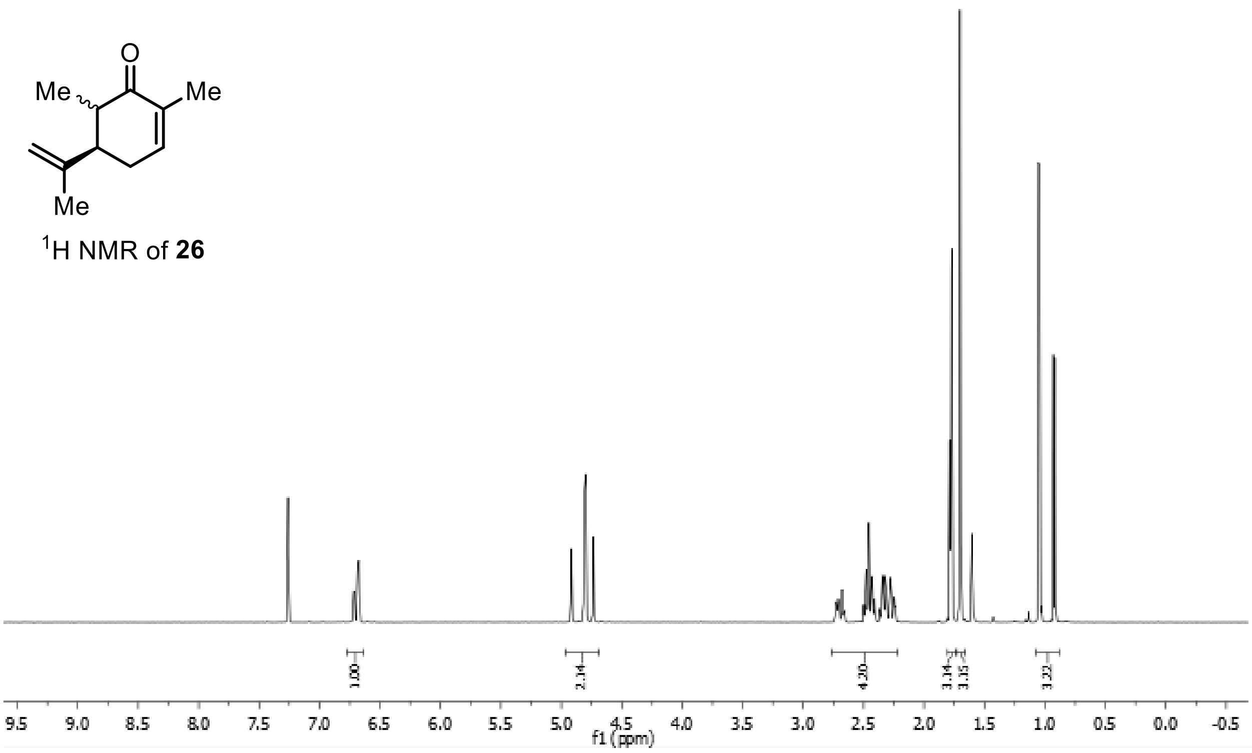


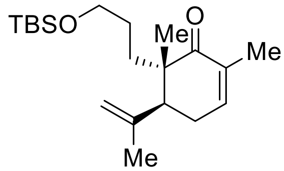
^{1}H NMR of **52**



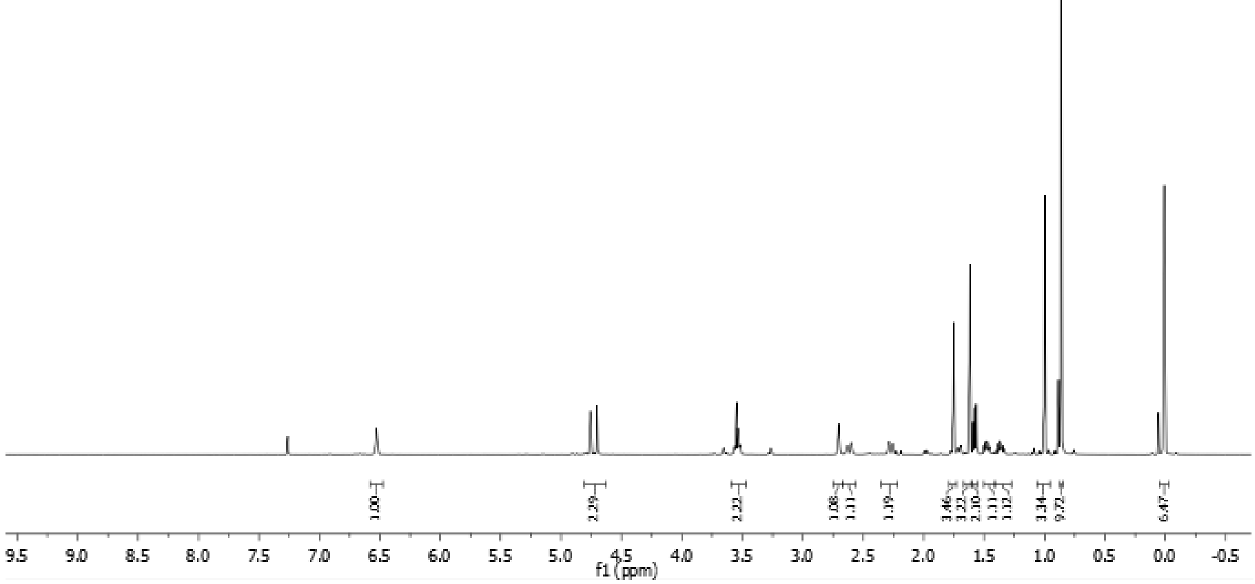
^{1}H NMR of **53**

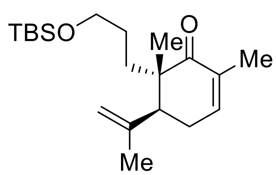

Me
O
Me
PhO2S
Me
1H NMR of 54
1.87
0.97
1.86
1.00
1.00
1.07
1.05
1.06
1.13
2.79
3.00
2.85
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5


O
Me
Me
Me
1H NMR of 26
1.00
2.14
4.20
3.14
3.15
3.22
9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0 -0.5
f1 (ppm)

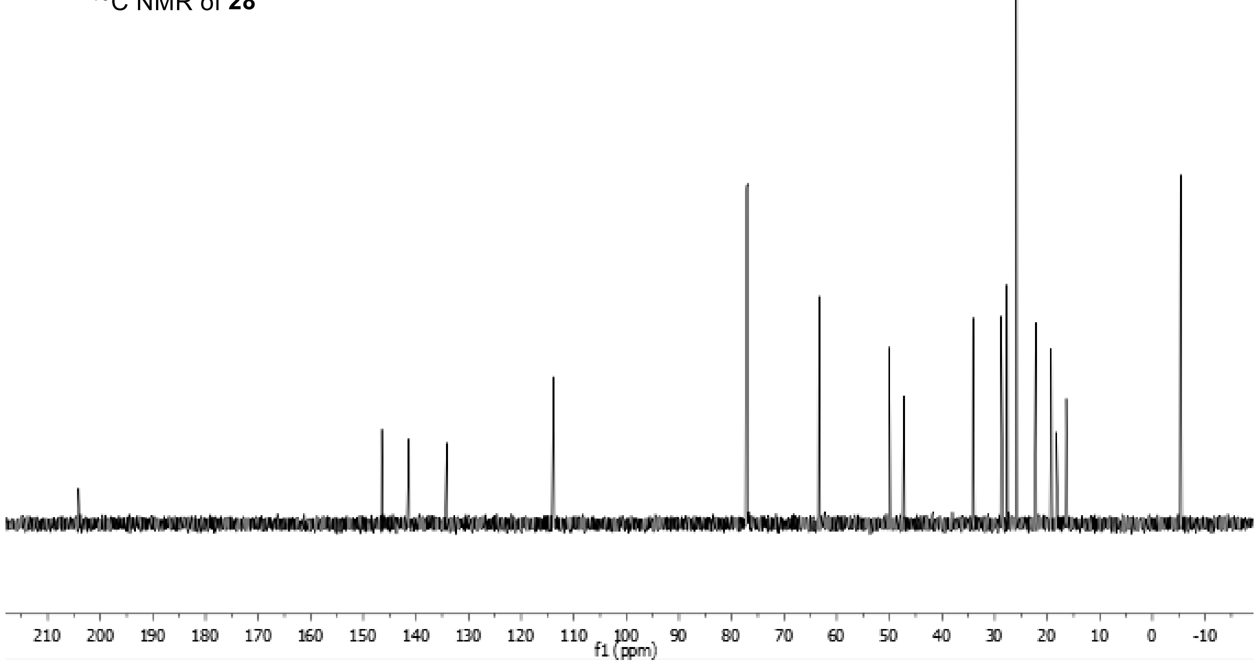


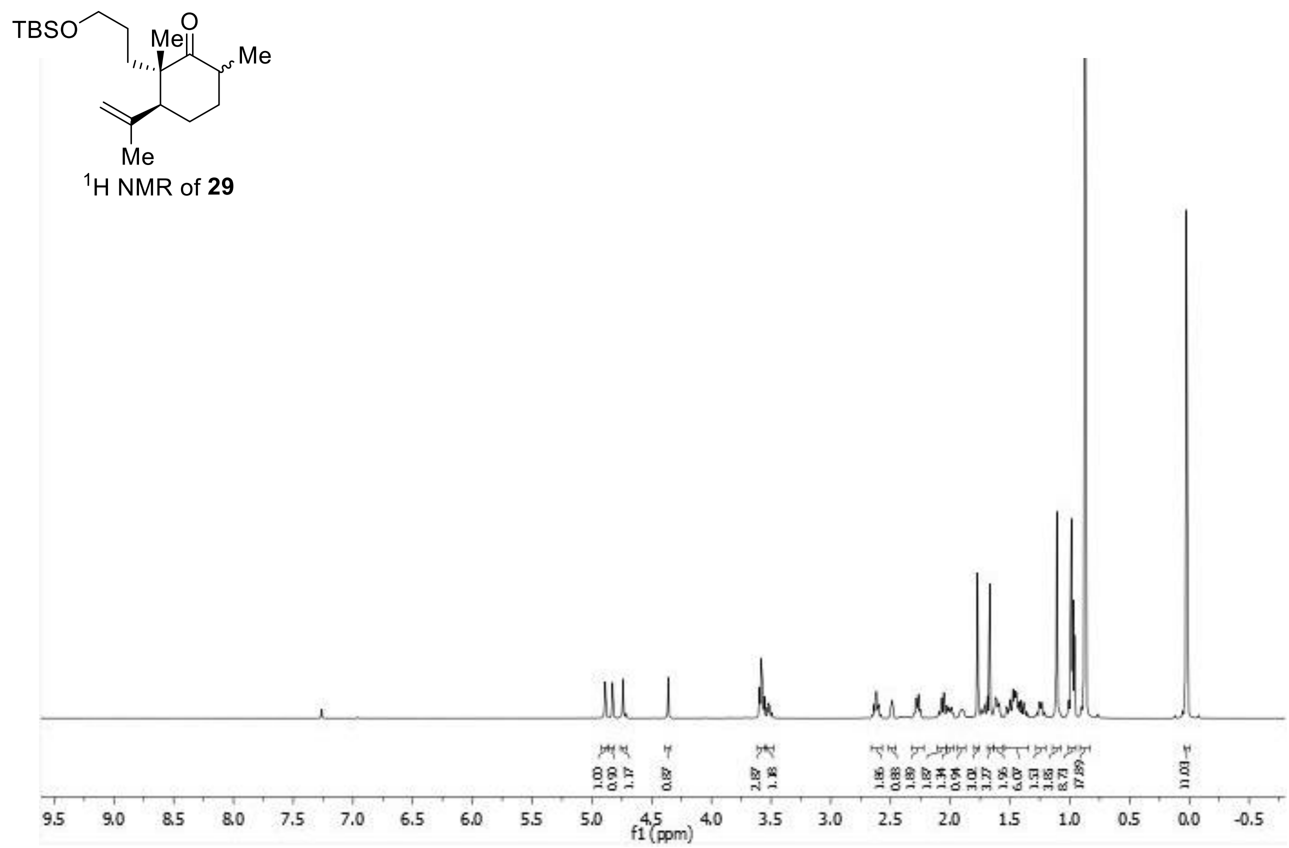
^{1}H NMR of **28**



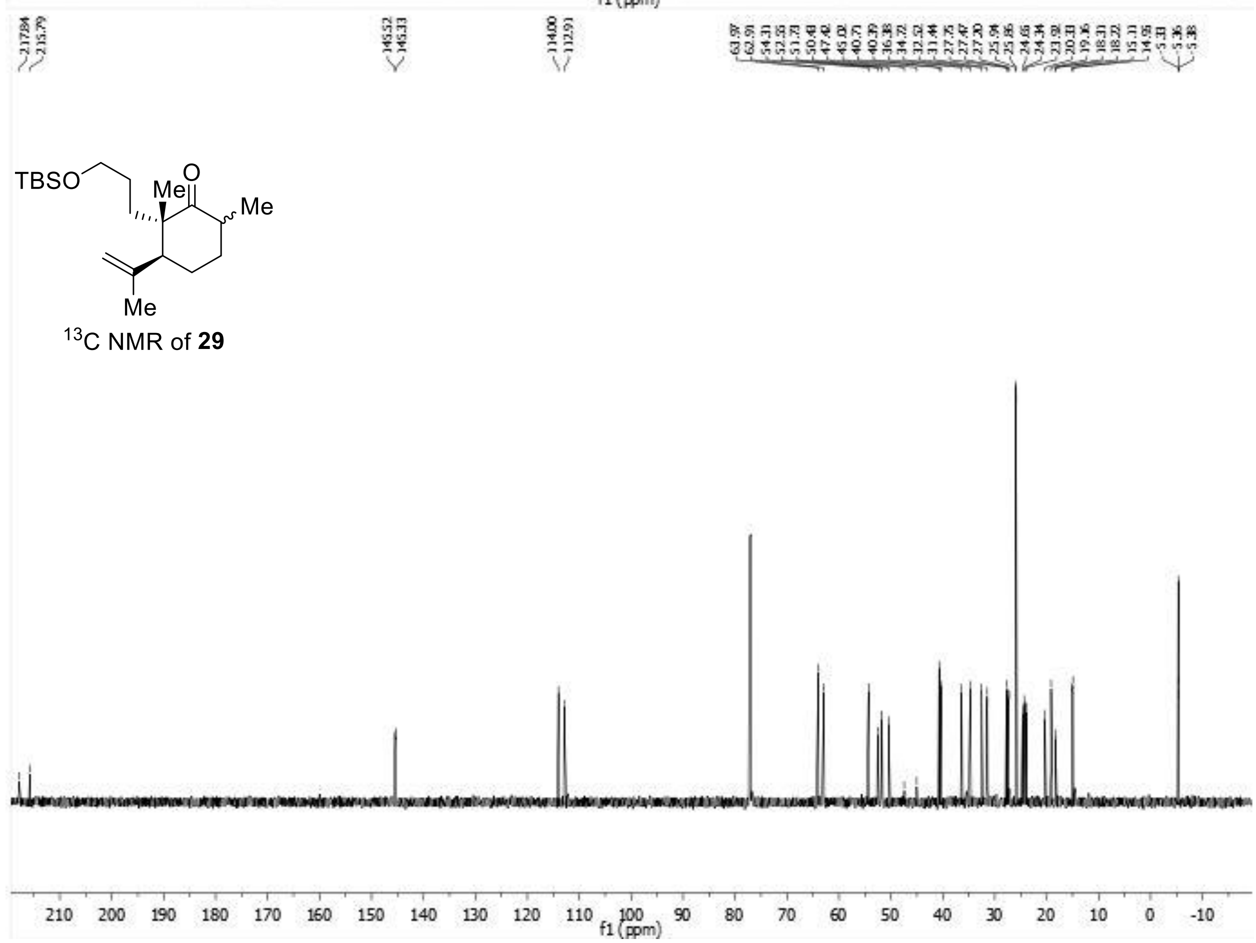


^{13}C NMR of **28**

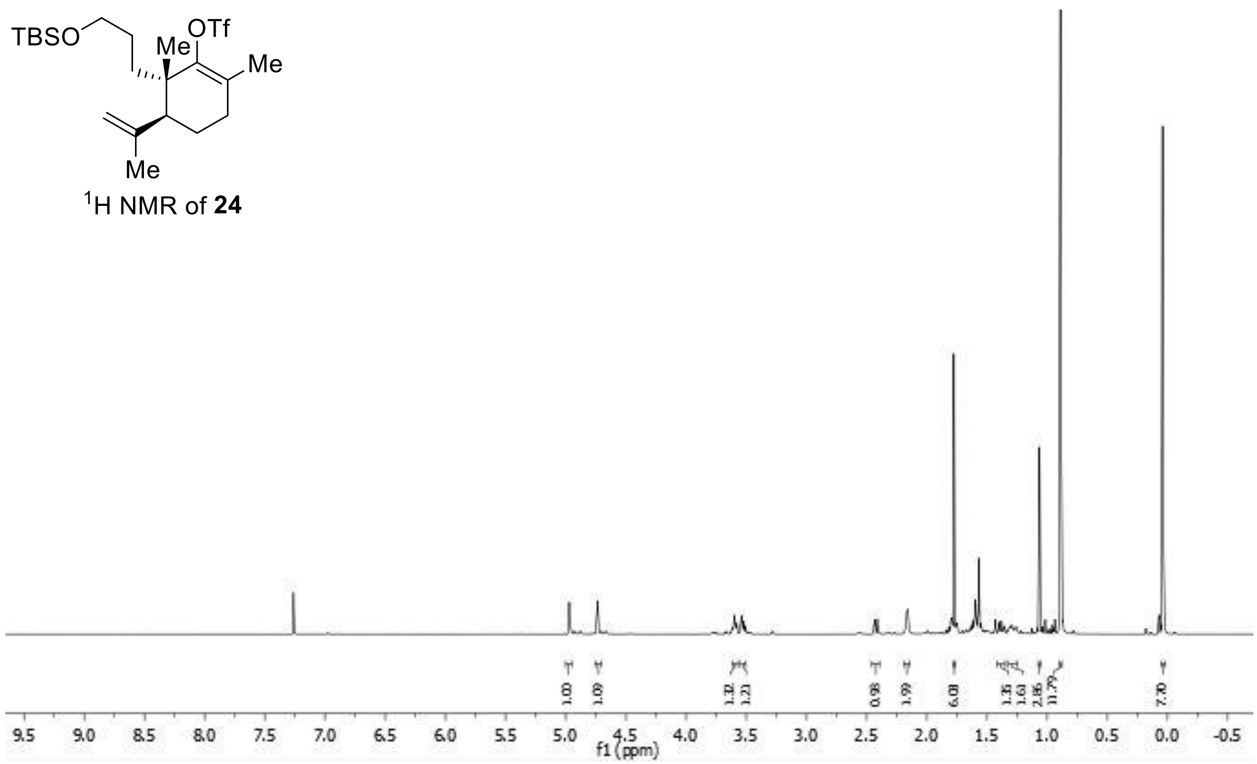




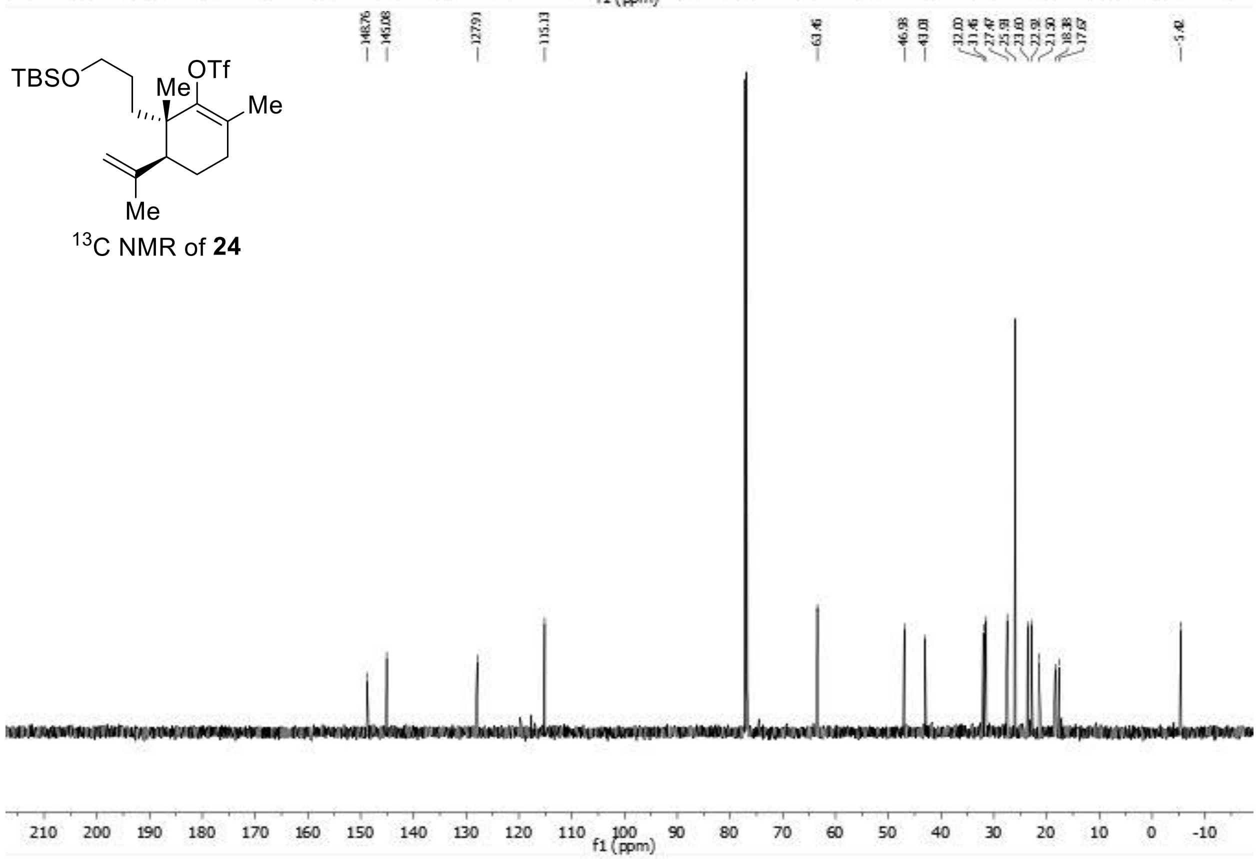
^{1}H NMR of **29**



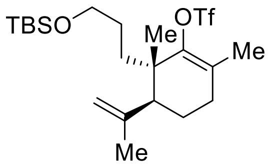
^{13}C NMR of **29**



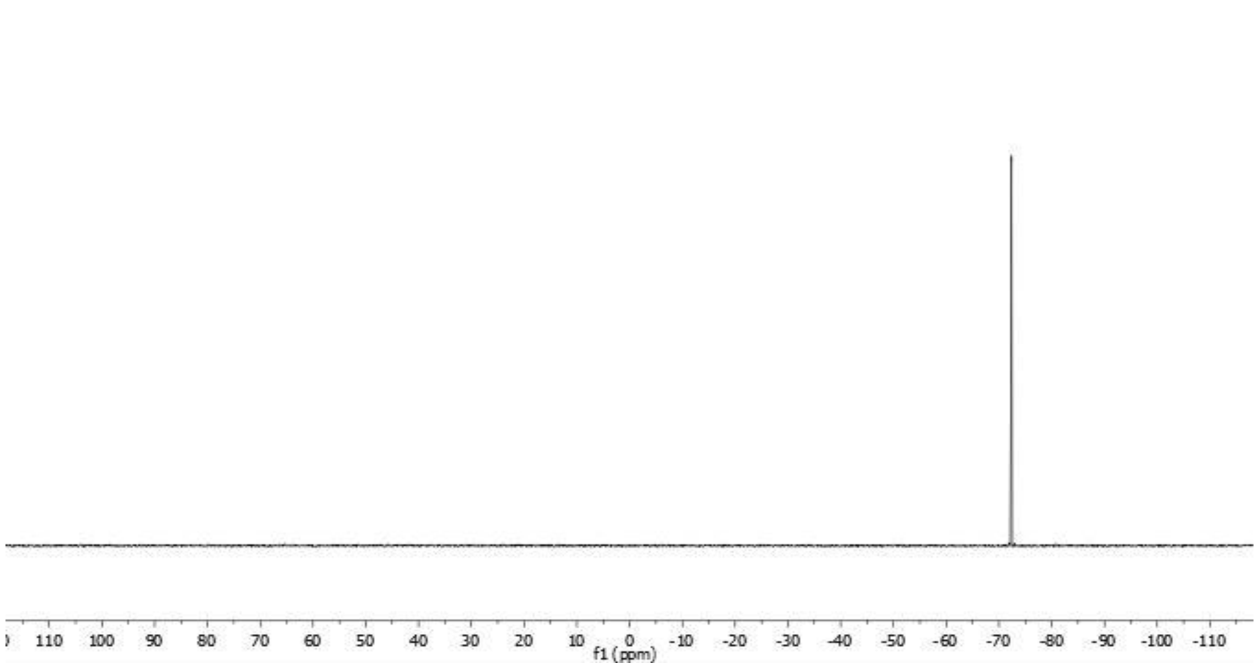
^{1}H NMR of **24**

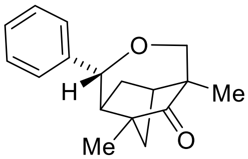


^{13}C NMR of **24**

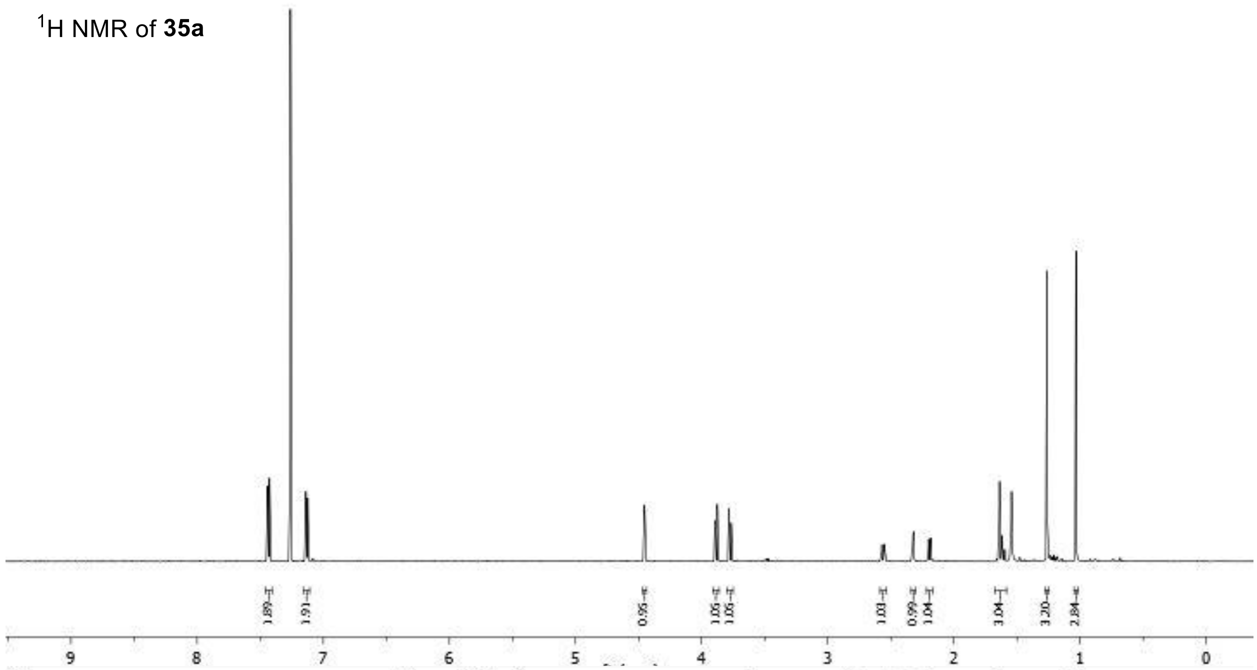


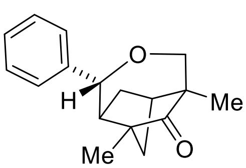
^{19}F NMR of **24**


-72.40
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
f1 (ppm)

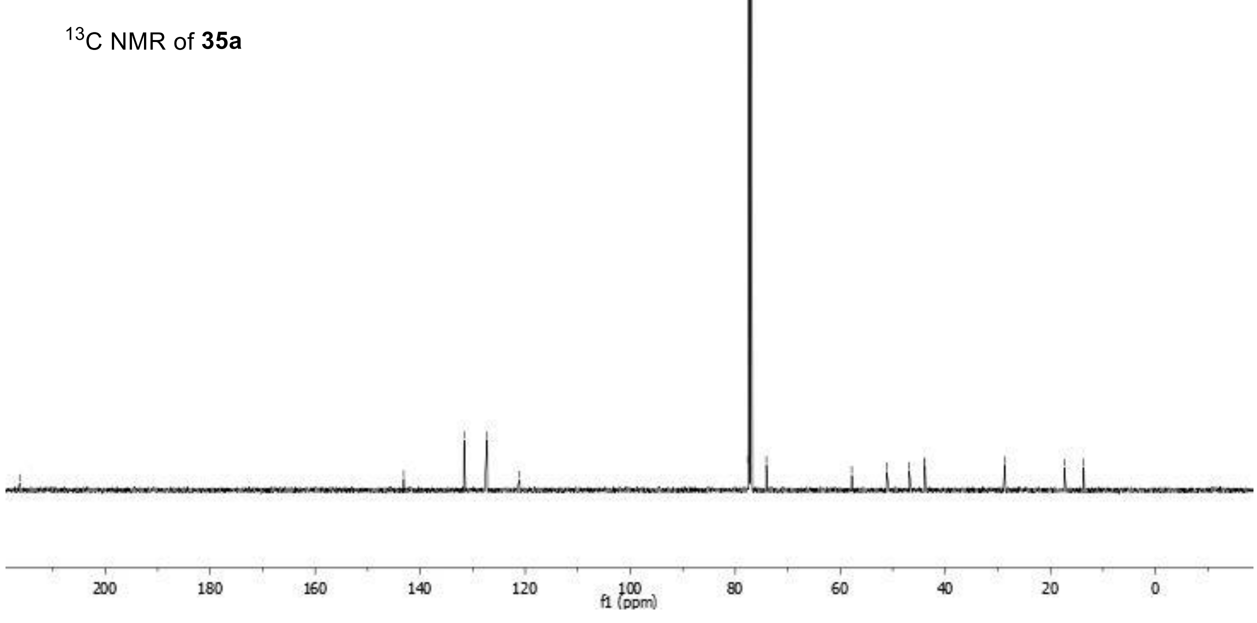


^{1}H NMR of **35a**





^{13}C NMR of **35a**



References

(1) *Cancer*. https://www.who.int/news-room/fact-sheets/detail/cancer (accessed 2022-03-04).
(2) Demain, A. L.; Vaishnav, P. *Microb. Biotechnol.* **2011**, *4*, 687–699.
(3) Ishikawa, K.; Sato, F.; Itabashi, T.; Wachi, H.; Takeda, H.; Wakana, D.; Yaguchi, T.; Kawai, K.-I.; Hosoe, T. *J. Nat. Prod.* **2016**, *79*, 2167–2174.
(4) Matsuda, Y.; Bai, T.; Phippen, C. B. W.; Nødvig, C. S.; Kjærbølling, I.; Vesth, T. C.; Andersen, M. R.; Mortensen, U. H.; Gotfredsen, C. H.; Abe, I.; Larsen, T. O. *Nat. Commun.* **2018**, *9*, 2587.
(5) Wang, J. P.; Hielscher, A. *J. Cancer* **2017**, *8*, 674–682.
(6) Mitra, A. K.; Sawada, K.; Tiwari, P.; Mui, K.; Gwin, K.; Lengyel, E. *Oncogene* **2011**, *30*, 1566–1576.
(7) Pontiggia, O.; Sampayo, R.; Raffo, D.; Motter, A.; Xu, R.; Bissell, M. J.; Joffé, E. B. de K.; Simian, M. *Breast Cancer Res. Treat.* **2012**, *133*, 459–471.
(8) Ioachim, E.; Charchanti, A.; Briasoulis, E.; Karavasilis, V.; Tsanou, H.; Arvanitis, D. L.; Agnantis, N. J.; Pavlidis, N. *Eur. J. Cancer Oxf. Engl. 1990* **2002**, *38*, 2362–2370.
(9) Ishikawa, K.; Hosoe, T.; Itabashi, T.; Sato, F.; Wachi, H.; Nagase, H.; Yaguchi, T.; Kawai, K.-I. *Sci. Pharm.* **2011**, *79*, 937–950.
(10) Yang, F.; Porco, J. A. *J. Am. Chem. Soc.* **2022**, *144*, 12970–12978.
(11) Corey, E. J.; Das, J. *J. Am. Chem. Soc.* **1982**, *124*, 5551–5553.
(12) McMurry, J. E.; Erion, M. D. *J. Am. Chem. Soc.* **1985**, *107*, 2712–2720.
(13) Dethe, D. H.; Dherange, B. D.; Ali, S.; Parsutkar, M. M. *Org. Biomol. Chem.* **2016**, *15*, 65–68.
(14) Lockner, J. W. Studies in Meroterpenoid Synthesis. Ph.D., The Scripps Research Institute, United States -- California.
(15) Finkbeiner, P.; Murai, K.; Röpke, M.; Sarpong, R. *J. Am. Chem. Soc.* **2017**, *139*, 11349–11352.
(16) Kuroda, Y.; Nicacio, K. J.; da Silva-Jr, I. A.; Leger, P. R.; Chang, S.; Gubiani, J. R.; Deflon, V. M.; Nagashima, N.; Rode, A.; Blackford, K.; Ferreira, A. G.; Sette, L. D.; Williams, D. E.; Andersen, R. J.; Jancar, S.; Berlinck, R. G. S.; Sarpong, R. *Nat. Chem.* **2018**, *10*, 938–945.
(17) Nishimura, H.; Hiramoto, S.; Mizutani, J.; Noma, Y.; Furusaki, A.; Matsumoto, T. *Agric. Biol. Chem.* **1983**, *47*, 2697–2699.
(18) Bermejo, F. A.; Fernández Mateos, A.; Marcos Escribano, A.; Martín Lago, R.; Mateos Burón, L.; Rodríguez López, M.; Rubio González, R. *Tetrahedron* **2006**, *62*, 8933–8942.
(19) Martín-Rodríguez, M.; Galán-Fernández, R.; Marcos-Escribano, A.; Bermejo, F. A. *J. Org. Chem.* **2009**, *74*, 1798–1801.
(20) Masarwa, A.; Weber, M.; Sarpong, R. *J. Am. Chem. Soc.* **2015**, *137*, 6327–6334.
(21) Bates, R. G.; Paabo, M. MEASUREMENT OF PH. In *Handbook of Biochemistry and Molecular Biology*; CRC Press, 2010.
(22) Hare, S. R.; Tantillo, D. J. *Pure Appl. Chem.* **2017**, *89*, 679–698.
(23) Chai, J.-D.; Head-Gordon, M. *Phys. Chem. Chem. Phys.* **2008**, *10*, 6615–6620.
(24) Ditchfield, R.; Hehre, W. J.; Pople, J. A. *J. Chem. Phys.* **1971**, *54*, 724–728.
(25) Zhou, G.; Ting, P. C.; Aslanian, R. G. *Tetrahedron Lett.* **2010**, *51*, 939–941.
(26) Molawi, K.; Delpont, N.; Echavarren, A. M. *Angew. Chem. Int. Ed.* **2010**, *49*, 3517–3519.
(27) Müller, S. N.; Batra, R.; Senn, M.; Giese, B.; Kisel, M.; Shadyro, O. *J. Am. Chem. Soc.* **1997**, *119*, 2795–2803.

(28) Liu, L.-Z.; Han, J.-C.; Yue, G.-Z.; Li, C.-C.; Yang, Z. *J. Am. Chem. Soc.* **2010**, *132*, 13608–13609.
(29) Cory, R. M.; Renneboog, R. M. *J. Org. Chem.* **1984**, *49*, 3898–3904.

Chapter Contributions

The work described in this chapter would not have been possible without the contributions of Marcus Blümel, Shota Nagasawa, Stephanie Pitch, Dean Tantillo, and Richmond Sarpong. Marcus Blümel discovered the Prins/semipinacol rearrangement. Marcus Blümel, Shota Nagasawa, and I all worked to optimize and investigate the substrate scope of this reaction. Quantum chemical studies into the nature of the rearrangement were performed by Stephanie Hare and Dean Tantillo. I performed all experiments described in this chapter that were not related to our investigation of the Prins/semipinacol rearrangement sequence. Richmond Sarpong directed this research project.

Chapter 2.

Investigating Metacognitive Regulation in Student Approaches to Solving Organic Chemistry Problems

Abstract

Problem solving is a key component of authentic scientific research and practice in organic chemistry. One factor that has been shown to have a major role in successful problem solving in a variety of disciplines is metacognitive regulation, defined as the control of one's thought processes through the use of planning, monitoring, and evaluation strategies. Despite the growing interest in assessing and promoting metacognition in the field of chemical education, few studies have investigated this topic in the context of organic chemistry students. To gain a deeper understanding of how and why students make use of strategies related to metacognitive regulation when solving problems, we conducted two studies with Organic Chemistry I, Organic Chemistry II, and graduate organic chemistry students. In Study 1, 38 students participated in interviews in which they verbalized their thoughts as they worked on complex predict-the-product problems and then completed a self-report instrument indicating which behaviors associated with planning, monitoring, and evaluation they had engaged in while completing each problem. In Study 2, over 800 students completed a similar survey in which they reported how frequently they used these strategies while working on assignments for their organic chemistry courses. Students' strategy usage was compared to identify differences between students with different levels of experience and between more and less successful problem solvers. In both studies, we observed a positive relationship between metacognitive regulation and problem-solving performance or course performance. When asked during interviews why they did or did not use certain metacognitive strategies, students indicated a number of factors, such as not feeling able to use these strategies effectively or believing that using these strategies was unnecessary. The results of these two studies support the importance of teaching metacognitive problem-solving strategies in organic chemistry courses and suggest several methods for the assessment and instruction of metacognition.

Introduction

In teaching chemistry, our major goal is to help students develop their ability to engage in chemical thinking and to ask and answer questions related to authentic chemical practices.[1,2] A common criticism of traditional chemistry curricula is that they are typically "fact-based and encyclopedic" and focused on broad coverage of isolated topics rather than on "big ideas" and scientific practices.[1,3] Efforts to reform chemistry curricula have emphasized the importance of guiding students toward understanding and applying fundamental chemical concepts across a variety of situations and toward engaging in practices that are both central to the discipline and broadly useful for non-chemistry and chemistry majors alike.[3,4] An essential component of authentic scientific research and practice in organic chemistry is problem solving, defined by Schoenfeld[5] as "learning to grapple with new and unfamiliar tasks when the relevant solution methods (even if only partly mastered) are not known" and by Wheatley[6] as "what you do, when you do not know what to do." Much of the research in organic chemistry education has therefore focused on how students solve different types of problems and how problem-solving skills can be taught.[7]

The types of problems that are most commonly used to assess student knowledge in organic chemistry can be classified into three major categories, each of which correspond to authentic questions routinely encountered by practicing chemists.[8,9] These include predict-the-product problems that ask students to predict the outcome of a given chemical reaction, mechanism problems that require students to explain how a reaction occurred, and synthesis problems that ask students to design a series of reactions to generate a given molecule. Among these types of problems, predict-the-product problems are distinctive in that students are not provided with an endpoint to work towards. Studies have shown that when students attempt to solve mechanistic problems in which the final product is given, they typically focus on proposing steps that "get me [closer] to the product" by reducing the number of structural differences between the reactants and products.[10–12] Work by DeCocq and Bhattacharyya[13] demonstrated that knowing the overall product of a transformation led to a dramatic change in the reasoning strategies organic chemistry students used when asked to provide the intermediate product and curved arrows for a single elementary step of a multi-step mechanism. In the absence of information about the final product of the transformation, students primarily proposed intermediate products based on their knowledge of the chemical properties of the reactants. After students were provided with the final product, many changed their answers to structures that more closely resembled this product. It is clear from these studies that student reasoning is highly affected by the information given in the problem statement, and that students' approaches to problems in which the ultimate product is not known, such as predict-the-product problems, may more accurately reflect their ability to engage in chemical reasoning. For this reason, along with the relatively small number of studies investigating student reasoning on problems of this type and level of difficulty, recent work in our research group has centered on investigating student approaches to open-ended predict-the-product problems that are relatively complex and potentially ambiguous.[9]

Our previous research on student approaches to open-ended predict-the-product problems involved analyzing think-aloud interviews in order to categorize student approaches in terms of common problem-solving actions.[9] The results of this analysis were used to develop a general workflow model that describes the ways in which students with different levels of expertise in organic chemistry solve problems that rely on predicting reactivity. While completing this work, we became interested in examining additional strategies that students engage in while solving these types of problems as well as other problems they encounter in their organic chemistry courses, especially strategies that may differentiate between successful and unsuccessful problem solvers.

One of the factors that has been shown to have a significant impact on problem-solving across disciplines is a student's ability to engage in metacognition, defined as the knowledge and control of one's own thought processes.[5,14,15] There has been growing interest among chemical education researchers in assessing and promoting metacognition, yet few studies have focused on organic chemistry courses.[16] In a review of research conducted in the field of organic chemistry education, Graulich[7] suggested that one of the main areas of future progress in this domain should be fostering metacognitive and learning strategies. Developing ways to teach metacognition and scaffold the development of specific metacognitive problem-solving skills in this context is made easier by having an understanding of both how and why students use these strategies in their approach to solving organic chemistry problems. In the two studies described in this chapter, we therefore sought to examine students' use of metacognitive regulation strategies when solving organic chemistry problems. Study 1 builds upon our previous research on student approaches to complex predict-the-product problems by providing a more comprehensive, multi-method examination of students' use of metacognitive regulation strategies when solving problems of this type. Study 2 focuses more broadly on students' approaches to problems they encounter on assignments for their organic chemistry courses, providing a more general examination of how metacognitive regulation manifests in organic chemistry students.

Theoretical Framework

<u>Metacognition and Its Importance in Problem Solving</u>

Metacognition, commonly defined as "thinking about thinking," refers to the awareness and control of one's own cognitive processes.[14,17] This complex construct can be divided into two major components: metacognitive knowledge and metacognitive regulation.[17,18] Metacognitive knowledge refers to what a person knows about their own thinking processes, and includes declarative, procedural, and conditional knowledge. Declarative knowledge involves knowing about one's thought processes and the factors that influence one's learning, procedural knowledge relates to knowing how to use strategies and skills to accomplish tasks, and conditional knowledge involves knowing when and in what context it is appropriate to use different strategies. Metacognitive regulation refers to the strategies used to control one's thinking and learning and includes the skills of planning, monitoring, and evaluation. Planning typically takes place before beginning a task and can involve activating relevant background knowledge, setting goals, making predictions, selecting strategies to use, and allocating time and resources. Monitoring would occur during the process of completing the task; this would include checking one's understanding and determining whether one's chosen strategies are working. Evaluation would then involve reflecting upon and assessing the outcomes of a task as well as the processes used while completing that task. In our work, we focused on the regulatory component of metacognition, which is particularly vital for successful problem solving.

Metacognition has been shown to have a significant impact on problem-solving success in specific disciplines such as chemistry[15,19] and mathematics[20–22] as well as in general critical thinking tasks.[23,24] Schoenfeld,[21] for example, found that in the absence of metacognitive regulation, college students enrolled in his mathematical problem-solving course often continued down unproductive paths, despite having the requisite mathematical knowledge to solve the problem, because they did not pause to consider whether they were making progress in the right direction. This indicates that simply being familiar with the relevant concepts is not sufficient for solving genuine problems. Work by Swanson[23] suggests that a high level of metacognition could in fact compensate for lower aptitudes; using think-aloud interview techniques, he observed that children with higher levels of metacognition performed better on problem-solving tasks than those with lower metacognitive activity regardless of differences in general academic aptitude. This association between metacognitive ability and problem-solving skills underscores the importance of studying metacognition in disciplines where problem solving is a central practice.

Measuring Metacognition

Methods of assessing metacognition can be divided into two major categories: on-line measures and off-line measures.[25] On-line measures, also known as concurrent measures, are taken at the same time as a study participant is completing a task. Examples include think-aloud interviews, observations, eye-tracking, and logging of participants' actions while performing a task on a computer.[25] Off-line measures, which commonly take the form of self-report questionnaires or retrospective interviews, are administered asynchronously with task performance. Learners are asked to report on their likelihood of engaging in certain metacognitive behaviors or using particular metacognitive strategies, either in a specific context or in general. The decision regarding which type of measure to use depends on several factors, one of which is a researcher's belief about the theoretical nature of metacognition. One of the major assumptions underlying the use of different measures of metacognition is whether metacognition is conceptualized as a general aptitude or a specific event.[26] When metacognitive ability is seen as an aptitude or trait, it can be assumed that students' use of metacognitive strategies is stable across different situations and contexts. If metacognition is instead viewed as an event, it would be expected that students' metacognitive behavior would vary depending on the contextual features and demands of a task. Concurrent measures are bound to a specific task and would therefore correspond with the assumption that metacognition is an event.[26] Self-report measures, on the other hand, are more typically used when measuring metacognition as an aptitude. In general, self-report measures only weakly correlate with concurrent measures, which indicates that the choice of measurement may have a significant impact on the results of a study.[25,27] According to Desoete,[28] when it comes to measuring metacognition, there is evidence that "how you test is what you get" (p. 204). For this reason, one's choice of assessment should be carefully considered when measuring metacognition.

There are benefits and drawbacks to the various measures of metacognition. Concurrent assessments are generally considered to better align with actual behavior than off-line measures, likely because these measures require the learner to make judgments based on reconstructing their previous cognitive processes from memory.[25,29] The issue of distortion due to memory failure can be partially mitigated by administering self-report measures immediately after completing a task and asking students to consider their behavior in a specific situation.[30,31] While this does not resolve all of the issues with self-report questionnaires, including the inclination to give socially desirable responses, being asked to consider one's behavior in a specific situation can make it easier for participants to recall their actual behavior.[25] Task-specific questionnaires typically correlate more strongly with concurrent methods than general questionnaires; for example, Schellings et al.[32] observed a correlation of r=0.63 between think-aloud protocols and a task-specific questionnaire that was directly based on a taxonomy for coding those think-aloud protocols. The major drawback of concurrent assessments is that they tend to be much more time-consuming to administer and analyze, so it is not typically feasible to use them with large groups. Also, though thinking aloud is not considered to alter student behavior apart from increasing the time taken to complete a task, assessing metacognition in this way may lead to underestimations of metacognitive behavior.[30,31] This is because students may not be consciously aware of their self-regulatory processes, as these processes are often highly automated in adults.[29,33] To overcome the drawbacks associated with these individual measures of metacognition, many researchers have emphasized the advantage of using multiple methods to assess metacognition.[28,32,34,35]

Metacognition in Chemical Education

Metacognition has been studied extensively as a psychological construct since the 1970s, but it is primarily in the past two decades that interest has grown in studying metacognition in the context of chemical education.[16,36,37] Much of this work has centered on evaluating interventions designed to promote metacognitive behaviors in chemistry students. Interventions that involve explicitly teaching metacognitive learning strategies to students were found to result in improved course grades[38,39] and increases in student self-efficacy.[40] Other interventions made use of pre- or post-class activities such as online homework-based metacognitive training[41] or the use of question-embedded videos as a replacement for pre-class textbook readings.[42] These interventions both led to improvements in learning outcomes and metacognitive skillfulness as measured by calibration accuracy. Several interventions focused more closely on the connection between metacognition and successful problem solving. Macphail and coworkers[43] developed and evaluated a general chemistry recitation section that was designed to help students develop metacognitive and problem-solving skills through the process of analyzing, solving, and manipulating problems. Heidbrink and Weinrich[44] conducted think-aloud problem-solving interviews with biochemistry students and determined that implicitly targeting metacognition via reflective prompts led to increases in the number of students who exhibited metacognitive behaviors related to declarative knowledge, conditional knowledge, monitoring, and evaluating. Sandi-Urena, Cooper, and Stevens[45] found that a collaborative intervention involving problem-solving and reflective prompting resulted in an increase in metacognitive awareness and in the ability to solve difficult non-algorithmic chemistry problems in the treatment group as compared to the control group.

To evaluate interventions designed to promote metacognition and to investigate the nature of metacognition in chemistry problem solving, chemical education researchers need to assess students' metacognitive ability. Researchers have most commonly used self-report instruments, either alone or in combination with other methods, for this purpose. Examples of general metacognitive self-report instruments that have been applied to chemical education research include the Inventory of Metacognitive Self-Regulation[46,47] and the Metacognitive Awareness Inventory.[19,48] The Metacognitive Activities Inventory (MCAI),[49] developed by Cooper and Sandi-Urena, is an example of a domain-specific self-report instrument that was designed to measure metacognitive skillfulness in chemistry problem solving. Concurrent methods such as think-aloud interviews[44,47,50] and an automated online instrument known as Interactive MultiMedia Exercises or IMMEX[34] are among the other measures researchers have used to assess metacognition in chemistry students. Several of these studies made use of multiple measures.[34,47,50] In their investigation of metacognition use in general chemistry problem-solving, Cooper, Sandi-Urena, and Stevens[34] observed convergence between the scores students received on the MCAI (a self-report instrument) and the IMMEX (a concurrent measure). Wang[47] examined characteristics of students' metacognition in different general chemistry topics using data from self-report measures, think-aloud interviews, and students' judgments of their performance. Kadioglu-Akbulut and Uzuntiryaki-Kondakci[50] investigated the effectiveness of self-regulatory instruction in a high school chemistry classroom using the Cognitive and Metacognitive Strategies Scale (a self-report instrument), think-aloud protocols, and journal entries.

Despite the growing interest in the role of metacognition in chemistry education, few studies have focused on organic chemistry students. In a recent review of metacognition in higher education chemistry, 27 out of the 31 articles that met the inclusion criteria examined metacognition in students that were enrolled in introductory, general, or preparatory chemistry course.[16] Problems students encounter in organic chemistry courses differ from those encountered in general chemistry courses in that they are primarily non-mathematical and require a different set of fundamental skills.[51] According to Dye and Stanton,[52] many of the students they interviewed as part of their study on metacognition in upper-division biology students stated that organic chemistry was the first course in which they had to be metacognitive to succeed, likely due to their lack of experience with the type of problem solving required in organic chemistry courses. This suggests that investigating metacognition in organic chemistry students would be particularly valuable.

Several reports on metacognition in organic chemistry students have been published.[42,53–55] Lopez et al.[54] investigated the study strategies used by ethnically diverse organic chemistry students and found that students typically used strategies that involved reviewing course materials rather than more metacognitive study strategies and that there were no significant correlations between study strategies used and course performance. Mathabathe and Potgieter[55] examined organic chemistry students' use of metacognitive regulation during the collaborative planning of a laboratory group project. Graulich et al.[53] described the use of an instructional scaffold to promote metacognition while solving an organic chemistry case-comparison problem. Pulukuri and Abrams[42] compared metacognitive monitoring proficiency and learning gains between students who used different learning resources and found that students who learned organic chemistry concepts from question-embedded videos did better on both outcomes than those who learned from a textbook. Each of these studies suggests ways that metacognition can be observed in or encouraged in organic chemistry students.

Research Questions

The present research bridges the gap between two current areas of study in chemical education: problem solving in organic chemistry and metacognition. While many studies have explored student approaches to solving organic chemistry problems,[9,56–60] none have focused specifically on investigating students' self-reported or concurrent use of metacognitive strategies during the process of solving organic chemistry problems. The major aim of this work is to characterize the behaviors related to metacognitive regulation that students exhibit in two problem-solving contexts, one specific and one more general:

- Study 1: Relatively complex predict-the-product problems
- Study 2: Problems encountered on assignments for organic chemistry courses

As a part of Study 1, we also sought to determine the reasons why students use certain metacognitive strategies because, while there are some reports on why students use metacognitive strategies in the context of reading comprehension,[61,62] there are none related to problem solving. Without an understanding of why students choose to use or not use metacognitive strategies, one cannot design effective instruction that will persuade students to adopt these strategies.

Understanding which metacognitive strategies students with different levels of expertise use when working on organic chemistry problems, how the use of these strategies connects to successful problem solving, and why students choose to engage in these behaviors would provide a useful starting point for instructors to design interventions that teach these strategies to students. In this investigation, we were therefore guided by the following five research questions:

1. What metacognitive strategies do undergraduate and graduate students use when solving organic chemistry predict-the-product problems? **(Study 1)**
2. How do students who are more and less successful at solving organic chemistry predict-the-product problems differ in their use of metacognitive regulatory strategies? **(Study 1)**
3. What reasons do students have for using or not using metacognitive strategies while solving organic chemistry problems? **(Study 1)**
4. What metacognitive strategies do undergraduate and graduate students use when solving problems on assignments for their organic chemistry courses? **(Study 2)**
5. How does students' self-reported usage of metacognitive strategies connect to their performance in their organic chemistry courses? **(Study 2)**

Study 1: Methods

Participants and Context

All work associated with Study 1 was conducted at the University of California, Berkeley, a large, research-intensive public institution located in the Western United States, during the 2020-2021 academic year. This study was approved by the university's Institutional Review Board (IRB), Protocol #2015-08-7858, and informed consent was obtained from all participants. Interviews were conducted with undergraduate and graduate students who were enrolled in organic chemistry courses or were conducting research related to organic chemistry. Undergraduate interview participants were recruited from two courses, Chem 3A (Organic Chemistry I) and Chem 3B (Organic Chemistry II), both of which are intended for students who are not majoring in chemistry, chemical biology, or chemical engineering. Recruitment announcements were posted on the learning management systems for these courses at the end of the Fall 2020 semester. Graduate students were recruited at the end of the Spring 2021 semester via an email sent to all students enrolled in the synthetic or chemical biology divisions of UC Berkeley's chemistry Ph.D. program. Students were entered into a gift card drawing as a reward for their participation. In total, 10 Organic Chemistry I students, 16 Organic Chemistry II students, and 12 graduate students participated in Study 1. A summary of information about the interview participants' educational and demographic background is included in Table 2.1. All participants were asked questions about their year in their program and their undergraduate major or graduate research topic during the interview, and most of the undergraduate and all of the graduate student participants also completed a survey that contained questions about demographic information prior to the interview.

Table 2.1. Summary of Information Related to Interview Participants' Demographic and Educational Background

Type of Information	Undergraduate Participants (N=26)	Graduate Participants (N=12)
Gender	Women (65%) Men (19%) Non-Binary or Unsure (4%) Did Not Answer (15%)	Men (66%) Women (25%) Non-Binary or Unsure (8%)
Race/Ethnicity	East Asian (50%) South Asian (15%) African American/Black (8%) Mexican American/Chicano (8%) White/Caucasian (8%) Did Not Answer (20%)	White/Caucasian (75%) American Indian/Alaska Native (8%) East Asian (8%) Mexican American/Chicano (8%) Middle Eastern/North African (8%) South Asian (8%)
Year in Undergraduate or Graduate Program	First Year (12%) Second Year (85%) Third Year (4%)	First Year (25%) Second Year (17%) Third Year (8%) Fourth Year (42%) Fifth Year (8%)
Undergraduate Major or Graduate Research Focus	Life Science (77%) Engineering (15%) Public Health (8%) Social Science (4%)	Organic Chemistry (100%) Biological Chemistry (58%) Analytical Chemistry (16%) Inorganic Chemistry (16%) Materials Chemistry (8%)

It is important to note that the undergraduate students who volunteered to participate in interviews are not a fully representative sample of those enrolled in Organic Chemistry I or II. Overall, the interview participants received final percentage grades in the course that were 0.5 standard deviations above the class average, and less than 20% received a grade lower than the class mean. However, as shown in Figure 2.1, the interviewees did differ widely in their performance in the course, ranging from over one standard deviation below the class average to over one standard deviation above the class average.

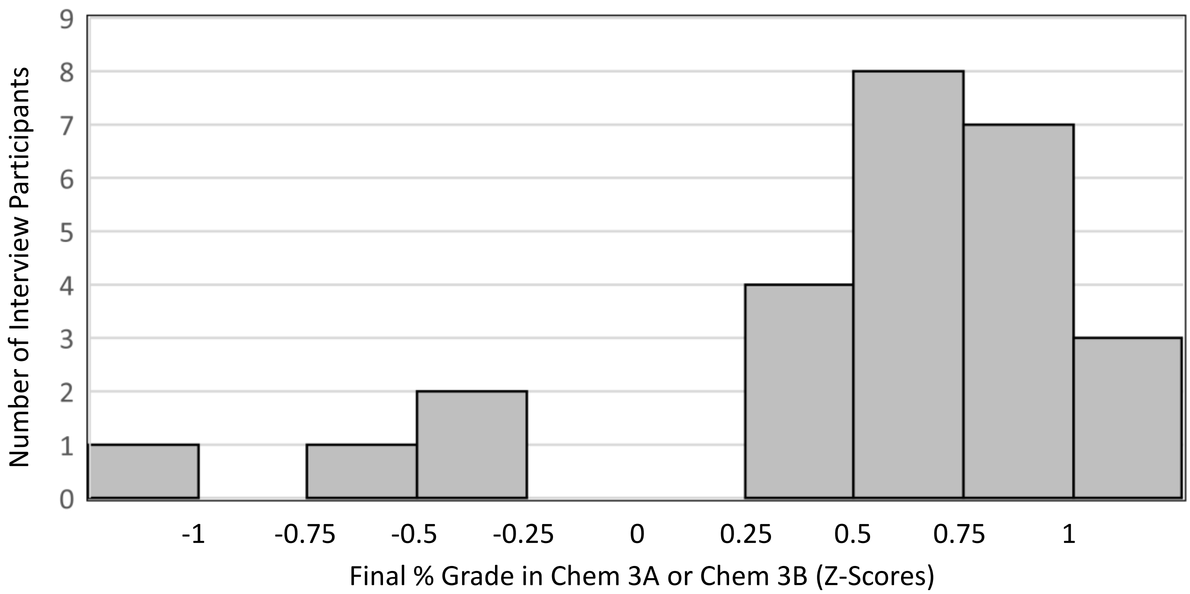


Figure 2.1. Distribution of final percentage grades among undergraduate interview participants in the organic course they were enrolled in at the time of the interview. Raw percentage scores were converted to z-scores in order to present data combined from the different courses.

Development of List of Metacognitive Strategies Used in Interview Coding Scheme and Self-Report Instrument

An initial list of 37 metacognitive skills that we believed would help students succeed in solving organic chemistry problems was developed in consultation with chemistry and education faculty members and graduate students. This list consisted of items drawn from the Cooper and Sandi-Urena's Metacognitive Activities Inventory (MCAI)[49] and Schraw and Dennison's Metacognitive Awareness Inventory (MAI),[48] some of which were modified to better suit the context of problem-solving in organic chemistry, as well as additional metacognitive behaviors that we had observed students engaging in during think-aloud interviews as part of our previous study into student approaches toward open-ended predict-the-product problems.[9] When deciding what to include in this initial list, we prioritized behaviors that we believed would be useful for students when solving organic chemistry problems and that were related to the planning, monitoring, and evaluation skills that comprise the construct of metacognitive regulation.

This initial list of metacognitive activities was introduced to seven students who had previously taken one or more organic chemistry courses and had volunteered to participate in focus groups. During these focus groups, students completed a survey that asked how often they engaged in each activity while working on organic chemistry problems. They were then asked to provide feedback on the clarity of the questions and instructions. The wording of some items was changed in response to this round of feedback, while other items were removed from the list entirely. The final list (see Table 2.2) was narrowed down to nine strategies that students might use during the planning phase before attempting a solution, five monitoring strategies that students might use during the problem-solving process, and six strategies that students could use to evaluate the products and process of their approach after reaching a solution.

Table 2.2. Final List of 20 Strategies Included in the Interview Coding Scheme and Self-Report Instrument.

Type of Strategy	Individual Item on Self-Report Instrument/Coding Scheme	Abbreviation
Planning	I set goals (ex. "I need to make this bond," or "I want to make this functional group") before attempting a solution.	Set Goals
	Before I started working, I sorted through the information in the problem to determine what is relevant.[a]	Sort Relevant Info
	Before I started working, I looked for any reactions I recognized.	Look for Reactions Recognized
	I reflected upon things I know that are relevant to the problem before I started working.[a]	Reflect Relevant Knowledge
	I tried to relate unfamiliar problems with previous problems I've encountered.[a]	Relate to Previous Problems
	I jotted down my ideas or things I know that are related to the problem before attempting a solution.[a]	Jot Down Ideas
	I made predictions about what would happen before I started working on the problem.	Make Predictions
	I brainstormed multiple ways to solve a problem before I actually started solving it.[b]	Brainstorm Multiple Ways
	I considered whether my proposed steps were reasonable before I actually started solving the problem.[a]	Consider If Plan Reasonable
Monitoring	When I was in the middle of working on the problem, I paused to consider whether there was another way to solve it.[b]	Consider Another Way
	While I was working on the problem, I paused to consider whether I was making progress toward my goals.[b]	Monitor Progress Toward Goals
	I paused to consider whether what I was doing was correct while I was working on the problem.[b]	Monitor Correctness
	I took note of what I was uncertain about as I worked on the problem.	Note Uncertainty
	As I worked on the problem, I periodically checked back over what I had done so far to make sure my overall approach was reasonable.	Periodically Check If Reasonable
Evaluation	I thought about whether my answer was reasonable after I finished the problem.[a]	Consider If Answer Reasonable
	I made sure that my solution actually answered the question.[a]	Check If Answered Question
	I checked back over my work after I finished the problem to make sure I didn't make any mistakes.[a]	Check For Mistakes
	Once I reached an answer, I checked to see that it agreed with what I predicted.[a]	Check If Agreed With Prediction
	Once I finished the problem, I summarized the main take-away lesson I learned.[b]	Summarize Main Takeaways
	After I finished the problem, I considered how I might change my approach for future problems.	Consider Changes For Future

[a] Duplicated or modified from an existing item on the MCAI.[49]
[b] Duplicated or modified from an existing item on the MAI.[48]

We believed that this list could function as a measure of students' use of metacognitive regulation strategies in the context of both a self-report instrument and a coding scheme for use with interview transcripts. To ensure this dual functionality, we also conducted pilot interviews with five Organic Chemistry I or Organic Chemistry II students during the semester before the main data collection took place. These pilot interviews followed the same protocol described in the "interview protocol" section of this work. Transcripts of the think-aloud problem-solving portion of these pilot interviews, as well as similar interviews that one of the authors had conducted with students enrolled in different organic chemistry courses, were analyzed to determine whether student usage of each skill was evident or not evident in order to confirm that these behaviors could be detected in students' verbalizations of their thinking processes.

Interview Protocol

Each undergraduate or graduate student volunteer participated in an individual interview, which typically lasted about an hour. Copies of the interview protocol and the surveys students completed during the interview are provided in Appendices 2.1 and 2.2. Because this study was conducted during the COVID-19 pandemic, all interviews took place over the Zoom video conferencing platform. Interviews were audio and video recorded for later viewing and transcription.

A summary of the interview protocol is provided in Figure 2.2. At the beginning of the interview, a PDF file containing the problems used in the interview was emailed to each participant. Participants were then asked a brief series of questions about their educational background and prior experience with organic chemistry. After they answered these introductory questions, students were given guidelines for how they should use the think-aloud technique to verbalize their thoughts while solving a problem. They were then asked to solve an organic chemistry problem while vocalizing their thought processes. The same instructions were given for all problems: "Predict the major organic product(s) of the following reactions. Please indicate stereochemistry where appropriate." Participants were asked to either use the screenshare feature while annotating the PDF file or, if they preferred to write on paper, angle their camera toward that sheet of paper. Students worked on the problem without interruptions, except for occasional prompts to speak up or brief feedback on their think-aloud technique, until they indicated that they had reached their final answer. Students were then provided with a link to a survey hosted on Qualtrics, where they were asked to indicate whether they had used in each of the 20 metacognitive strategies introduced in Table 2.2 while solving the first interview problem. For each item, students were able to select "yes" or "no." Students were then asked several questions about their problem-solving approach, including questions about their reasons for carrying out certain metacognitive activities either on the problem they had just worked on during the interview or in their organic chemistry course in general. Following this discussion, students were asked to complete a second problem, which had identical instructions, while thinking aloud. They were then prompted to fill out a second survey to indicate whether they had used each strategy while working on that problem.

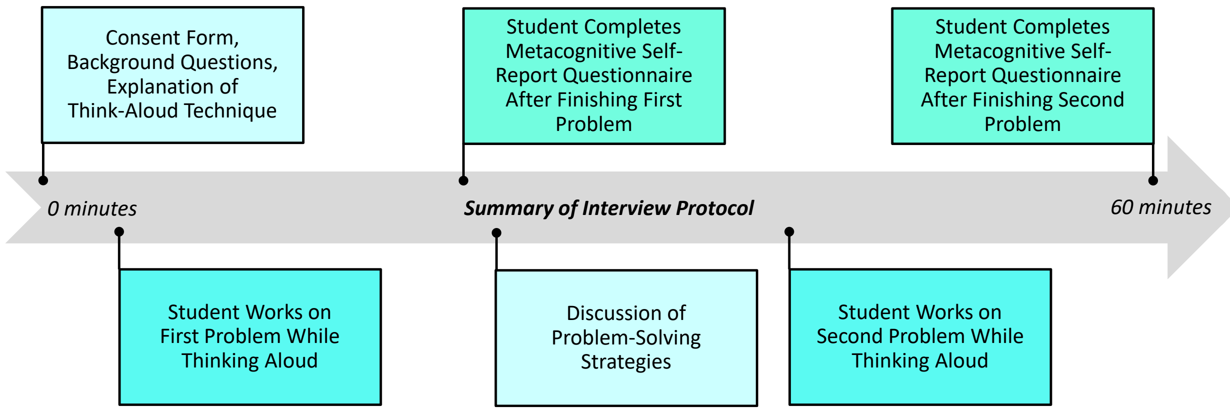


Figure 2.2. Summary of interview protocol, including typical one-hour timeline.

We chose to use both concurrent and self-report measures in order to get a more complete understanding of students' usage of strategies related to metacognitive regulation when solving organic chemistry problems. The think-aloud interview method was chosen because it allows for an in-depth analysis of students' problem-solving processes, and concurrent measures of metacognition are considered to better align with actual behavior as compared to off-line methods.[29] However, data collected using think-aloud protocols may not be complete if interview participants do not or cannot verbalize all of their thoughts.[31] For this reason, we chose to additionally ask students about their behavior using a retrospective, task-specific self-report questionnaire. We chose to administer this questionnaire immediately after students had finished solving each problem in order to minimize memory distortions.

Problem Design

The problems students completed during the think-aloud portion of the interview, along with the accepted answers for each problem, are shown in Figure 2.3. Mechanistic drawings showing the formation of these products are provided in Appendix 2.5. Each of these problems was previously used when conducting think-aloud interviews with a different population of undergraduate and graduate organic chemistry students at this institution as a part of our ongoing research into student approaches to open-ended predict-the-product problems.[9,63] In the present study, Problems A and B were completed by undergraduates enrolled in Organic Chemistry I, while Problems C and D were completed by undergraduates enrolled in Organic Chemistry II as well as graduate students. The order in which each participant completed the problems was randomized. Several possible reactions could occur in Problem A, including an acid-catalyzed hydration of the alkene or epoxide or an intramolecular cyclization involving both functional groups. Problem B is an E2 reaction followed by an addition of methanol to the resulting alkene under acidic conditions. This addition of methanol includes a carbocation rearrangement. The reactants in Problem C could undergo either a Mannich reaction or an amine-catalyzed intramolecular aldol reaction. The first step of Problem D involves hydrolysis of the acetal to generate an aldehyde, which then reacts with a Horner-Wadsworth-Emmons (HWE) reagent in the second step. The product of the HWE reaction could then potentially cyclize to form a six-membered ring via an intramolecular oxa-Michael addition.

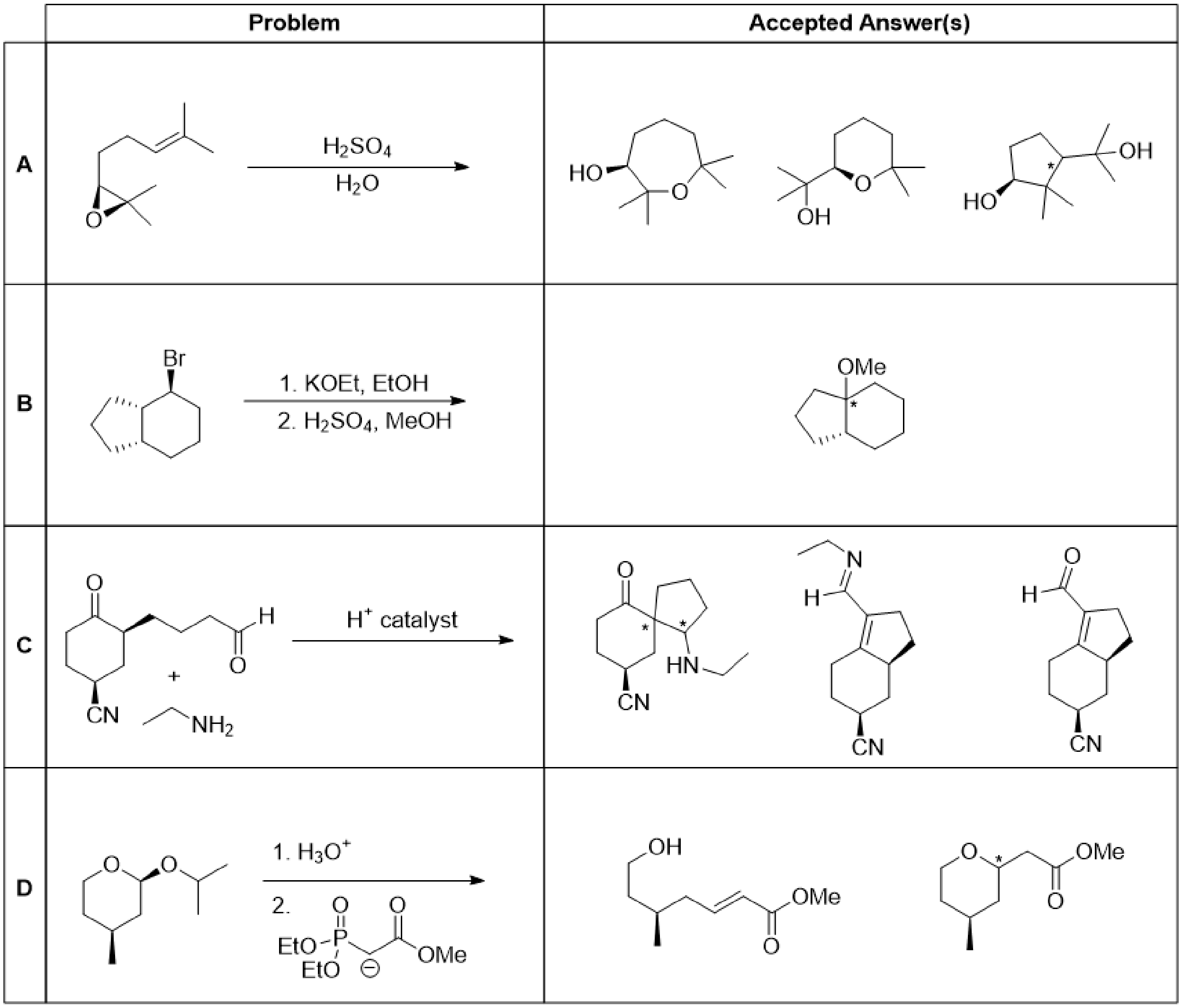


Figure 2.3. Organic chemistry problems that students completed during think-aloud interviews. Problems A and B were completed by Organic Chemistry I students, while problems C and D were completed by Organic Chemistry II students and graduate students.

We believed that, for the majority of interview participants, these problems would function as novel problems as opposed to routine exercises.[64] Whether any given chemistry question functions as a problem or an exercise depends on how familiar the person solving the task is with the material rather than on the innate difficulty of the task. For example, a stoichiometry problem that would serve as a routine exercise for a practicing chemist would be a novel problem for a student enrolled in their first chemistry course. The practicing chemist would likely complete the task in a logical, linear fashion based on recalled algorithms, while the student may take a more circuitous approach involving false starts and dead ends. The ambiguity and open-endedness of the chosen problems presented an opportunity for us to investigate how students approach less familiar problems where simple recall of information is not enough, and made it more likely that students would display the use of metacognitive behaviors during the process of solving these problems.[65] Prior studies suggest that concurrent assessment of metacognitive regulation should be conducted using tasks that are of a level of complexity that would require the interview participants to intentionally control their thinking processes.[66] Multiple sources of ambiguity were included in the design of these problems, including polyfunctional starting materials, an absence of detailed reaction conditions (e.g. temperature, equivalents), and the possibility of multiple potential products or completing solution pathways. Pilot interviews conducted with Organic Chemistry I and Organic Chemistry II students during the semester prior to the main study confirmed that students were generally interpreting the problems as expected and were able to at least generate some reasonable ideas about each problem despite their potential difficulty.

Data Analysis

Students' answers to the interview problems were evaluated for correctness, with partial credit given for partially correct answers or pathways. Rubrics used to score each question are provided in Appendix 2.5. Average scores received on each problem were calculated for the Organic Chemistry I, Organic Chemistry II, and graduate students, and are reported as percentages, e.g. a score of 3 points on an individual problem scored out of 4 points would correspond to a percent score of 75%.

Interviews were fully transcribed, and the transcripts were annotated to indicate what students were writing as they spoke aloud. These transcripts were then coded by several members of the research team using MaxQDA qualitative data analysis software. Two different coding schemes were developed, one for analysis of the think-aloud portion of the interview and the other for analysis of the discussion portion. Definitions and examples of all codes are provided in Appendices 2.3 and 2.4. The first scheme includes codes that correspond to each of the 20 metacognitive strategies included in Table 2.2. These codes were assigned to each think-aloud problem transcript according to whether a student's usage of each skill was evident or not evident in the transcript. Definitions and criteria for the inclusion or exclusion of certain statements under each code were developed following extensive discussion between members of the research team, which included undergraduates who were currently enrolled in organic chemistry courses. The second scheme was developed to categorize the most common reasons that students gave for using or not using the metacognitive strategies described in Table 2.2. Codes and their definitions were developed inductively using a constant comparative method that consisted of reading the transcripts, noting down emerging themes and potential codes, and meeting to discuss agreements and disagreements between members of the research team. Saturation was reached with a set of 16 codes: nine corresponding to reasons students reported using the metacognitive skills, and seven corresponding to reasons for not using these skills (Table 2.3).

After coding approximately 10% of the transcripts as a group, each remaining think-aloud or discussion transcript was coded independently by at least two members of the research team. The average interrater agreements between pairs of researchers for metacognitive skills observed during the think-aloud interview and for reasons for using or not using metacognitive strategies mentioned during the discussion portion of the interview were κ=0.83 and κ=0.80, respectively. All members of the research team met periodically to compare notes on the coding process and resolve any discrepancies in coding.

Table 2.3. List of Codes Developed to Classify Reasons Students Gave for Using or Not Using Metacognitive Strategies.

Code	Description
Reasons for Using Strategies: The student uses this strategy because...	
Builds confidence	It helps them feel more confident in their answer or thought process.
Many reactions to consider	They recognize that a wide variety of reactions or types of reactivity exist and could possibly be relevant to the problem.
Helps them learn/ improve	It helps them learn or improve their knowledge or problem-solving skills.
Avoid wasting time/effort	It helps them avoid wasting time or effort during the problem-solving process.
Get started/narrow focus	It helps them get started on the problem or narrow their focus to certain pathways.
Keeps them on right track	It helps them stay on the right path and continue making progress toward an answer.
Keeps them from forgetting	It helps prevent them from forgetting an idea or piece of information.
Someone encouraged use	Another person, such as an instructor or tutor, encouraged them to use this skill.
Helps avoid mistakes	It helps them avoid making mistakes.
Reasons for Not Using Strategies: The student does not use this strategy because...	
Prevents success: distracting	It distracts them and they therefore consider it to be detrimental to their success in solving the problem.
Prevents success: other	They consider it to be detrimental to their success in solving the problem for another reason, or they state that it is detrimental without stating a specific reason.
Issues with timing	There is not typically enough time for them to use it.
Unable to use effectively	They believe they are unable to use the skill effectively, often because they do not feel experienced enough to do so.
Unnecessary: have answer	They consider it to be unnecessary when they have already found an answer to the problem.
Unnecessary: redundant	They consider it to be unnecessary because they either use a different strategy for the same purpose or use a similar strategy at a different time in the problem.
Unnecessary: other	They consider it to be unnecessary for another reason, or they state that it is unnecessary without stating a specific reason.

After coding was complete, the average number of strategies students were observed using and the number of strategies that they self-reported using on at least one of the interview problems was calculated for Organic Chemistry I students, Organic Chemistry II students, and graduate students. The number of strategies students were observed using was determined using the coding scheme, while the number of strategies they self-reported using was determined using the surveys students took after completing each problem. The average percent agreement between observed and self-reported use of metacognitive skills was then calculated for each of these groups. A percent agreement of zero would indicate that there was no overlap between the strategies that a student self-reported using and the strategies that they were observed using on a specific problem. Percentages of students who self-reported or were observed using a strategy on at least one of the interview problems were also calculated for each of these groups. The average number of strategies students self-reported or were observed using was also calculated for students who received a performance score of less than or equal to 60% on the interview problems and those who scored greater than 60% on the interview problems. T-tests were used to compare self-reported and observed strategy usage between these groups of higher and lower-performing students. IBM SPSS 27.0 was used for all statistical analysis. The number of times that students gave a certain reason for using or not using one of the 20 metacognitive strategies during the discussion portion of the interview was also determined.

Study 1: Results and Discussion

Research Question 1: What metacognitive strategies do undergraduate and graduate students use when solving organic chemistry predict-the-product problems?

In our analysis, we were interested in determining which out of the list of twenty metacognitive strategies were used most and least frequently by students, and whether this varied between students with different levels of experience. Percentages of students who self-reported using or were observed using each of the listed metacognitive strategies are displayed in Table 2.4. Before commenting on discrepancies between these two measures of metacognition, we will discuss instances where these two measures were generally in agreement.

Some strategies were used by nearly every student, others were rarely used by any student, and others were used more often by more or less experienced students. Among undergraduates in either organic chemistry course and graduate students, more than 90% reported and were observed sorting through the problem statement to determine what was relevant, reflecting upon prior knowledge they had that was relevant to the problem at hand, and monitoring whether what they were doing was correct as they worked on the problem. On the other hand, fewer than 50% of students reported or were observed jotting down their ideas prior to starting the problem, summarizing the main takeaway lessons learned after finishing the problem, or considering ways they might change their approach for future problems. It may be that students view the initial planning strategies such as sorting through the problem statement or reflecting upon their prior knowledge as necessary for determining how to solve the problem at hand, while evaluation strategies related to learning from the experience of doing problems, such as summarizing main takeaway lessons or considering how they might change their approach for the future, are primarily useful for improving one's performance on future problems.

Strategies with differences in usage between groups of students included making predictions and setting goals before beginning the problem, which were both performed more often by graduate students according to both measures. Both of these strategies require a student to think multiple steps ahead before beginning to work on the problem, which is likely more difficult for the undergraduate students, who had less experience with solving organic chemistry problems. Organic Chemistry I students, who had the least experience with organic chemistry, were more likely than other students to take note of what they were uncertain about when solving the problem; 100% of these participants exhibited this behavior according to both self-report surveys and observations.

Table 2.4. Percent of Interview Participants Who Used Listed Strategies While Solving At Least One Interview Problem, Grouped by Course. Increased Color Saturation Indicates a Larger Percentage.

Strategy	Percent Self-Reporting Use of Strategy			Percent Observed Using Strategy		
	Organic I (*N*=10)	Organic II (*N*=16)	Graduates (*N*=12)	Organic I (*N*=10)	Organic II (*N*=16)	Graduates (*N*=12)
Set Goals	80	69	92	10	13	33
Sort Relevant Info	90	94	100	100	100	100
Look for Reactions Recognized	100	94	100	60	31	75
Reflect Relevant Knowledge	100	100	100	100	94	100
Relate to Previous Problems	80	100	92	10	6	0
Jot Down Ideas	50	38	33	40	31	25
Make Predictions	70	63	100	60	50	83
Brainstorm Multiple Ways	60	38	50	60	69	75
Consider If Plan Reasonable	90	94	67	40	19	42
Consider Another Way	100	88	92	80	69	83
Monitor Progress Toward Goals	100	75	75	10	13	8
Monitor Correctness	100	94	100	90	94	100
Note Uncertainty	100	75	83	100	81	67
Periodically Check If Reasonable	90	69	75	40	50	33
Consider If Answer Reasonable	90	100	100	50	88	100
Check If Answered Question	100	88	100	10	31	17
Check For Mistakes	60	69	67	10	63	33
Check If Agreed With Prediction	80	44	75	0	6	0
Summarize Main Takeaways	40	19	25	0	0	8
Consider Changes For Future	50	31	33	0	0	0

Though some strategies were used approximately equally often according to both self-report and concurrent measures, there was in general a large discrepancy between the two measures. Table 2.5 summarizes the average number of strategies that Organic Chemistry I, Organic Chemistry II, and graduate students used during the interview according to both measures. On average, the number of strategies students reported using while solving either one of the interview problems was 66% greater than the number of strategies that they were observed using according to coding of their think-aloud interview transcripts. The average percent agreement between self-reported and observed usage of metacognitive regulatory strategies, which takes into account agreement between the two measures for each individual strategy, was 57%. There are several possible reasons for the observed discrepancies between the two measures of metacognitive behavior. Students may have reported using a greater number of strategies than they actually used due to social desirability bias, which is the tendency of survey or interview respondents to give answers that they believe will be viewed favorably by others.[67] Students' interpretation of the strategies described by the self-report items also may have differed from the definitions used by the researchers when coding the think-aloud protocols. Students were not asked to explain how they interpreted the items on the self-report measure used in this study, but studies on the response process validity of metacognitive self-report items in high school students have shown that some students find some items confusing or ambiguous, especially items related to planning skills[68] or items with more abstract terms or phrases such as "concepts," "drawing conclusions," or "finding information."[69] It is also possible that some of the students' thought processes were not included in their verbalizations. This is more likely when processes are highly automated or when a task is particularly difficult or requires a lot of effort.[30,70] When working on more difficult tasks, like the problems students were asked to solve in this study, learners are more likely to occasionally fall silent instead of continuously verbalizing their thoughts.[30] These occasional silences were observed in most of the interviews we conducted, despite urging students to continue verbalizing their thoughts. Students' use of metacognitive strategies may be overestimated by their responses to the self-report survey and underestimated by coding of their verbalized thought processes, which means that the true number of strategies they made use of while solving the interview problems is likely somewhere between the two values.

Table 2.5. Comparison of Strategies (Mean ± SD) Students Self-Reported Using or Were Observed Using While Solving At Least One Interview Problem, Grouped by Course

Group of Students	*N*	# Strategies Used During Interview		Self-Reported vs. Observed % Agreement
		Self-Reported	Observed	
Organic I	10	16.3 ± 1.5	8.7 ± 2.4	53.8 ± 14.3
Organic II	16	14.4 ± 2.9	9.1 ± 1.9	56.1 ± 9.7
Graduates	12	15.6 ± 1.4	9.8 ± 2.3	59.8 ± 6.7
All Students	38	15.3 ± 2.3	9.2 ± 2.2	56.7 ± 10.4

There were particularly low levels of agreement between the two measures for several of the individual metacognitive strategies. In each of these cases, many more students self-reported using these strategies than were observed using these strategies. For instance, the percentage of students who stated that, during the think-aloud portion of the interview, they had tried to relate an unfamiliar problem to previous problems they had encountered ranged from 80-100% depending on the course, but usage of this strategy was only detected in 0-10% of interview transcripts. This could be because students were more likely to verbalize that they were trying to relate a problem to previous problems they had encountered if they did in fact recall some similarity to a problem they had seen before. The use of the strategy itself may be less conscious, and it is only when using this strategy leads the student to notice something useful or unexpected that it surfaces in students' verbalizations. Veenman et al.[29] noted that "many evaluation and self-monitoring processes run in the 'background' of the cognitive processes that are being executed. Only after an error is detected, rightfully or not, the system becomes alerted" (p. 6). This could also explain the large differences that were seen with the "check if answered question" (self-reported: 88-100%, observed: 10-31%), "check if agreed with prediction" (self-reported: 44-80%, observed: 0-6%), and "monitor progress toward goals" (self-reported: 75-100%, observed: 8-13%) strategies. Students may be more likely to verbalize thoughts related to these strategies if, in using these strategies, they notice a problem with their answer or their progress. If certain strategies were more difficult to discern from the think-aloud protocols than other strategies, this supports the importance of using multiple methods to determine which strategies students use during the problem-solving process.

Research Question 2: How do students who are more and less successful at solving organic chemistry predict-the-product problems differ in their use of metacognitive regulatory strategies?

We hypothesized that students who scored higher on an interview problem would tend to engage in more metacognitive behaviors during the process of solving that problem, as measured by the number of strategies they self-reported or were observed using. In order to test this hypothesis, we first had to evaluate the correctness of students' responses to each interview problem. Students' average scores on these problems are shown in Table 2.6. Within each group of students, there were no significant differences when comparing performance on Problem A with Problem B, Problem C with Problem D, or the first problem students completed with the second problem they completed. This demonstrates that the two problems each student completed were of similar difficulty and that the randomized order in which students completed the problems did not affect their performance. For this reason, rather than forming comparison groups for each individual problem, we chose to look at more and less successful solutions across all 76 problems solved by the 38 participants.

Table 2.6. Performance Scores (% of Possible Points) on Think-Aloud Problems, Grouped by Course

Group of Students	*N*	Performance Score on Problems: Mean (SD)					
		First Problem	Second Problem	Problem A	Problem B	Problem C	Problem D
Organic I	10	50.0 (25.0)	37.5 (16.7)	46.3 (21.3)	41.3 (22.9)	-	-
Organic II	16	46.1 (20.3)	49.2 (23.9)	-	-	46.9 (21.2)	48.4 (23.2)
Graduates	12	81.3 (22.3)	78.1 (29.3)	-	-	78.1 (20.7)	81.3 (30.4)

Due to the difficulty of the problems, only 12 solutions were fully correct, and most of these solutions were generated by graduate students. Therefore, we chose to consider any solution that received a score greater than 60% to be "more successful," which corresponded to 20%, 25%, and 83% of the solutions generated by Organic Chemistry I, Organic Chemistry II, and graduate students, respectively. The number of metacognitive strategies students used in the process of generating more and less successful solutions is displayed in Figure 2.4. When comparing all interview participants, those who generated more successful solutions self-reported using a significantly greater number of strategies related to metacognitive regulation than those who were less successful ($p = 0.003$, Cohen's $d = 0.67$). Because the distribution of solutions that were considered more successful heavily favored graduate students, we also made comparisons that only considered undergraduate participants. Similar results were observed; undergraduates whose solutions were considered more successful self-reported using more metacognitive strategies while solving these problems ($p = 0.015$, Cohen's $d = 0.83$). Among undergraduate participants and participants as whole, observed strategy usage trended in the same direction, but these differences were only approaching statistical significance ($p = 0.053$ and $p = 0.067$, respectively).

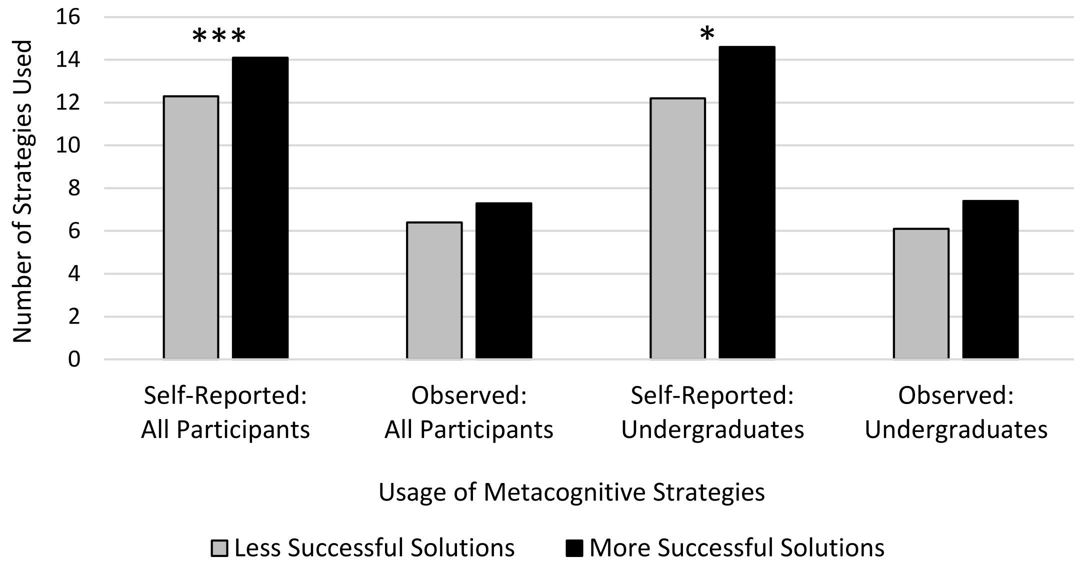


Figure 2.4. Metacognitive strategies used by participants during the process of generating more and less successful solutions (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.005$). More successful solutions were defined as those receiving scores greater than 60%.

The finding that students who generated more successful solutions to organic chemistry problem-solving tasks also reported using a significantly greater number of strategies related to metacognitive regulation is consistent with our hypotheses as well as with previously published research conducted with general chemistry students. In their study involving students enrolled in a general chemistry laboratory course, Cooper, Sandi-Urena, and Stevens[34] found that students with a higher level of metacognition usage according to their scores on a concurrent measure scored significantly higher on a metacognitive self-report instrument and also showed a significantly higher ability to solve ill-defined problems. Wang[47] observed significant positive correlations between students' performance on problem-solving tasks related to thermodynamics and molecular polarity and their metacognitive regulation according to both a self-report questionnaire and analysis of think-aloud interview transcripts. This connection between metacognitive regulation and performance on problem-solving tasks across multiple disciplines of chemistry reinforces the importance of assessing and promoting metacognitive strategy use in chemistry courses.

<u>Metacognition and Success: Individual Problem-Solving Cases</u>

Thus far, we have presented aggregate data on the relationship between use of metacognitive regulatory strategies and task performance. To illustrate how metacognitive regulation can be connected to task performance in a more descriptive, qualitative manner, we have selected four individual problem-solving cases that serve as examples of more and less successful solutions for problems A-D generated by students who exhibited a larger or smaller number of metacognitive behaviors during the process of solving these problems. A summary of these four cases is provided in Table 2.7, and a chart that shows which strategies each student self-reported and was observed using is included in Appendix 2.6.

Table 2.7. Summary of Four Students' Scores on Selected Interview Problems and their Use of Metacognitive Strategies During the Problem-Solving Process

Student Pseudonym	Problem Solved	Performance Score on Problem (% of Possible Points)	# of Strategies Used While Solving Problem	
			Self-Reported	Observed
Andrew	A	38	10	4
Lily	B	50	18	11
Ben	C	75	14	4
Marta	D	100	15	10

Less Successful Solution, Fewer Metacognitive Strategies Used:

Andrew received a relatively low score (38%) on Problem A and also exhibited fewer metacognitive behaviors than average according to both self-reported and concurrent measures. Andrew began the problem by reading the directions aloud. He then stated that the first thing he was looking for was the reactive site, and he noted that there was an alkene and an epoxide present in the starting material (*Code: Sort Relevant Info*). He predicted that the epoxide "is what would be breaking in this example" (*Code: Make Predictions*). He identified that the "H_2SO_4" present in the reaction conditions was an acid, which would protonate the epoxide and cause the epoxide to break apart to form a tertiary carbocation at the more substituted position of the epoxide *(Code: Reflect Relevant Knowledge)*. He then stated that a water molecule would attack this carbocation, and that he was "pretty sure this is anti addition." After drawing his final products (shown in Figure 2.5), he looked back over what he had done to "make sure the stoichiometry and the equation is balanced" *(Code: Check for Mistakes)*. In addition to the behaviors that were observed in his transcript according to the coding scheme, Andrew also reported that he had set goals, looked for reactions he recognized, related the problem to a previous problem he'd encountered, considered if his proposed steps were reasonable, considered if his answer was reasonable, checked if he'd answered the question, and checked if his answer agreed with his prediction. Andrew's final answer was partially correct in that he performed the hydration of the epoxide with the correct regioselectivity. However, he did not propose any reaction involving the alkene, and he drew an additional unreasonable stereoisomeric product.

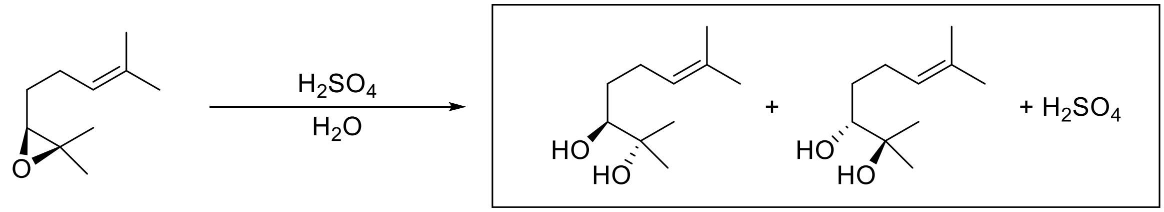


Figure 2.5. Final products proposed by Andrew for Problem A.

Less Successful Solution, More Metacognitive Strategies Used:

Lily received a score of 50% on her response to Problem B, which was categorized as "less successful," but she was above-average in terms of the number of metacognitive strategies she reported and was observed using while solving this problem. Lily started by reading the directions aloud and stating that she noticed there was a bromide present in the starting material, which she predicted would act as a leaving group at some point during the reaction (*Codes: Sort Relevant*

Info, Make Predictions). Drawing on her knowledge of nucleophile strength and substitution reactions, she proposed that the potassium ethoxide would react with the alkyl bromide in an SN2 reaction *(Codes: Reflect Relevant Knowledge, Look for Reactions Recognized)*. After completing this SN2 reaction, she stated that she was now stuck because she didn't know what to do with the ethanol that was also present in the reaction conditions, and she wanted to use every listed reagent in the reactions she proposed *(Code: Note Uncertainty)*. She considered using the potassium ethoxide to deprotonate the ethanol, but she didn't think this made sense, and she questioned whether the SN2 reaction was the correct path *(Code: Monitoring Correctness)*. She considered carrying out an E2 reaction in step 1 instead, but realized that she had still not met her goal of using every listed reagent, since the ethanol did not participate in her proposed E2 reaction either (*Codes: Consider Another Way, Monitor Progress Toward Goals*). In the end, she returned to her initial proposed SN2 reaction because she thought she had seen potassium ethoxide act as a strong nucleophile more often than as a strong base.

Moving on to the second set of reagents, Lily proposed that the ethoxy group on her SN2 product could be protonated by the sulfuric acid because she had seen something similar happen in a previous problem, but she wasn't sure what to do after this protonation *(Code: Relate to Previous Problems)*. At this point, Lily went back over her previous work and again thought about whether her product for step 1 was reasonable *(Code: Periodically Check if Reasonable)*. Her conclusion was "I still think the final product of reaction one is not correct, but I have no other way. I need to base it on that to solve the next question." She then proposed a second SN2 reaction between methanol and the protonated ethoxy group of her intermediate product, and stated that the resulting final product (shown in Figure 2.6) "looks fine" and that there would be no further reactivity *(Code: Consider if Answer Reasonable)*. Other strategies that Lily reported using included setting goals, brainstorming multiple ways to approach the problem before she started working, considering whether her proposed steps were reasonable, checking if she had answered the question, checking for mistakes, checking that her answer agreed with what she had predicted, summarizing the main takeaway lesson, and considering how she could change her approach for the future. Lily's final answer received some partial credit because, though she had proposed SN2 reactions rather than the more favorable E2 and SN1/E1 reactions for each step of the problem, she carried out the reactions that she did propose with correct stereochemistry and regioselectivity.

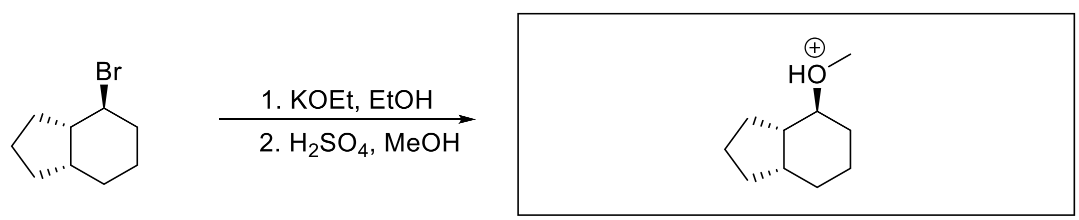


Figure 2.6. Final product proposed by Lily for Problem B.

More Successful Solution, Fewer Metacognitive Strategies Used:

Ben's solution to Problem C received a score of 75%, and was therefore categorized as "more successful." According to his response to the self-report survey, he used an approximately average number of metacognitive strategies, but the number of strategies he was observed using was below average. At the beginning of the problem-solving process, Ben noted that the conditions were acidic and that there were several sites on the starting materials that could potentially be protonated (*Code: Sort Relevant Info*). He considered protonating each of these sites *(Code:*

Brainstorm Multiple Ways). He then determined that protonation of the aldehyde would be the most productive option because he knew that the amine would most likely function as a nucleophile, and the aldehyde was the most electrophilic functional group present *(Code: Reflect Relevant Knowledge)*. Once he had decided on the nucleophile and electrophile, he drew out the mechanism for forming an imine from the aldehyde. After he reached this product (shown in Figure 2.7), he questioned whether the geometry of the imine was correct, but decided that the major product would be the one he had drawn and that he was done with the problem *(Consider if Answer Reasonable)*. In addition to the behaviors that were observed in his transcript, Ben also reported that he had set goals, looked for reactions he recognized, related the problem to a previous problem he'd encountered, made predictions, considered if his proposed steps were reasonable, considered if there was another way to solve the problem, monitored his progress toward his goals, considered whether what he was doing was correct, noted what he was uncertain about, checked if he'd answered the question, and checked if his answer agreed with his prediction. Because Ben did form an imine by reacting the amine with the more reactive of the two carbonyls, did not make any stereochemical errors, and did not propose any additional unreasonable reactions, his answer was considered "more successful." He was not fully successful, however, because he did not consider whether any additional reactivity was possible after forming the imine, such as the Mannich reaction or an amine-catalyzed aldol reaction.

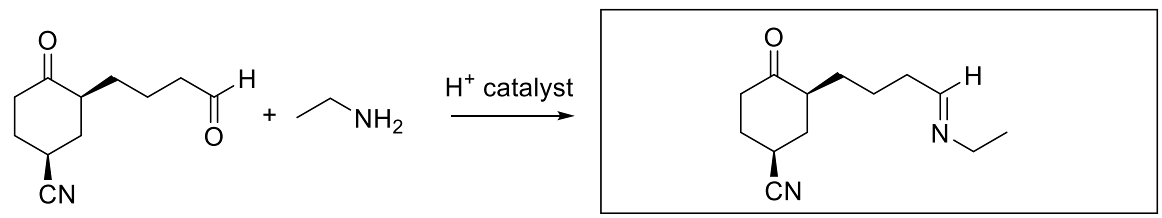


Figure 2.7. Final product proposed by Ben for Problem C.

More Successful Solution, More Metacognitive Strategies Used:

Marta received a score of 100% on Problem D, and she used an above-average number of metacognitive strategies according to both self-report and concurrent measures. Upon first seeing the problem, she noted the presence of a phosphorus ylide as well as the acidic conditions *(Code: Sort Relevant Info)*. She then predicted that the first step of the reaction would reveal a carbonyl, because she recalled she had typically seen this type of phosphonate reagent reacting with carbonyls (*Codes: Make Predictions, Reflect Relevant Knowledge*). She stated that she was not sure which acetal oxygen she should protonate first, but she decided to choose the one in the ring, keeping in mind that she could try the oxygen that was part of the isopropoxy group as well if her first idea did not work *(Code: Brainstorm Multiple Ways)*. As she worked on cleaving the acetal, she recalled that she would need to indicate stereochemistry in her answer, so she made sure that she had considered this while drawing intermediate structures *(Code: Monitor Progress Toward Goals)*. Once she generated the correct aldehyde product of step 1, she looked back over her work to consider whether what she had done was reasonable and then decided to go back to the beginning and try protonating the isopropoxy group first instead *(Codes: Periodically Check if Reasonable, Consider Another Way)*. She erroneously determined that this path was incorrect and would not lead to the desired carbonyl product *(Code: Monitor Correctness)*.

Marta then continued on to the second step of the reaction. As she drew out the mechanism for the HWE reaction, she stated that she was not sure about one step of the mechanism and would want to look it up if she had access to an answer key *(Code: Note Uncertainty).* After she reached her final answer (shown in Figure 2.8), she repeatedly counted the atoms present in her answer and in her intermediates to make sure she had drawn the product correctly *(Code: Check for Mistakes)*. Marta also reported that she had set goals, looked for reactions she recognized, related the problem to a previous problem she'd encountered, considered if her proposed steps were reasonable, considered if her answer was reasonable, checked if she'd answered the question, and checked if her answer agreed with her prediction. Marta's answer was fully correct and was considered "more successful."

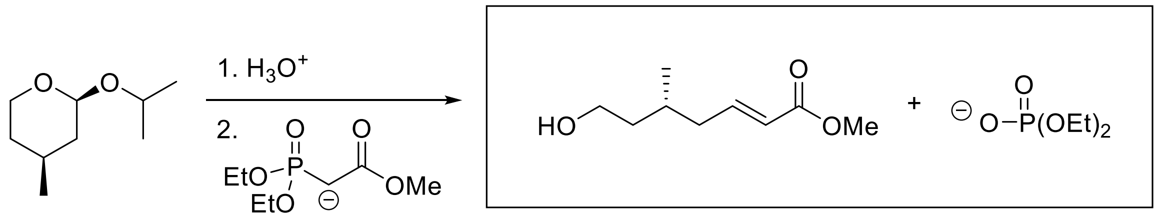


Figure 2.8. Final products proposed by Marta for Problem D.

Considering the interview participants as a group, students who generated more successful solutions tended to use a greater number of metacognitive regulatory strategies. From our analysis of the individual problem-solving pathways of Andrew, Lily, Ben, and Marta, however, it is clear that the relationship between metacognition and problem-solving success is more nuanced. Andrew and Ben both used a below-average number of metacognitive strategies in their approach to Problems A and C, respectively. Neither student received full points for their solutions because, after identifying a reasonable starting point with the use of planning strategies, they did not consider the potential for further reactivity. Had these students engaged in monitoring strategies such as pausing to consider whether there was another way to solve the problem, they may have received higher scores. Andrew's solution to Problem A received a lower performance score than Ben's solution to Problem C and was ultimately categorized as less successful because Andrew's solution contained stereochemical errors that point to a gap in his understanding of this concept. This difference in task performance between students with a similar level of metacognitive strategy usage was also seen when comparing the approaches of Lily and Marta. Lily and Marta both displayed an above-average number of metacognitive behaviors, yet Marta's solution to Problem D received full points, while Lily's solution to Problem B was considered less successful. Based on her verbalized thoughts, Lily seemed to be unsure about the role of the solvent and the favorability of different substitution or elimination reactions under the given reaction conditions, which led her to struggle to generate a reasonable solution. However, Lily's use of planning and monitoring strategies did help her to identify, consider, and dismiss several potential types of reactivity. Overall, these four cases suggest that when solving complex organic chemistry problems, a solid foundation of conceptual knowledge and metacognitive problem-solving skills can both be major contributors to success.

Research Question 3: What reasons do students have for using or not using metacognitive strategies while solving organic chemistry problems?

Based on data from self-report surveys and think-aloud interview coding, it is clear that some of the listed metacognitive strategies were used by the vast majority of interview participants, while others were hardly used by any. We believed that each of these strategies could be helpful for students to use while solving organic chemistry problems and were therefore interested in learning why students used certain strategies but chose not to use others. Understanding how and why students find certain strategies useful when solving problems could help instructors teach and encourage these behaviors in their own students. During the interviews, students were asked about their reasons for using or not using certain metacognitive strategies, either on the problem they had just worked on during the interview or in their organic chemistry course in general. A summary of how often each of the types of reasoning included in our coding scheme came up in reference to strategies classified as planning, monitoring, and evaluation skills is displayed in Table 2.8. A complete listing of what reasons students gave for using or not using each individual strategy is included in Appendix 2.7.

Table 2.8. Frequencies with which Interview Participants Gave Certain Reasons for Using or Not Using Planning, Monitoring, and Evaluation Strategies. Increased Color Saturation Indicates Higher Frequency.

Type of Strategy	**Reasons For Using Strategies**									**Reasons For Not Using Strategies**						
	Builds confidence	Many reactions to consider	Helps them learn/improve	Avoid wasting time/effort	Get started/narrow focus	Keeps them on right track	Keeps them from forgetting	Someone encouraged use	Helps avoid mistakes	Prevents success - distracting	Prevents success - other	Issues with timing	Unable to use effectively	Unnecessary - have answer	Unnecessary - redundant	Unnecessary - other
Planning	6	9	7	8	57	9	9	17	9	13	8	23	29	7	4	27
Monitoring	1	4	6	12	1	19	3		19	8	3	13	8	4	6	10
Evaluation	2		17	2			2	5	33			30	16	14	9	19

The reasons that students mentioned most frequently overall for using the metacognitive strategies were that they helped the student find a starting point or narrow down their options, avoid making mistakes, and learn or improve their problem-solving skills. For planning strategies in particular, students most often mentioned that they used these strategies because they helped them find a starting point. Individual strategies that students often mentioned in this context included sorting through the problem statement to determine what information was relevant and looking for reactions they recognized. Students also commonly used planning strategies, especially setting goals, based on the advice of their professors or tutors. Students stated that they used certain monitoring strategies, such as considering whether they were making progress toward their goals or whether their approach was correct, because they helped them avoid wasting time or effort and kept them on the right track. Students also used monitoring strategies like considering whether their approach was correct and periodically checking if their overall approach was reasonable because they wished to avoid making mistakes. Two major categories of reasoning came up as justifications for using evaluation strategies. Students typically said that they used strategies like checking for mistakes and checking if they actually answered the question because these strategies helped them avoid making mistakes. Students used other strategies, like summarizing the main takeaway lessons they learned and considering how they could change their problem-solving approach in the future, because using these strategies helped them learn and improve from their experience.

Students' reasons for not using certain strategies fell into four major categories. The most common reason students gave for not using a strategy was that they thought it wasn't necessary. This type of reasoning was used particularly often when students explained why they didn't jot down their ideas before they started working on a problem or summarize the main takeaway lessons after finishing a problem. Sometimes, this was because the student had already found an answer at the point they would have used the strategy, and after finding an answer they just wanted to move on to the next problem. Students also considered the use of some strategies to be unnecessary and redundant because they preferred to use another strategy for a similar purpose. For example, several students either stated that they didn't pause to consider whether what they were doing was correct or whether their approach was reasonable while working on the problem because they preferred to wait until after they had reached an answer to check their work, or that they didn't check their work after solving the problem because they had already done so repeatedly while solving the problem. Students also mentioned that they didn't typically have enough time or thought it would take too much time to use certain strategies, especially evaluation strategies that would be used at the end of the problem-solving process such as checking for mistakes. Some students stated that they didn't use certain strategies, particularly planning skills such as setting goals and making predictions, because they did not feel that they were experienced enough with organic chemistry to be able to use the strategy effectively. A smaller number of students believed that using particular strategies was not just unnecessary or unfeasible; these students believed using these strategies would actively prevent them from successfully solving the problem, often because they deemed their use to be distracting. For example, some students mentioned that they didn't set goals before they started working on the problem because this could close their mind to other possibilities. Others mentioned that they didn't jot down their ideas or pause to consider whether there was another way to solve a problem because they found these strategies to be too distracting.

The reasons students gave for using metacognitive planning, monitoring, and evaluation strategies mostly aligned with our expectations and showed that students used these strategies for their intended purposes. As expected, students generally used planning strategies to help identify and explore possible options, monitoring strategies to keep them on track and avoid making mistakes or wasting time or effort, and evaluation strategies to assess the merits of their answer and approach as well as to learn from their experience of solving the problem. Though we are not able to compare our findings to any existing studies on student reasons for using metacognitive strategies in the context of problem solving, students have been found to give similar reasons for using or not using metacognitive strategies while reading academic texts.[61,62] One interesting observation is that many students mentioned being encouraged by their instructors or tutors to use certain planning strategies, but this reasoning was mentioned less often in regard to monitoring or evaluation strategies. If instructors typically concentrate on teaching planning strategies, it would be useful to additionally introduce and model the use of various monitoring and evaluation strategies during class. Students' reasons against using metacognitive strategies, especially those related to feeling unable to use certain strategies effectively, point towards opportunities for instructors to provide students with additional guidance and support in implementing these strategies. It is important to note that our goal in advocating that instructors teach students about metacognitive regulation is not for students to use every strategy listed in Table 2.2 when working on every organic chemistry problem they encounter. Students may rightfully not find some strategies useful in every situation, especially for more straightforward problem-solving tasks.

Instead, we believe it is beneficial to introduce these skills and give students the tools to use them when needed.

The results of Study 1 provided us with a detailed description of how and why students engage in metacognitive behaviors while working on complex predict-the-product problems. This work built upon our research group's prior research on student approaches to this type of open-ended problem by looking specifically at students' usage of metacognitive strategies in their approaches to this type of problem. However, the number of students we were able to recruit for this type of interview-based qualitative study was limited, and our findings are tied to this specific problem-solving context. In Study 2, therefore, we sought to determine how a larger sample of students makes use of these strategies more broadly on assignments for their organic chemistry courses.

Study 2: Methods

Participants and Context

All work associated with Study 2 was conducted with undergraduate and graduate students at the University of California, Berkeley. Informed consent was obtained from all participants in accordance with a protocol approved by the university's Institutional Review Board (protocol #: 2015-08-7858). This study focused on undergraduate students enrolled in Chem 3A (Organic Chemistry I) and Chem 3B (Organic Chemistry II) as well as graduate students who were conducting research related to organic chemistry. Participants were recruited to participate in surveys via emails sent to all students enrolled in Organic Chemistry I or Organic Chemistry II in November 2020 and emails sent to all students who were enrolled in the synthetic or chemical biology divisions of UC Berkeley's chemistry Ph.D. program in May 2021. While we recognized that many students in the synthetic or chemical biology divisions would not be conducting research related to organic chemistry, we chose recruit potential graduate student participants broadly in order to include responses from students who were conducting research related to organic chemistry despite not being a member of an organic chemistry-focused research group. In total, the number of students who volunteered to participate in Study 2 includes 394 Organic Chemistry I students, 474 Organic Chemistry II students, and 42 graduate students. A summary of information about these participants' educational and demographic background is included in Table 2.9.

The Organic Chemistry I and Organic Chemistry II students who volunteered to participate differed slightly from the general course population in that their average course performance, as measured by final percentage grades, was 0.1 standard deviations above the full course average. This difference in course performance between survey participants and those who did not respond to the survey was significant for both the Organic Chemistry I course ($p < 0.004$, Cohen's $d = 0.22$) and the Organic Chemistry II course ($p < 0.001$, Cohen's $d = 0.49$) as measured by t-tests. This is a similar trend to that which was observed in Study 1, though larger discrepancies in course performance were observed between interview participants and the general course population than between survey participants and the general course population.

Table 2.9. Summary of Information Related to Survey Participants' Demographic and Educational Background

Type of Information	Undergraduate Participants (N=868)	Graduate Participants (N=42)
Gender	Women (73%) Men (25%) Non-Binary or Unsure (1%) Did Not Answer (0.7%)	Men (48%) Women (45%) Non-Binary or Unsure (5%) Did Not Answer (2%)
Race/Ethnicity	Asian (59%) White/Caucasian (26%) Latino (16%) Middle Eastern/North African (4%) African American/Black (2%) American Indian/Alaska Native (1%) Native Hawaiian/Pacific Islander (1%) Did Not Answer (3%)	White/Caucasian (83%) Asian (14%) Latino (5%) African American/Black (2%) American Indian/Alaska Native (2%) Middle Eastern/North African (2%) Did Not Answer (2%)
Year in Undergraduate or Graduate Program	Information Not Collected	First Year (19%) Second Year (31%) Third Year (12%) Fourth Year (26%) Fifth Year (12%)
Undergraduate Major or Graduate Research Focus	Life Science (61%) Public Health (9%) Physical Science (6%) Engineering (5%) Social Science (4%) Chemistry/Chemical Biology (3%) Humanities (1%) Other (10%) Did Not Answer (0.5%)	Organic Chemistry (74%) Biological Chemistry (45%) Inorganic Chemistry (19%) Materials Chemistry (19%) Analytical Chemistry (10%) Physical Chemistry (7%)

Data Collection

Data collected includes survey responses, which were collected from all study participants, and final percentage grades and letter grades, which were collected only for the participants who were enrolled in Organic Chemistry I or Organic Chemistry II. Grade data for all consenting students was obtained directly from the instructors of the focal courses after the semester was complete. The survey that participants completed, referred to herein as the Metacognitive Strategies Survey, contained two sections. In the first section, students were asked how frequently they used each of the 20 metacognitive strategies listed in Table 2.2 (see Study 1, section: "Development of List of Metacognitive Strategies Used in Interview Coding Scheme and Self-Report Instrument" for details of item design) when working on homework and exam problems in their organic chemistry courses. Students were able to choose between the following answer choices for each Likert item: "rarely/never," "sometimes," "most of the time," and "all the time." The second section of the survey contained several items related to educational and demographic background information. Copies of survey protocols for undergraduate and graduate students are provided in Appendices 2.8 and 2.9.

Participants completed the survey online via Qualtrics. Two points of extra credit were offered to Organic Chemistry I students and five points were offered to Organic Chemistry II students in order to incentivize survey completion; these extra credit points represent approximately 0.5% of the total points available in each course. If students did not wish to complete the survey, they were also offered the option to complete an alternative short essay assignment to receive these extra credit points. Graduate students were not compensated for their participation. Response rates for each participant population are provided in Table 2.10. Response rates were higher among the undergraduate students than the graduate students, which is likely partially due to the extra credit incentive that the undergraduate students were given. Another factor that may have contributed to the lower response rate among graduate students was that, due to our decision to send recruitment emails to graduate students from several divisions of the chemistry Ph.D. program, some students may have decided against completing a survey that was intended for students who were conducting research related to organic chemistry.

Table 2.10. Metacognitive Strategies Survey Participants and Response Rates

Sample	Participants (Response Rate)	Population	Responses Used in Analyses
Organic I	394 (54%)	732	380
Organic II	474 (81%)	587	467
Graduate Students	42 (20%)	205	31

Data Analysis

Survey responses were discarded from the dataset if participants did not finish the survey or if they answered every item with the same response. Responses from graduate students who did not include organic chemistry as one of their major research fields in response to the question "Which of the following areas of chemistry are most related to your graduate research? Please check all that apply" were also dropped from the dataset. As a result, 878 of the 910 collected responses were analyzed for this study. This includes 380 responses from Organic Chemistry I students, 467 from Organic Chemistry II students, and 31 from graduate students.

Student responses to Likert items about their frequency of metacognitive strategy usage were assigned numerical values (1=rarely or never, 2=sometimes, 3=most of the time, 4=always). Average scores on individual items and groups of items were calculated for Organic Chemistry I students, Organic Chemistry II students, and graduate students. One key metric to consider when calculating composite scores across groups of survey items is the internal consistency of the items in question. This is an assessment of how similarly different items that are purported to measure the same construct behave, and is usually measured using Cronbach's α values.[71] Values between 0.7 and 0.9 are considered to be ideal. As shown in Table 2.11, internal consistency was acceptable for the 20 items pertaining to strategy usage on homework problems and for the 20 items pertaining to strategy usage on exam problems.

Table 2.11. Cronbach's Alpha Values for Each Administration of the Metacognitive Strategies Survey

Survey Items	Number of Items	Cronbach's Alpha		
		Organic I (N=380)	Organic II (N=467)	Graduates (N=31)
Items Related to Strategy Usage on Homework Problems	20	0.87	0.85	0.87
Items Related to Strategy Usage on Exam Problems	20	0.85	0.87	0.86

One-way ANOVA tests were used to compare composite scores across the three groups of students, and paired t-tests were used to compare the frequency with which students reported using metacognitive strategies while working on homework problems to the frequency with which they reported using metacognitive strategies while working on exam problems. Pearson correlations between final course grades and frequency of reported metacognitive strategy use were determined for Organic Chemistry I and Organic Chemistry II students, and frequencies of reported metacognitive strategy use were compared for students receiving different letter grades in these courses using one-way ANOVA tests. Descriptive statistical analyses and statistical tests were performed using IBM SPSS 27.0.

Study 2: Results and Discussion

Research Question 4: What metacognitive strategies do undergraduate and graduate students use when solving problems on assignments for their organic chemistry courses?

One of our key goals in Study 2 was to determine which strategies related to planning, monitoring, and evaluation students use more and less frequently when solving problems in their organic chemistry courses. Table 2.12 shows group means for each of the 20 Metacognitive Strategies Survey items related to how frequently students reported using these strategies on homework and exam problems. The strategies that students reported using most frequently were evaluation strategies focused on making sure their answer was reasonable and that they had actually answered the question. Students also typically reported using planning and orientation strategies like sorting through the problem statement to determine what was relevant or looking for reactions they recognized most of the time or always. In contrast, students reported that they jotted down ideas, brainstormed or considered multiple ways to solve problems, and summarized main takeaway lessons more rarely. When comparing these results to Study 1, in which interview participants were asked whether they had used these same strategies when working on a specific predict-the-product problem, the strategies students most and least frequently reported using were mostly similar. Over 90% of the participants in Study 1 reported considering alternative ways to solve problems, though, whereas students who were surveyed for Study 2 tended to report using this strategy only sometimes when solving problems on assignments for their course. This is likely because the problems students completed during Study 1 were of a higher difficulty than many of the problems students would encounter in their courses. Overall, it is useful to see the trends we observed in a small number of participants as a part of the more qualitative Study 1 borne out among a larger and more representative sample of students from these organic chemistry courses.

Table 2.12. Mean Scores on Individual Metacognitive Strategies Survey Items, Grouped by Course and Assignment Type. Increased Color Saturation Indicates More Frequent Use of Strategy.

Strategy	Mean Score on Item: Frequency of Usage on Homework Problems [a]			Mean Score on Item: Frequency of Usage on Exam Problems [a]		
	Organic I (*N*=380)	Organic II (*N*=467)	Graduates (*N*=31)	Organic I (*N*=380)	Organic II (*N*=467)	Graduates (*N*=31)
Set Goals	2.7	2.8	3.4	2.9	3.1	3.2
Sort Relevant Info	3.0	3.1	3.3	3.2	3.3	3.3
Look for Reactions Recognized	3.1	3.5	3.4	3.2	3.6	3.4
Reflect Relevant Knowledge	2.9	2.9	2.7	3.1	3.1	2.7
Relate to Previous Problems	3.1	3.1	3.2	3.2	3.3	3.2
Jot Down Ideas	2.1	2.2	2.0	2.2	2.3	2.2
Make Predictions	2.3	2.3	2.5	2.4	2.4	2.6
Brainstorm Multiple Ways	2.1	2.2	2.3	2.2	2.3	2.0
Consider If Plan Reasonable	2.5	2.4	2.5	2.6	2.6	2.2
Consider Another Way	2.3	2.3	2.3	2.5	2.4	2.2
Monitor Progress Toward Goals	2.7	2.9	2.8	2.8	3.0	2.7
Monitor Correctness	3.1	3.1	3.0	3.3	3.3	2.9
Note Uncertainty	2.9	2.7	3.2	2.8	2.7	3.1
Periodically Check If Reasonable	2.8	2.7	2.8	3.0	2.9	2.8
Consider If Answer Reasonable	3.1	3.1	3.5	3.3	3.4	3.3
Check If Answered Question	3.3	3.3	3.5	3.4	3.5	3.6
Check For Mistakes	2.8	2.9	3.3	3.2	3.3	3.1
Check If Agreed With Prediction	2.6	2.6	2.6	2.7	2.8	2.5
Summarize Main Takeaways	2.1	2.1	1.7	1.8	1.8	1.4
Consider Changes For Future	2.4	2.3	1.9	2.1	2.0	1.5

[a] Scoring: “rarely or never” = 1, “sometimes” = 2, “most of the time” = 3, “always” = 4.

We also examined similarities and differences between students with different levels of experience with organic chemistry (Figure 2.9). According to a One-Way ANOVA, there were no differences in average scores on the Metacognitive Strategies Survey among Organic Chemistry I, Organic Chemistry II, and graduate students. We had hypothesized that graduate students would report using metacognitive strategies more frequently than undergraduates, because previous research has suggested that metacognitive skillfulness increases with expertise in chemistry[49] and that students with higher education levels tend to exhibit higher levels of metacognition,[72] so our finding that there were no differences in Metacognitive Strategies Survey scores between the three groups of students was somewhat unexpected. This led us to consider whether students with more expertise differed in their usage of any of the individual strategies shown in Table 2.12, despite not differing in overall Metacognitive Strategies Survey scores. Graduate students reported setting goals more frequently ($p = 0.001$, Cohen’s $d = 0.59$) and considering how they might change their approach for the future less frequently (p = 0.002, Cohen's d = 0.56) compared to undergraduates. We observed similar results in Study 1; undergraduate and graduate students did not differ significantly in the number of strategies they self-reported using or were observed using during the think-aloud interviews, but we did observe a greater tendency towards goal-setting among the graduate students.

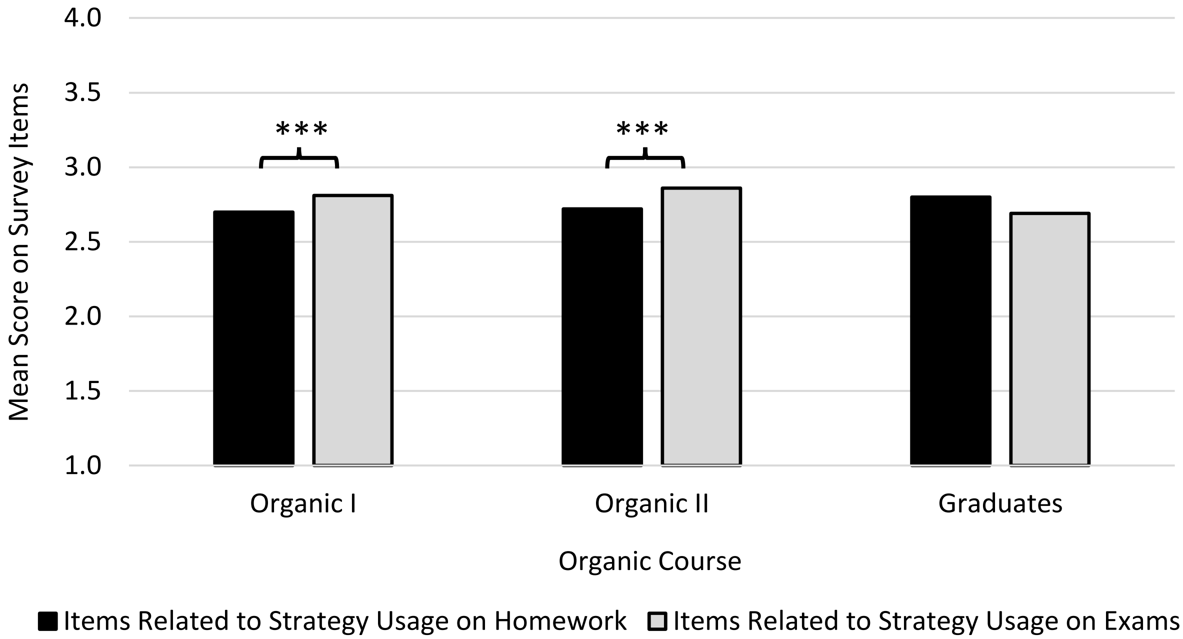


Figure 2.9. Mean scores on Metacognitive Strategies Survey. One-Way ANOVA tests were used to compare scores across courses, and paired t-tests were used to compare scores across assignment types. (* = p < 0.05, ** = p < 0.01, *** = p < 0.001; *N*=380 Organic Chemistry I students, 467 Organic Chemistry II students, 31 graduate students).

When considering different types of assignments, students in Organic Chemistry I and Organic Chemistry II tended to score slightly higher on the survey items pertaining to strategies used on exam problems (Figure 2.9). This means that, on average, they reported using metacognitive strategies more frequently on this type of assignment. These differences were significant according to paired t-tests (p < 0.001, Cohen's d = 0.30 for Organic Chemistry I students; p < 0.001, Cohen's d = 0.29 for Organic Chemistry II students. The opposite trend was observed among graduate students, though this difference was only approaching significance (p = 0.057). The differences in students' approaches to problems on these two types of assignments can potentially be explained by their learning goals and motivations. Students who are highly motivated by performance outcomes have been found to be less willing to engage in more effortful strategies when completing tasks that are less consequential for their grade.[73,74] In the Organic Chemistry I and Organic Chemistry II courses, homework assignments have a much smaller effect on final grades than exams, which could lead students to be less motivated to use metacognitive strategies on homework problems. Graduate students who have chosen to conduct research in organic chemistry may be motivated by extrinsic performance metrics to a lesser degree than the undergraduate population studied, who were primarily majoring in a field outside of chemistry. When looking at individual strategies, undergraduates on average reported engaging in each behavior slightly more often or just as often when approaching exam problems compared to homework problems, with two exceptions: summarizing main takeaways ($p < 0.001$, Cohen's d = 0.44) and considering changes they could make to their problem-solving approach in the future ($p < 0.001$, Cohen's d = 0.40). Results pertaining to differential strategy use on homework and exams were more mixed among the graduate students, though we observed the same trend with certain evaluation strategies being used more often for homework problems, including summarizing main takeaways ($p = 0.001$, Cohen's d = 0.62) and considering changes they could make to their problem-solving approach in the future ($p = 0.003$, Cohen's d = 0.61). In Study 1, the reason students typically gave for using these strategies was to learn from their experience of solving problems, which is an activity that students usually engage in while completing homework or studying rather than during the process of completing summative assessments. These results provide additional insights into students' motivations and their reasoning for using metacognitive strategies in different situations.

Research Question 5: How does students' self-reported usage of metacognitive strategies connect to their performance in their organic chemistry courses?

Based on prior research linking metacognitive skillfulness with problem-solving ability, we hypothesized that students who received higher grades in their organic chemistry courses would engage in metacognitive regulation with a higher frequency, as measured by their scores on the Metacognitive Strategies Survey. As shown in Table 2.13, weak positive correlations were observed between Metacognitive Strategies Survey scores and final percentage grades for the Organic Chemistry II students, but no statistically significant correlations were observed for the Organic Chemistry I students. Scores on Metacognitive Strategies Survey items related to how frequently students engaged in metacognitive regulation while working on exam problems were more strongly correlated with final percentage grades compared to items related to strategy usage on homework problems.

Table 2.13. Correlations Between Score on Metacognitive Strategies Survey Items and Final Percentage Grade by Course

Score on Metacognitive Strategies Survey Items	Correlation with Course Performance (Final % Grade)	
	Organic I	Organic II
Items Related to Strategy Usage on Homework Problems	0.024	.176**
Items Related to Strategy Usage on Exam Problems	0.091	.273**

While correlational analysis indicated that metacognitive strategy use was positively associated with performance for Organic Chemistry II students, this did not allow us to determine whether students who received a B in the course differed significantly from students who received a C in the course, for example. Therefore, we chose to additionally compare scores on the Metacognitive Strategies Survey between students who received different letter grades in their organic chemistry course. Figure 2.10 shows mean Metacognitive Strategies Survey scores for students who received final letter grades of A, B, C, or D/F in Organic Chemistry I or Organic Chemistry II. According to One-Way ANOVA tests, there were no significant differences in survey scores between students who received different letter grades in Organic Chemistry I, but there were significant differences for Organic Chemistry II students ($F(3, 437) = 4.923$, $p = 0.002$ for items relating to strategy usage on homework problems; $F(3, 416) = 12.759$, $p < 0.001$ for items relating to strategy usage on exam problems). Post hoc comparisons using the Tukey HSD test indicated that students who received a D/F in the course reported using metacognitive strategies less frequently on homework problems than students who received an A ($p = 0.036$) or C ($p = 0.016$) in the course. For exam problems, students who received a D/F in the course reported using metacognitive strategies less frequently than students who received an A ($p < 0.001$), B ($p = 0.026$), or C ($p < 0.001$) in the course, while students who received an A in the course reported using metacognitive strategies more frequently than students who received a B ($p = 0.031$), C ($p = 0.037$), or D/F ($p < 0.001$) in the course. No significant differences were observed between students who received a B in the course and those a received a C in the course. Overall, scores on the Metacognitive Strategies Survey were relatively similar when comparing student with low, intermediate, and high grades, corroborating the idea that metacognitive skillfulness is just one of many factors proposed to affect academic achievement.[75,76]

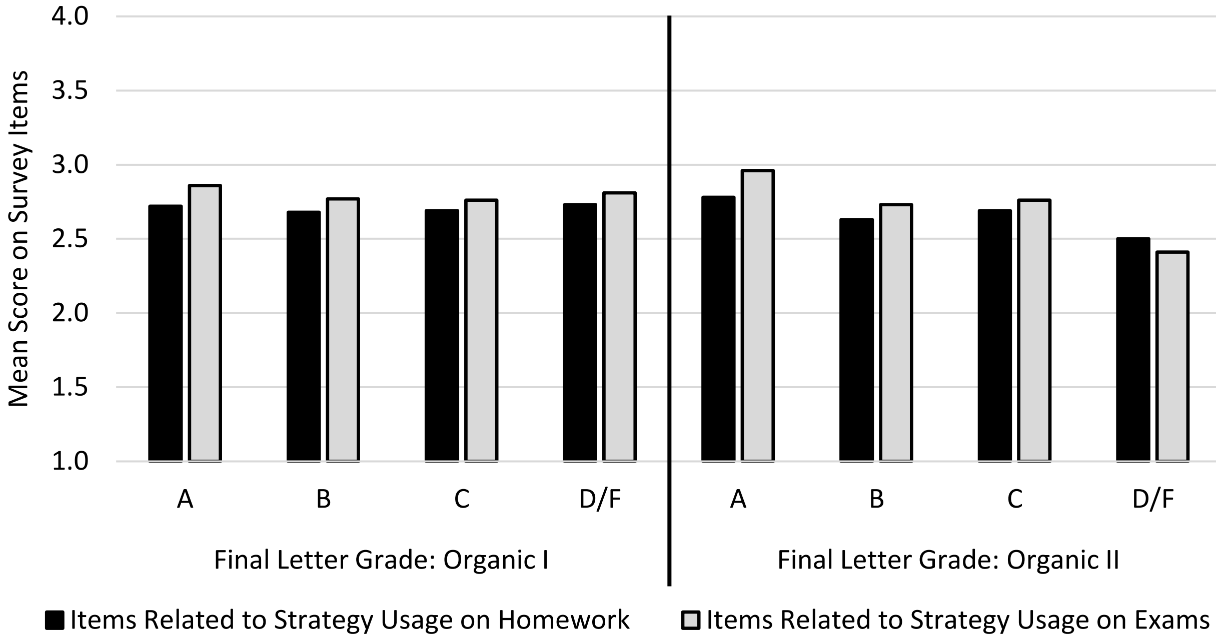


Figure 2.10. Mean scores on Metacognitive Strategies Survey by letter grade received in Organic Chemistry I or Organic Chemistry II (*N* for Organic Chemistry I students = 120 A, 105 B, 103 C, 16 D/F, *N* for Organic Chemistry II students = 280 A, 93 B, 50 C, 18 D/F).

Overall, both the correlational and comparative analyses suggest that metacognitive regulatory ability as measured by the Metacognitive Strategies Survey is positively associated with performance in one of the organic chemistry courses we studied. Positive associations have been found in several other studies that related student scores on metacognitive self-report instruments to performance in chemistry courses, though each of these studies focused on introductory or general chemistry courses rather than organic chemistry courses.[49,76,77] Cooper and Sandi-Urena[49] found that students who received a grade of A in a general chemistry course scored significantly higher on the MCAI, a self-report instrument that assesses metacognitive regulation in problem-solving, compared to students who received lower grades in the course. They also observed a correlation of 0.16 between grade point average in general chemistry and scores on the MCAI.[49] Using this same instrument, Dianovsky and Wink[77] observed a correlation of 0.56 with students' numerical grades in a general education chemistry course designed for pre-service teachers.

González and Paoloni[76] conducted a similar analysis using students' planning, monitoring, and evaluation scores on the Physics Metacognition Inventory. They found correlations of 0.64, 0.67, and 0.68, respectively, with final grades in introductory chemistry.[76] Our observed correlations are most similar in magnitude to those reported by Cooper and Sandi-Urena. In addition to being consistent with previous studies, our analysis also builds upon our work in Study 1, in which we found that students who generated more successful solutions to complex predict-the-product problems tended to use a greater number of these strategies. In Study 2, we have generalized the connection between metacognition and problem-solving performance to a more typical educational context.

While our results were mostly consistent with our hypotheses as well as prior research, we did observe two interesting findings regarding metacognition and academic performance. The connection between metacognition and performance was stronger when considering strategies students used on exam problems compared to strategies used on homework problems. The probable explanation is quite simple: students' final grades were primarily based on their performance on exam problems, leading students' use of metacognitive strategies on these assignments to be more associated with their final grades. Another observation that was consistent between the two analyses was that the predicted connection between metacognitive strategy usage and course grades was only seen for the Organic Chemistry II students. This may be explained by differences in the nature of the problems used to evaluate student knowledge and understanding in Organic Chemistry I as compared to the Organic Chemistry II course. Problems students are asked to solve during their first-semester organic chemistry course tend to be shorter and less complex than those they encounter during the second semester of the series. In their discussion of the association between metacognition and academic achievement as measured by course grades, Cooper and Sandi-Urena[46] explain that this association may only be significant "if the assessment is based on complex, high-level thinking that elicits and unmasks metacognitive differences in the participants" (p. 243). Previous studies have found that metacognitive regulation is a greater predictor of success in more ill-structured, complex problem solving,[46] which students would have been more likely to engage in during Organic Chemistry II. Together with the more qualitative results of Study 1, understanding the contexts in which metacognitive regulation has a higher impact on course performance could help instructors to design teaching interventions that promote academic success.

Limitations

One of the limitations of this work is the potential for self-selection bias among the students who volunteered to participate in Studies 1 and 2. Any student who responded to the interview recruitment announcements was invited to participate in Study 1, and, though all students in the focal populations were invited to complete the Metacognitive Strategies Survey in Study 2, response rates ranged from 20% for graduate students to 81% for Organic Chemistry II students. When comparing undergraduate students who volunteered to participate to the general course population, it is clear that they differed on at least one metric: course performance. Students who volunteered to be interviewed for Study 1 received final grades that were at least half of a standard deviation above the mean in their organic chemistry course. Understandably, it appears that students who were not performing as well in their organic chemistry courses were not as likely to volunteer to be observed while working on organic chemistry problems. Students who chose to participate in Study 2 also received final grades that were slightly higher than the course average. This should be taken into consideration when interpreting the results of this study.

Several factors also affect the generalizability of the outcomes of this work. Because the number of participants in Study 1 is relatively small, the results of this study should be interpreted from a primarily qualitative perspective, and statistical results should be interpreted with caution. Study 1 was also focused on students' use of metacognitive strategies when approaching a specific type of organic chemistry problem. The problems that students were asked to solve were all relatively complex predict-the-product problems. It is likely that students' use of metacognitive strategies would differ for more straightforward exercises or for problems related to proposing mechanisms or syntheses. For Study 2, very few graduate students participated in the Metacognitive Strategies Survey compared to undergraduates, limiting the comparisons that can be made between these two groups. It also important to note that both Study 1 and Study 2 were conducted during the COVID-19 pandemic. As a result, the distribution of final grades as well as the means by which students were taught and assessed in the Organic Chemistry I and Organic Chemistry II courses were atypical. It is probable that students' performance in their courses and their approach to completing their assignments in a time of fully-remote instruction, unproctored assessments, and the expanded use of the pass/no-pass grading option would differ from more typical semesters unaffected by COVID-19.

Conclusions and Implications

The goal of this work was to quantitatively and qualitatively investigate the behaviors related to metacognitive regulation that students engage in when approaching organic chemistry problems. Very few studies have focused specifically on metacognition in students' approaches to solving organic chemistry problems, which involve very different skills than the more quantitative problems typically encountered in general chemistry courses. We therefore sought to link the existing literature on problem solving in organic chemistry and metacognition. Our work in Study 1 provides a thorough analysis of metacognitive regulation in the specific context of solving difficult, open-ended organic chemistry problems, including not only what students say they do, but also what we've observed them doing and what their reasons are for doing what they're doing. Study 2 then explores student usage of these strategies in a more general educational context: problems completed on assignments for their organic chemistry courses.

Analysis of the interviews conducted in Study 1 and the Metacognitive Strategies Survey responses collected in Study 2 led us to conclude that the strategies most commonly used by students were those related to identifying relevant information, recalling prior knowledge, and monitoring or evaluating the correctness of one's progress or products, whereas far fewer students engaged in evaluation strategies that involved reflecting and learning from the experience of problem solving. When comparing the approaches of graduate and undergraduate students, one trend we observed was the higher prevalence of forward-thinking strategies, including setting goals or making predictions at the beginning of the problem, among graduate students. These are specific strategies that instructors of introductory organic chemistry courses could focus on modeling while explaining their thought process as they go over example problems during class. Instructors could also provide students with an opportunity to practice using these strategies on homework or in-class assignments that include explicit prompts to write down goals or predictions before solving a problem or to write down "main take-away lessons" after completing a problem.

When examining students' use of metacognitive regulation strategies measured concurrently during think-aloud interviews as compared to their self-reported use of these same strategies, significant discrepancies between these two measures were found. This emphasizes the importance of using multiple measures to detect metacognitive regulation in students, as the use of a single measure may result in an incomplete understanding of students' cognitive processes related to this complex construct. The reasons for the observed discrepancies are not entirely clear; however, possible factors include social desirability bias,[67] differences in students interpretation of the strategies described by the self-report items compared to the definitions used by the researchers when coding the think-aloud protocols, or a lack of inclusion of some of student's more automated cognitive processes in their think-aloud interview verbalizations.[30] We suggest that future studies that rely upon self-report assessments of metacognitive regulation could make use of cognitive interviews where students are asked to explain their thought process as they answer each item of the questionnaire.[68,69] Analysis of these interviews could help explain the reasons for any disagreement between self-reported and observed metacognition as well as point to ways in which survey items or coding definitions could be modified to better assess strategy usage in students.

In addition to examining metacognitive regulation in students with different levels of experience with organic chemistry, we also sought to determine whether there was a connection between students' use of metacognitive strategies and their problem-solving performance. In both studies, students who performed better according to their scores on the interview problems or their final grades in their organic chemistry course reported greater usage of metacognitive regulation strategies, though in Study 2 this relationship was only observed among the Organic Chemistry II students. Analyzing individual examples of student problem-solving pathways showed that, while the use of a greater number of metacognitive strategies does not always lead to greater success on non-trivial organic chemistry predict-the-product problems, using these strategies can help students generate possible ideas, ensure that they are making progress in the right direction, and determine whether their answer is reasonable and complete. This suggests that problem-solving success is mediated by metacognitive skillfulness in addition to a solid foundation of conceptual understanding, supporting the importance of integrating metacognitive training with the teaching of subject content.

Interview participants stated that they found many of the strategies described herein to be useful for helping narrow down options, avoid mistakes, and keep themselves on track during the process of problem solving. Yet students also had several reasons for not using these strategies, such as believing that using a strategy was unnecessary or distracting or that they were not capable of using the strategy effectively. Students' prior experiences with using metacognitive strategies and their memories of their past successes and failures influence their subsequent metacognitive and self-regulatory strategy choices.[74] Giving students opportunities to practice using metacognitive strategies on scaffolded assignments or with the help of problem-solving workflows could enable students to feel more confident in their ability to use these strategies effectively, including in situations where they are constrained for time. Examples of problem-solving scaffolds that could promote discipline-specific metacognition in students include the "Goldilocks Help" workflow, developed by Yuriev et al.[78] in order to scaffold the development of metacognitive self-regulation and problem-solving skills in general and physical chemistry courses, and a problem-solving workflow designed for predicting organic reactivity that was developed by our research group.[9] We have also recently piloted a series of problem-solving workshops with a small number of organic chemistry students at our institution based on the results of this investigation. According to Arslantas et al.,[16] metacognitive instruction should include "explicit instruction, modeling, integration of metacognitive skills with course content, and opportunities for practice and reflection" (p. 59). These workshops therefore begin with explicit instruction on metacognition and its importance, drawing on data collected during this study on the reasons students use certain strategies. This is followed by instructor modeling of strategies that we identified as particularly underused among undergraduate students, such as making predictions or summarizing main takeaway lessons. Students then complete scaffolded worksheets in which they are asked to write down their answers to prompts related to these strategies before, during, and after working on organic chemistry problems. Preliminary data suggests that these workshops were helpful to students, though additional research is needed to determine their efficacy in a larger classroom setting.

References

(1) Talanquer, V.; Pollard, J. *Chem Educ Res Pr.* **2010**, *11*, 74–83.
(2) Sevian, H.; Talanquer, V. *Chem Educ Res Pr.* **2014**, *15*, 10–23.
(3) Cooper, M. M.; Stowe, R. L. *Chem. Rev.* **2018**, *118*, 6053–6087.
(4) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; The National Academies Press: Washington, DC, 2012.
(5) Schoenfeld, A. H. *J. Educ.* **2016**, *196*, 1–38.
(6) Wheatley, G. H. Problem Solving in School Mathematics. MEPS Technical Report 84.01, School Mathematics and Science Center, Purdue University, West Lafayette, IN. **1984**.
(7) Graulich, N. *Chem Educ Res Pr.* **2015**, *16*, 9–21.
(8) Austin, A. C.; Ben-Daat, H.; Zhu, M.; Atkinson, R.; Barrows, N.; Gould, I. R. *Chem. Educ. Res. Pract.* **2015**, *16*, 168–178.
(9) Helix, M. R.; Blackford, K. A.; Firestein, Z. M.; Greenbaum, J. C.; Gibson, K.; Baranger, A. M. *Chem. Educ. Res. Pract.* **2022**, Advance Article.
(10) Bhattacharyya, G.; Bodner, G. M. *J. Chem. Educ.* **2005**, *82*, 1402–1407.
(11) Caspari, I.; Weinrich, M. L.; Sevian, H.; Graulich, N. *Chem. Educ. Res. Pract.* **2018**, *19*, 42–59.
(12) Ferguson, R.; Bodner, G. M. *Chem. Educ. Res. Pract.* **2008**, *9*, 102–113.
(13) DeCocq, V.; Bhattacharyya, G. *Chem. Educ. Res. Pract.* **2019**, *20*, 213–228.
(14) Flavell, J. H. *Am. Psychol.* **1979**, *34*, 906–911.
(15) Rickey, D.; Stacy, A. M. *J. Chem. Educ.* **2000**, *77*, 915–920.
(16) Arslantas, F.; Wood, E.; MacNeil, S. Metacognitive Foundations in Higher Education Chemistry. In *International Perspectives on Chemistry Education Research and Practice*; ACS Symposium Series; American Chemical Society, 2018; Vol. 1293, pp 57–77.
(17) Livingston, J. A. *Psychology* **2003**, 13, 259–266.
(18) Schraw, G.; Moshman, D. *Educ. Psychol. Rev.* **1995**, *7*, 351–371.
(19) Gulacar, O.; Cox, C.; Tribble, E.; Rothbart, N.; Cohen-Sandler, R. *Can. J. Chem.* **2020**, *98*, 676–682.
(20) Jacobse, A. E.; Harskamp, E. G. *Metacognition Learn.* **2012**, *7*, 133–149.
(21) Schoenfeld, A. H. What's All the Fuss about Metacognition? In *Cognitive Science and Mathematics Education*; Routledge: New York, 1987; pp 189–215.
(22) Artz, A. F.; Armour-Thomas, E. *Cogn. Instr.* **1992**, *9*, 137–175.
(23) Swanson, H. L. *J. Educ. Psychol.* **1990**, *82*, 306–314.
(24) Ku, K. Y. L.; Ho, I. T. *Metacognition Learn.* **2010**, *5*, 251–267.
(25) Van Hout-Wolters, B. *Pedagog. Stud.* **2009**, *86*, 110–129.

(26) Winne, P. H.; Perry, N. E. Chapter 16 - Measuring Self-Regulated Learning. In *Handbook of Self-Regulation*; Boekaerts, M., Pintrich, P. R., Zeidner, M., Eds.; Academic Press: San Diego, 2000; pp 531–566.
(27) Craig, K.; Hale, D.; Grainger, C.; Stewart, M. E. *Metacognition Learn.* **2020**, *15*, 155–213.
(28) Desoete, A. *Metacognition Learn.* **2008**, *3*, 189.
(29) Veenman, M. V. J.; Van Hout-Wolters, B. H. A. M.; Afflerbach, P. *Metacognition Learn.* **2006**, *1*, 3–14.
(30) Ericsson, K. A.; Simon, H. A. *Protocol analysis: Verbal reports as data*; MIT Press: Cambridge, MA, 1993.
(31) Veenman, M. V. J. *Metacognition Learn.* **2011**, *6*, 205–211.
(32) Schellings, G. L. M.; van Hout-Wolters, B. H. A. M.; Veenman, M. V. J.; Meijer, J. *Eur. J. Psychol. Educ.* **2013**, *28*, 963–990.
(33) Schraw, G.; Crippen, K. J.; Hartley, K. *Res. Sci. Educ.* **2006**, *36*, 111–139.
(34) Cooper, M. M.; Sandi-Urena, S.; Stevens, R. *Chem. Educ. Res. Pract.* **2008**, *9*, 18–24.
(35) Veenman, M. V. J. The Assessment of Metacognitive Skills: What Can Be Learned from Multi-Method Designs? In *Lernstrategien und Metakognition: Implikationen fur Forschung und Praxis*; Artelt, C., Moschner, B., Eds.; Waxmann: Munster, 2005; pp 77–99.
(36) Avargil, S.; Lavi, R.; Dori, Y. J. Students' Metacognition and Metacognitive Strategies in Science Education. In *Cognition, Metacognition, and Culture in STEM Education: Learning, Teaching and Assessment*; Dori, Y. J., Mevarech, Z. R., Baker, D. R., Eds.; Innovations in Science Education and Technology; Springer International Publishing: Cham, 2018; pp 33–64.
(37) Lavi, R.; Shwartz, G.; Dori, Y. J. *Isr. J. Chem.* **2019**, *59*, 583–597.
(38) Cook, E.; Kennedy, E.; McGuire, S. Y. *J. Chem. Educ.* **2013**, *90*, 961–967.
(39) Mutambuki, J. M.; Mwavita, M.; Muteti, C. Z.; Jacob, B. I.; Mohanty, S. *J. Chem. Educ.* **2020**, *97*, 1832–1840.
(40) Graham, K. J.; Bohn-Gettler, C. M.; Raigoza, A. F. *J. Chem. Educ.* **2019**, *96*, 1539–1547.
(41) Casselman, B. L.; Atwood, C. H. *J. Chem. Educ.* **2017**, *94*, 1811–1821.
(42) Pulukuri, S.; Abrams, B. *J. Chem. Educ.* **2021**, *98*, 2156–2166.
(43) Parker Siburt, C. J.; Bissell, A. N.; Macphail, R. A. *J. Chem. Educ.* **2011**, *88*, 1489–1495.
(44) Heidbrink, A.; Weinrich, M. *J. Chem. Educ.* **2021**, *98*, 2765–2774.
(45) Sandi-Urena, S.; Cooper, M. M.; Stevens, R. H. *Int. J. Sci. Educ.* **2011**, *33*, 323–340.
(46) Howard, B. C.; McGee, S.; Shia, R.; Hong, N. S. Metacognitive Self-Regulation and Problem-Solving: Expanding the Theory Base through Factor Analysis. In *Proceedings of the Annual Meeting of the American Educational Research Association*, New Orleans, LA., 2000.
(47) Wang, C.-Y. *Res. Sci. Educ.* **2015**, *45*, 555–579.
(48) Schraw, G.; Dennison, R. S. *Contemp. Educ. Psychol.* **1994**, *19*, 460–475.
(49) Cooper, M. M.; Sandi-Urena, S. *J. Chem. Educ.* **2009**, *86*, 240–245.
(50) Kadioglu-Akbulut, C.; Uzuntiryaki-Kondakci, E. *Chem. Educ. Res. Pract.* **2021**, *22*, 12–29.
(51) Cartrette, D. P.; Bodner, G. M. *J. Res. Sci. Teach.* **2010**, *47*, 643–660.
(52) Dye, K. M.; Stanton, J. D. *CBE—Life Sci. Educ.* **2017**, *16*, ar31-1–ar31-14.
(53) Graulich, N.; Langner, A.; Vo, K.; Yuriev, E. Chapter 3. Scaffolding Metacognition and Resource Activation During Problem Solving: A Continuum Perspective. In *Advances in*

Chemistry Education Series; Tsaparlis, G., Ed.; Royal Society of Chemistry: Cambridge, 2021; pp 38–67.
(54) Lopez, E. J.; Nandagopal, K.; Shavelson, R. J.; Szu, E.; Penn, J. *J. Res. Sci. Teach.* **2013**, *50*, 660–676.
(55) Mathabathe, K. C.; Potgieter, M. *Int. J. Sci. Educ.* **2017**, *39*, 1465–1484.
(56) Cruz-Ramírez de Arellano, D.; Towns, M. H. *Chem. Educ. Res. Pract.* **2014**, *15*, 501–515.
(57) Finkenstaedt-Quinn, S. A.; Watts, F. M.; Petterson, M. N.; Archer, S. R.; Snyder-White, E. P.; Shultz, G. V. *J. Chem. Educ.* **2020**, *97*, 1852–1862.
(58) Grove, N. P.; Cooper, M. M.; Cox, E. L. *J. Chem. Educ.* **2012**, *89*, 850–853.
(59) Grove, N. P.; Cooper, M. M.; Rush, K. M. *J. Chem. Educ.* **2012**, *89*, 844–849.
(60) Webber, D. M.; Flynn, A. B. *J. Chem. Educ.* **2018**, *95*, 1451–1467.
(61) Andriani, E.; Mbato, C. L. *J. Engl. Foreign Lang.* **2021**, *11*, 275–296.
(62) Thuy, N. T. T. *Theory Pract. Lang. Stud.* **2020**, *10*, 157–167.
(63) Helix, M. R. Unpublished Work, University of California, Berkeley, United States -- California, 2021.
(64) Bodner, G. M. *Univ. Chem. Educ.* **2003**, *7*, 37–45.
(65) Carr, M.; Taasoobshirazi, G. Metacognition in the Gifted: Connections to Expertise. In *Meta-Cognition: A Recent Review of Research, Theory and Perspectives*; Shaughnessy, M. F., Veenman, M. V. J., Kleyn-Kennedy, C., Eds.; Nova Science: Hauppauge, 2008; pp 109–125.
(66) Shin, N.; Jonassen, D. H.; McGee, S. *J. Res. Sci. Teach.* **2003**, *40*, 6–33.
(67) Paulhus, D. L. Chapter 2 - Measurement and Control of Response Bias. In *Measures of Personality and Social Psychological Attitudes*; Robinson, J. P., Shaver, P. R., Wrightsman, L. S., Eds.; Academic Press, 1991; pp 17–59.
(68) Berger, J.-L.; Karabenick, S. A. *Educ. Assess.* **2016**, *21*, 19–33.
(69) Schellings, G. *Metacognition Learn.* **2011**, *6*, 91–109.
(70) Veenman, M. V. J. Learning to Self-Monitor and Self-Regulate. In *Handbook of Research on Learning and Instruction*; Mayer, R. E., Alexander, P. A., Eds.; Routledge: New York, 2016.
(71) Bland, J. M.; Altman, D. G. Statistics Notes: Cronbach's Alpha. *BMJ* **1997**, *314*, 572.
(72) O'Neil, H. F.; Abedi, J. *J. Educ. Res.* **1996**, *89*, 234–245.
(73) Finn, B. *Measuring Motivation in Low-Stakes Assessments*; ETS Research Report Series; 2015; pp 1–17.
(74) Finn, B. *J. Appl. Res. Mem. Cogn.* **2020**, *9*, 461–467.
(75) Xu, X.; Villafane, S. M.; Lewis, J. E. *Chem. Educ. Res. Pract.* **2013**, *14*, 188–200.
(76) González, A.; Paoloni, P.-V. *Chem. Educ. Res. Pract.* **2015**, *16*, 640–653.
(77) Dianovsky, M. T.; Wink, D. J. *Sci. Educ.* **2012**, *96*, 543–565.
(78) Yuriev, E.; Naidu, S.; Schembri, L. S.; Short, J. L. *Chem. Educ. Res. Pract.* **2017**, *18*, 486–504.

Chapter Contributions

The work described in this chapter would not have been possible without the contributions of Anne Baranger, Julia Greenbaum, Max Helix, Nelson Gaillard, and Nikita Redkar. Each member of this group provided me with constructive feedback and advice on the survey items, coding scheme, interview protocols, or other aspects of the research methodology. Julia Greenbaum, Nelson Gaillard, and Nikita Redkar helped me with transcribing and coding interview data from Study 1. I performed all other data collection, data analysis, and additional research activities described in this chapter.

Appendices

Appendix 2.1: Interview Protocol for Study 1

Introduction and Background Questions:

Thanks so much for coming, I really appreciate your help. First, I just want to start off with a couple background questions and some general questions about your experience with organic chemistry.

Undergraduates:

1. What organic chemistry courses have you taken so far?
2. What is your year in school and intended major?

Graduate Students:

1. What year are you in your program?
2. Which research group are you in?
    - How long have you been working with them?
    - Can you briefly (~1-2 min) describe your project?
3. Have you taken any organic courses in graduate school?
    - If yes, what were they?
    - If no, when was the last organic course you took?
4. Have you taught any organic chemistry courses?
    - If yes, what were they?

Instructions for Think-Aloud Portion:

Part of what I'm trying to study is the detailed thought processes that go on in people's minds while they are working on solving typical organic chemistry problems. What I'm going to have you do is work through a predict-the-product organic problem, and I want you to vocalize your thoughts as you have them, to the best of your ability.

You are not being evaluated on whether you get the "right" answer – there might not even be one specific "right" answer. Mainly what I'm hoping to get insight into is how people end up at a variety of answers, what the thought processes are that lead to those answers, and what kinds of things people are considering that don't make it onto the page or into their "final answer."

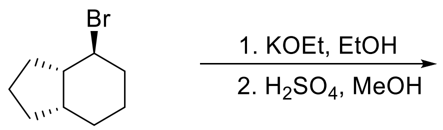
Do you have any questions for me?

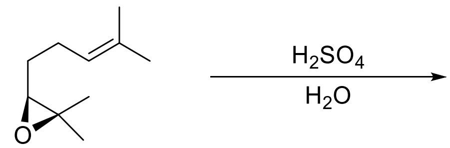
Please vocalize your thoughts as you have them, and let me know when you have finished working on the problem. If you are completely unsure and don't have thoughts on how to proceed further, just give me your best guess. We're trying to get at the best approximation of the thoughts you'd have if you were sitting alone, working on this problem without any cameras. Please try to keep talking, even if your thoughts aren't fully formed yet.

First Think-Aloud Problem:

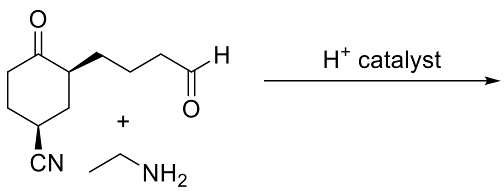
Each student works on two problems over the course of the interview. They work on the first problem before the discussion portion of the interview. The order of the problems is chosen randomly prior to the interview.

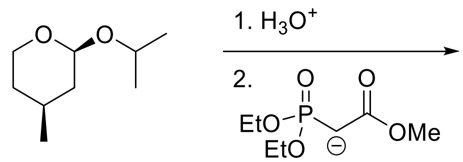
Problems Completed by Organic Chemistry I Students





Problems Completed by Organic Chemistry II Students and Graduate Students





Survey Completed After the Student Finishes the First Problem:

Great job! The next thing I'd like you to do is fill out this short survey. After you've filled out the survey, we'll discuss your answers and then talk more about how you approach organic chemistry problems.

The student is sent a link to a survey hosted on Qualtrics. Once they finish it, they engage in a guided discussion about their problem-solving strategies.

Discussion Questions:

- There are many different strategies mentioned on this survey.
  - Can you explain why you do use [strategies the student said they used often]?
  - Can you explain why you don't use [strategies the student said they did not often use]?
- Are there some strategies you use all the time, and some you only use when you're having trouble with a problem?
- What is your strategy when solving a problem on an exam?
- Would your strategy change at all if it was a problem on a homework assignment?
- Does time pressure lead you to change your strategy? What about access to notes?
- How did you come to use the strategies you use?

Second Think-Aloud Problem and Accompanying Survey:

The student completes a second problem while vocalizing their thoughts. After they finish, the student is sent a link to a second survey hosted on Qualtrics.

Thank you so much for completing that survey and for participating in this interview. Please let me know if you have any questions for me before we end the interview.

Appendix 2.2: Survey Taken on Qualtrics after Interview Problems

Notes:

- *The answer choices were the same for each question in Part 1. For brevity, these answer choices are only displayed for the first item in this Appendix. Part 1 is a copy of the Metacognitive Strategies Survey described in Study 2.*
- *After the first interview problem, students completed both Part 1 and Part 2. After the second interview problem, students completed only Part 2.*

Part 1: Please indicate how frequently you used the following strategies when solving organic chemistry problems on homework and on exams for the most recent course you have taken that was related to organic chemistry. Choose the option that best represents your actual behavior when solving problems, not what your behavior would have ideally been if you had more time, had studied more, etc.

1. I set goals (ex. "I need to make this bond," or "I want to make this functional group") before attempting a solution.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework				
While working on exams				

2. Before I start working on a problem, I sort through the information in the problem to determine what is relevant.
3. Before I start working on a problem, I look for any reactions I recognize.
4. I reflect upon things I know that are relevant to a problem before I start working.
5. I try to relate unfamiliar problems with previous problems I've encountered.
6. I jot down my ideas or things I know that are related to the problem before attempting a solution.
7. I make predictions about what will happen before I start working on a problem.
8. I brainstorm multiple ways to solve a problem before I actually start solving it.
9. I consider whether my proposed steps are reasonable before I actually start solving a problem.
10. When I'm the middle of working on a problem, I pause to consider whether there is another way to solve it.
11. While I'm working on a problem, I pause to consider whether I am making progress towards my goals.
12. I pause to consider whether what I am doing is correct while I'm working on a problem.
13. I take note of what I am uncertain about as I work on a problem.
14. As I work on a problem, I periodically check back over what I have done so far to make sure my overall approach is reasonable.
15. I think about whether my answer is reasonable after I finish a problem.
16. I make sure that my solution actually answers the question.
17. I check back over my work once I finish a problem to make sure I didn’t make any mistakes.
18. Once I reach an answer, I check to see that it agrees with what I predicted.
19. Once I finish a problem, I summarize the main take-away lesson I have learned.
20. After I finish a problem, I consider how I might change my approach for future problems.

Part 2: Please indicate whether you used these strategies when working on the interview problem.

	Yes	No
I set goals (ex. "I need to make this bond," or "I want to make this functional group") before attempting a solution.		
Before I started working, I sorted through the information in the problem to determine what is relevant.		
Before I started working, I looked for any reactions I recognized.		
I reflected upon things I know that are relevant to the problem before I started working.		
I tried to relate unfamiliar problems with previous problems I've encountered.		
I jotted down my ideas or things I know that are related to the problem before attempting a solution.		
I made predictions about what would happen before I started working on the problem.		
I brainstormed multiple ways to solve a problem before I actually started solving it.		
I considered whether my proposed steps were reasonable before I actually started solving the problem.		
When I was in the middle of working on the problem, I paused to consider whether there was another way to solve it.		
While I was working on the problem, I paused to consider whether I was making progress towards my goals.		
I paused to consider whether what I was doing was correct while I was working on the problem.		
I took note of what I was uncertain about as I worked on the problem.		
As I worked on the problem, I periodically checked back over what I had done so far to make sure my overall approach was reasonable.		
I thought about whether my answer was reasonable after I finished the problem.		
I made sure that my solution actually answered the question.		
I checked back over my work after I finished the problem to make sure I didn’t make any mistakes.		
Once I reached an answer, I checked to see that it agreed with what I predicted.		
Once I finished the problem, I summarized the main take-away lesson I learned.		
After I finished the problem, I considered how I might change my approach for future problems.		

Appendix 2.3: Metacognitive Strategies Coding Scheme

General Notes on Usage of Planning, Monitoring, and Evaluation Codes:

- Planning Codes should only be assigned before the student draws their first new chemical structure. If the problem consists of multiple steps, planning codes can also be assigned when the student begins talking about the second step of the reaction.
- Monitoring Codes should only be assigned after the student has started drawing their first new chemical structure, but has not yet reached an answer.
- Evaluation Codes should only be assigned after the student has reached their final answer, or what they initially stated was their answer if they later changed their mind.

Table A2.3.1. Names, Definitions, and Examples of All Codes in Metacognitive Strategies Coding Scheme

Code	Description	Example(s)
Set Goals	*"I set goals (ex. "I need to make this bond" or "I want to make this functional group") before attempting a solution."* The student states something they want or think they'll need to do to answer the question.	"So somehow... I guess I have to make that into a carbonyl" "I have to figure out where it would attack and why this acid would make it attack there."
Sort Relevant Info	*"Before I started working on the problem, I sorted through the information in the problem to determine what was relevant."* The student verbally identifies, highlights, or circles instructions, reagents, functional groups, etc. that they notice in the problem statement.	"Ok so I see a lot of carbons here" "I see a double bond" *Student highlights "stereochemistry" in problem statement*
Look for Reactions Recognized	*"Before I start working on a problem, I look for any reactions I recognize."* The student identifies or states that they are looking for known reactions.	"This is kind of like a Wittig" "The first thing I would say...is does it look like anything I'm immediately familiar with, anything I know."
Reflect Relevant Knowledge	*"I reflected upon things I know that are relevant to the problem before I started working."* The student states what they know about reactions or structural features they've identified in the problem.	"The Wittig-type would give the double bond here" "I know oxygen is a pretty good nucleophile" "We learned this is the trans"
Relate to Previous Problems	*"I tried to relate unfamiliar problems with previous problems I've encountered"* The student refers back to a problem they had previously solved and compares it to the problem they are currently working on.	"My first prediction is that this oxygen right here is going to get a hydrogen from the sulfate. And why I did that is because I think I've seen this in a past question."
Make Predictions	*"I made predictions about what would happen before I started working on the problem."* The student makes a prediction about what reactivity will occur beginning from the starting material (or an intermediate product in the case of a multi-step reaction).	"This presumably would hydrolyze the acetal to get back to either a hemiacetal or an aldehyde" "You're probably making an alkene" "First this will make an imine"

Jot Down Ideas	*"I jotted down my ideas or things I know that are related to the problem before attempting a solution."* At the beginning of the problem, the student writes downs things they know or adds other written annotations to the problem.	*Student writes "strong acid" beside H_2SO_4* *Student writes "1. open the epoxide 2. methyl shift"* *Student writes "6 memb ring?"*
Brainstorm Multiple Ways	*"I brainstormed multiple ways to solve the problem before I actually started solving it."* The student proposes multiple possible ways to solve the problem, at the beginning of the problem-solving process.	"I feel like there's many things I could do here. I feel like I could do either like maybe open the epoxide, or I could maybe do a methyl shift."
Consider If Plan Reasonable	*"I considered whether my proposed steps were reasonable before I actually started solving the problem."* The student makes a judgement about whether their proposed steps are correct or likely, before they draw their first new structure.	"Right away I think 'it's acid so it's going to protonate the amine'…but that's not really a useful reaction because it's just going to sit there."
Consider Another Way	*"While I was working on a problem, I paused to consider whether there was another way to solve it."* After they have started down one path, the student considers an alternate chemical path or an alternate problem-solving approach.	"Maybe I'll just try to do the protonation of the other one and see what happens" "Hm, maybe I should think more about the mechanism"
Monitor Progress Towards Goals	*"I paused to consider whether I was making progress towards my goals as I worked on the problem."* The student considers whether what they have done so far has gotten them closer to a goal they had previously stated or considers what they still need to do in order to achieve their goals/continue making progress.	"Ok so now we're catalytic in acid" (Note: Student previously set a goal to find a way to make the reaction catalytic in acid, and they're confirming that they've done that) "I'm just trying to make a carbonyl group, so would that help?" "That's probably not going to get me anywhere useful for this."
Monitor Correctness	*"I paused to consider whether what I was doing was correct as I worked on the problem."* The student asks themselves whether something is correct, or states that something they've done or are proposing to do is right/reasonable or wrong/unreasonable.	"That leaves a positive charge there, so you don't want to do that" "This looks so wrong" "This is kind of reasonable" "I think this works"
Note Uncertainty	*"I took note of what I was uncertain about as I worked on the problem."* The student states what they are not sure about or what they do not know.	"And then I am a little stuck on what to do with the second solvent in this first step." "I don't have a periodic table so I'm not exactly sure if sulfur is the one that would be donating electrons."
Periodically Check If Reasonable	*"As I was working on the problem, I periodically checked back over what I had done so far to make sure my overall approach was reasonable."*	"I like that step, and I like that step. I'm a little iffy about these steps." "Ok, let's see. Do I like this? Let me think. Am I forgetting anything?"

	The student looks back over what they've done so far to confirm that their steps were reasonable.	(Note: They are checking back on what they've done so far, in the middle of the problem)
Consider If Answer Reasonable	*"I thought about whether my answer was reasonable after I finished the problem."* Once they have reached an answer, the student states whether they think their answer is correct or reasonable.	"It doesn't look that bad, hm, ok I think I'm happy with it "I don't agree with the product. Because that looks off."
Check if Answered Question	*"I made sure that my solution actually answered the question."* The student refers back to the question statement to make sure that they followed the directions or that their answer fulfills all components of the prompt.	"So am I happy with that? Let's look. Major products. I want to say this is the major product." (Note: They refer back to the instructions, which said to predict the major products.)
Check For Mistakes	*"I checked back over my work after finishing the problem to make sure I didn't make any mistakes."* The student goes over what they've done to make sure their answer is correct and free of mistakes.	"Then count my atoms just to make sure I didn't miss anything. This one's here, this one's right here." "Is there anything else that I'm missing? Charges? Oxygen has a good charge, all the other ones have a good charge. Ok."
Check If Agreed With Prediction	*"Once I reached an answer, I checked to see that it agreed with what I predicted."* After reaching an answer, the student refers back to a prediction that they had made during the problem and considers whether their answer agrees with that prediction.	"So I think this is my final answer. I also said there would be no acid-base, but water is there so maybe?" (Note: This student had predicted there would be no acid-base chemistry involved in the reaction. They are referring back to this prediction.)
Summarize Main Takeaways	*"Once I finished the problem, I summarized the main take-away lesson I learned."* After reaching an answer, the student considers what they learned from the problem.	"There's a divergence that could give you that product, but I just kept going with mine. I see that you have to draw your product and then really sit and think about it."
Consider Changes For Future	*"After I finished the problem, I considered how I might change my approach for future problems."* The student suggests a way that they could change or improve the way they approach problem solving in the future.	A possible example would be a student stating that they should check their work more in the future.

Appendix 2.4: Coding Scheme: Reasons for Using or Not Using Metacognitive Strategies

Table A2.4.1. Names, Definitions, and Examples of Codes Related to Reasons for Using Strategies

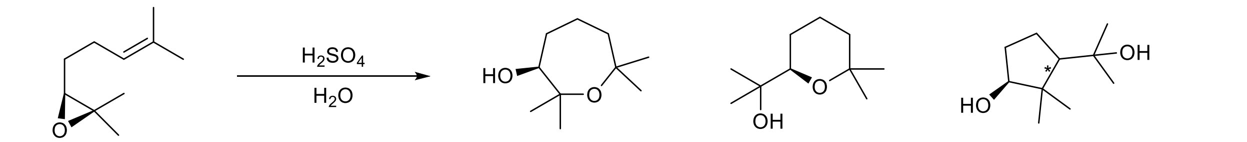
Code	Description	Example(s)
Builds confidence	The student uses this strategy because it helps them feel more confident in their answer or thought process.	"If I see something unfamiliar and I think, you know, how is this similar to something I've done before...that'll make me feel a lot more confident."
Many reactions to consider	The student uses this strategy because they recognize that a wide variety of reactions or types of reactivity exist and could possibly be relevant to the problem.	"The more organic chem classes you take, you learn a lot more reactions, and I think having that much information to go through is kind of a lot. And so being able to break it down into smaller chunks I find very useful."
Helps them learn/ improve	The student uses this strategy because it helps them learn or improve their knowledge or problem-solving skills.	"I thought it was important for me to summarize what did I learn from the solution...because that'll help me in the future when I encounter this type of problem."
Avoid wasting time/effort	The student uses this strategy because it helps them avoid wasting time or effort during the problem-solving process.	"If I'm not certain about something, I don't want to waste too much time on it. And so I'll star it, try to guess something, and then come back to it at the end if I have time."
Get started/ narrow focus	The student uses this strategy because it helps them get started on the problem or narrow their focus to certain pathways.	"Identifying specifically the bonds that need to be made or broken really helps you narrow the focus of a 1000 molecular weight molecule down to the 5 or 6 atoms that are actually relevant to the question and that takes out a lot of options."
Keeps them on right track	The student uses this strategy because it helps them stay on the right path and continue making progress towards an answer.	"It helps with making sure you're going down the right path, making sure you're getting the right steps. Especially when I get stuck, I think just looking at what I need to get to is a key thing I do."
Keeps them from forgetting	The student uses this strategy because it helps prevent them from forgetting an idea or piece of information.	"Yeah, I would sometimes do that because I don't want to just rely on my brain to remember everything."
Someone encouraged use	The student uses this strategy because another person, such as an instructor or tutor, encouraged them to use this strategy.	"I definitely always look at what bond I need to make and what functional group I need to make if there is a product written out for me. Because not only [my professor], but my [teaching assistant], reiterated that a lot. So that's just how I learned o-chem."
Helps avoid mistakes	The student uses this strategy because it helps them avoid making mistakes.	"One of my biggest mistakes could be with forgetting atoms or incorrect stereochemistry. So I made sure, for this example, to double check my stereochemistry, and I was trying to count the carbons in one of the chains in the ring that opened."

Table A2.4.2. Names, Definitions, and Examples of Codes Related to Reasons for Not Using Strategies

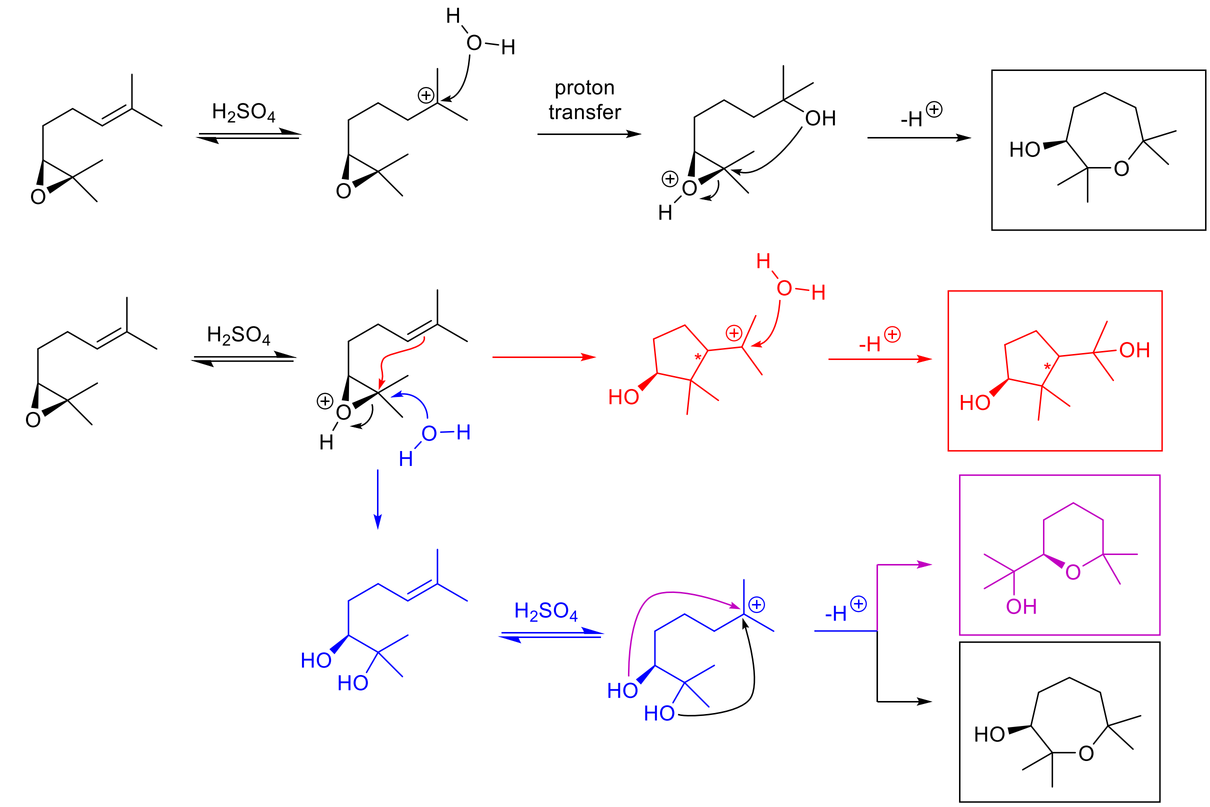
Code	Description	Example
Prevents success: distracting	The student does not use this strategy because it distracts them and they therefore consider it to be detrimental to their success in solving the problem.	"So that one is mainly just because I tend to work things out to the end and then I go back to evaluate whether what I got was reasonable so when I'm working on something I'm not as distracted by what other things could be happening."
Prevents success: other	The student does not use this strategy because they consider it to be detrimental to their success in solving the problem for another reason, or they state that it is detrimental without stating a specific reason.	"I think the setting goals could be potentially dangerous if it leads you down a wrong path. Especially when approaching certain problems like mechanism or predict-the-products you kind of have to be open-minded until you've at least narrowed it down."
Issues with timing	The student does not use this strategy because there is not typically enough time for them to use it.	"Yeah, I think just because of the time constraints, I don't normally do that...I don't really have time to list it out."
Unable to use effectively	The student does not use this strategy because they believe they are unable to use the strategy effectively, often because they do not feel experienced enough to do so.	"I never really predict products because it's really hard for me to visualize what's going to happen."
Unnecessary: have answer	The student does not use this strategy because they consider it to be unnecessary when they have already found an answer to the problem.	"But like brainstorming other ways to solve it, I feel like in some cases that would kind of be a waste of time or unnecessary since if you're already doing it in your way and that's going to lead to the desired product and you already know that, then you don't really need to brainstorm ways to do it...you're just trying to get to the answer or something."
Unnecessary: redundant	The student does not use this strategy because they consider it to be unnecessary because they either use a different strategy for the same purpose or use a similar strategy at a different time in the problem.	"After I finish a problem I usually immediately get to the next problem, so that's why I marked "no" on a lot of those, like after the problem checked to see if it made sense, checked to see if you answered the question, I feel like I double-check myself enough times each step if I could actually get to an answer that there's no need to go past that."
Unnecessary: other	The student does not use this strategy because they consider it to be unnecessary for another reason, or they state that it is unnecessary without stating a specific reason.	"I just don't find it very helpful. I know some people like to make lots of thought maps to understand where the initial reactant could lead them to, but to me, that just seems like a waste of brainpower."

Appendix 2.5: Accepted Answers, Mechanisms, and Grading Rubrics for Problems A-D

Accepted Answer(s): Problem A



Mechanism:



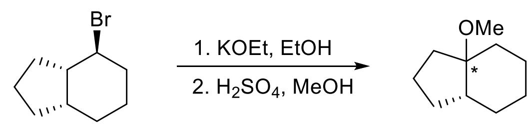
Grading Rubric:

Minimum score: 0 (fully incorrect; no partial credit possible), Maximum score: 4 (fully correct)

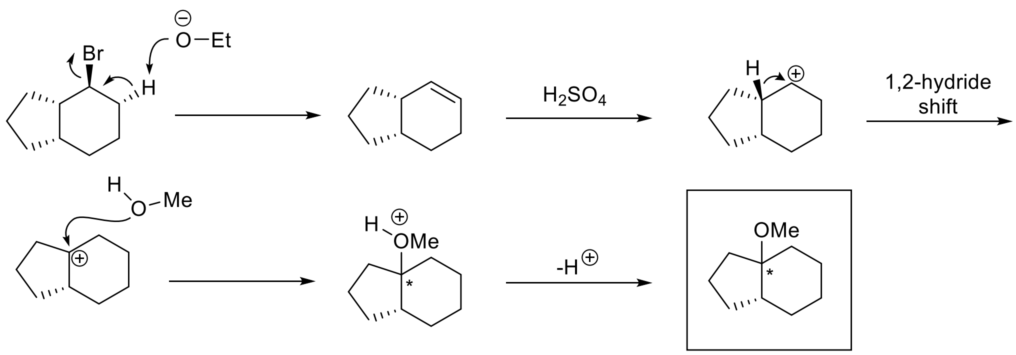
Partial Credit Options and Point Deductions:

+2 points	Student's product involved a reasonable reaction between the epoxide and the given reagents, but there was no involvement of the alkene
+2 points	Student's product involved a reasonable reaction between the alkene and the given reagents, but there was no involvement of the epoxide
+3 points	Student's product involved reasonable reactions between both the alkene and the epoxide with the given reagents, but no intramolecular cyclization
-0.5 points	Student's product included the result of unreasonable further reactivity
-0.5 points	Stereochemical errors or minor drawing errors are present in the product(s) the student drew. *Note: these errors should not be considered when determining whether an answer qualifies for other partial credit options.*

Accepted Answer(s): Problem B



Mechanism:



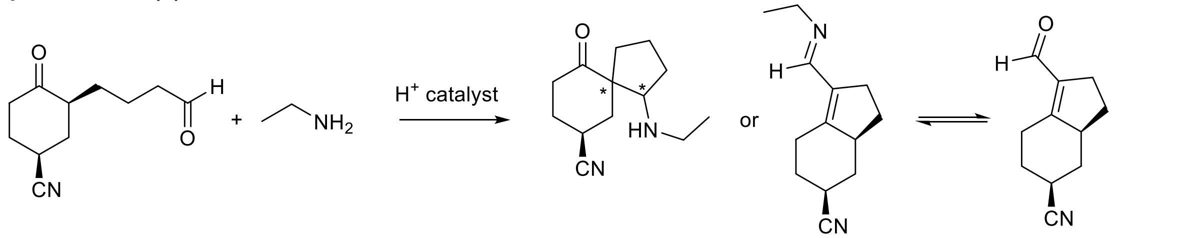
Grading Rubric:

Minimum score: 0 (fully incorrect; no partial credit possible), Maximum score: 4 (fully correct)

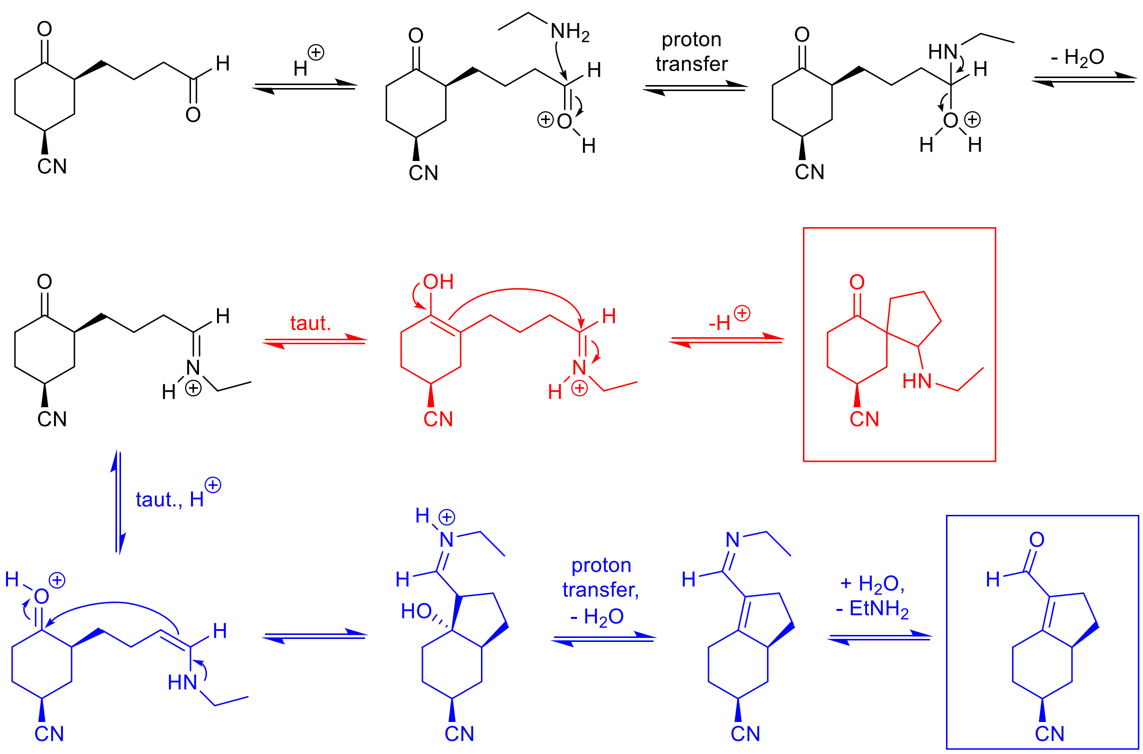
Partial Credit Options and Point Deductions:

+1 point	Student chose incorrect reaction type (i.e. E1, SN1, or SN2 instead of E2) for step 1, but completed chosen reaction correctly, OR chose correct reaction type (E2) but completed chosen reaction incorrectly
+2 points	Student completed step 1 correctly
+1 point	Based on their answer to step 1, student chose incorrect reaction type for step 2, but completed chosen reaction correctly, OR chose correct reaction type for step 2 but completed chosen reaction incorrectly
+2 points	Student generated correct product in step 2 based on the product they generated in step 1
-0.5 points	Stereochemical errors or minor drawing errors are present in the product(s) the student drew for step 1 and/or step 2. *Note: these errors should not be considered when determining whether an answer qualifies for other partial credit options.*

Accepted Answer(s): Problem C



Mechanism:



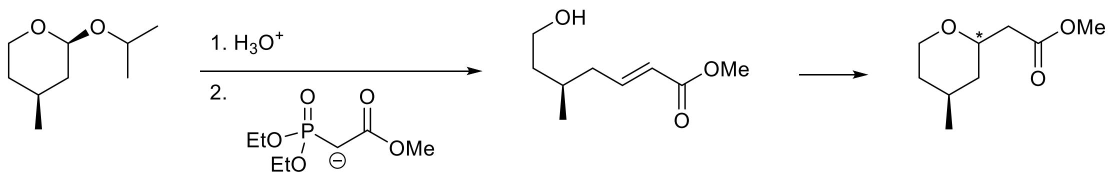
Grading Rubric:

Minimum score: 0 (fully incorrect; no partial credit possible), maximum score: 4 (fully correct)

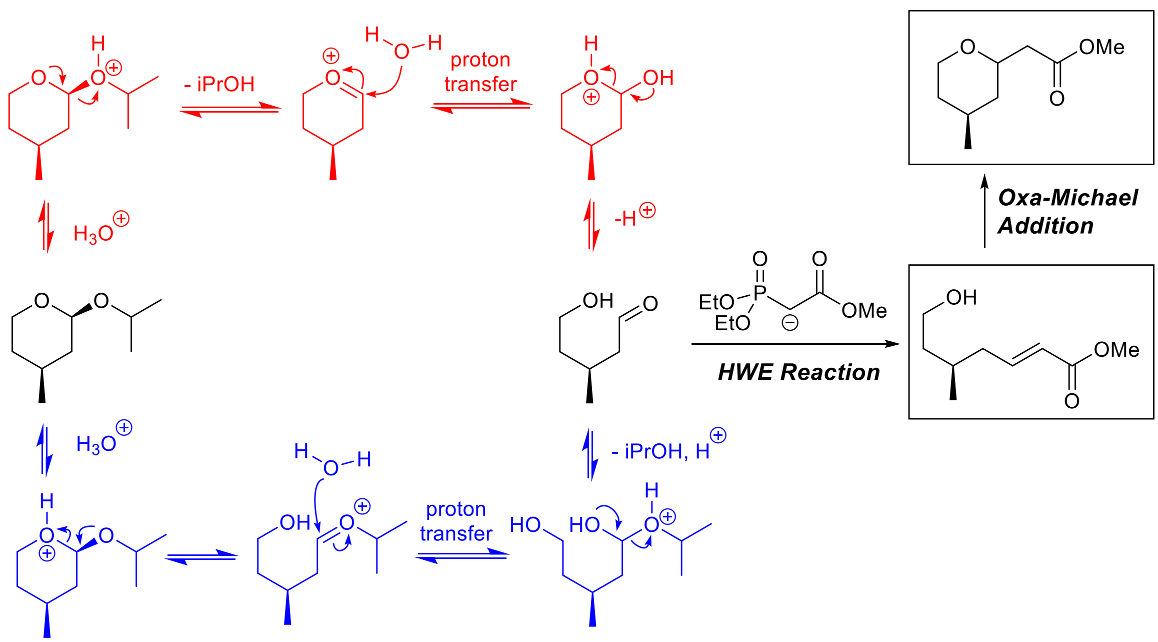
Partial Credit Options and Point Deductions:

+1 point	Student used ethylamine as a nucleophile to react with one of the carbonyls
+1 point	Student chose correct carbonyl as the electrophile
+1 point	Student generated an imine, iminium ion, or enamine after reacting ethylamine with their chosen carbonyl.
+1 point	Student completed a reasonable intramolecular Mannich reaction or amine-catalyzed aldol reaction after generating an imine, iminium ion, or enamine.
-0.5 points	Student's product included the result of unreasonable further reactivity
-0.5 points	Stereochemical errors or minor drawing errors are present in the product(s) the student drew. *Note: these errors should not be considered when determining whether an answer qualifies for other partial credit options.*

Accepted Answer(s): Problem D



Mechanism: (Note - two possible mechanisms are possible for the hydrolysis of the acetal)



Grading Rubric:

Minimum score: 0 (fully incorrect; no partial credit possible), maximum score: 4 (fully correct)

Partial Credit Options and Point Deductions:

+1 point	Student completed initial steps of the acetal hydrolysis reaction in step 1, but they did not complete the overall acetal hydrolysis transformation correctly
+2 points	Student completed step 1 correctly
+1 point	Student completed first step of the HWE reaction with the product they generated in step 1, but they did not complete the overall HWE transformation correctly
+2 points	Student generated correct product of HWE reaction in step 2 based on the product they generated in step 1
-0.5 points	Stereochemical errors or minor drawing errors are present in the product(s) the student drew. *Note: these errors should not be considered when determining whether an answer qualifies for other partial credit options.*

Appendix 2.6: Strategies Used By Students During Selected Problem-Solving Cases

Table A2.6.1. Strategies Used By Students During Selected Problem-Solving Cases. Shaded Cells Indicate Strategy Usage

Strategy	Andrew (Less Successful, Lower Metacognition)		Lily (Less Successful, Higher Metacognition)		Ben (More Successful, Lower Metacognition)		Marta (More Successful, Higher Metacognition)	
	Strategy Used?		Strategy Used?		Strategy Used?		Strategy Used?	
	SR [a]	OB [b]	SR	OB	SR	OB	SR	OB
Set Goals	■		■		■		■	
Sort Relevant Info	■	■	■	■	■	■	■	■
Look for Reactions Recognized	■		■	■	■		■	
Reflect Relevant Knowledge	■	■	■	■	■	■	■	■
Relate to Previous Problems	■		■	■	■		■	
Jot Down Ideas								
Make Predictions	■	■	■	■	■		■	■
Brainstorm Multiple Ways			■			■		■
Consider If Plan Reasonable	■		■		■		■	
Consider Another Way			■	■	■		■	■
Monitor Progress Toward Goals			■	■	■		■	■
Monitor Correctness			■	■	■		■	■
Note Uncertainty				■	■		■	■
Periodically Check If Reasonable			■	■			■	■
Consider If Answer Reasonable	■		■	■	■	■	■	
Check If Answered Question	■		■		■		■	
Check For Mistakes		■	■					■
Check If Agreed with Prediction	■		■		■		■	
Summarize Main Takeaways			■					
Consider Changes for Future			■					

[a] Self-reported strategy usage: student selected "yes" when asked on the post-problem survey if they had used this strategy while solving the problem
[b] Observed strategy usage: evidence of this behavior was detected in think-aloud transcript

Appendix 2.7: Frequencies with which Interview Participants Gave Certain Reasons for Using or Not Using Individual Strategies

Table A2.7.1. Frequencies with which Interview Participants Gave Certain Reasons for Using or Not Using Individual Strategies. Increased Color Saturation Indicates Higher Frequency.

Strategy	Builds confidence	Many reactions to consider	Helps them learn/improve	Avoid wasting time/effort	Get started/narrow focus	Keeps them on right track	Keeps them from forgetting	Someone encouraged use	Helps avoid mistakes	Prevents success - other	Prevents success - distracting	Issues with timing	Not experienced enough	Unnecessary - other	Unnecessary – have answer	Unnecessary - redundant
Set Goals	2	2		1	8	3	1	6	1	4		2	5	3	1	
Sort Relevant Info		1		1	14	1		2				1				
Look for Reactions Recognized	1	4		1	11			2		1						
Reflect Relevant Knowledge			1	1	6	3	1	3	1			1	1	1		
Relate to Previous Problems	1	1	4	1	7			1	1	1	1	1	1	3		
Jot Down Ideas	1	1	2	1	7	1	7	2	3		7	9	4	14	1	
Make Predictions	1			2	2	1		1	2	1	1		11	1	1	
Brainstorm Multiple Ways					2					1	3	8	2	5	4	2
Consider if Plan Reasonable									1		1	1	5			2
Consider Another Way		3		1		1			3	1	4	1	2	1	4	
Monitor Progress Toward Goals				4		4			1			2	3	1		1
Monitor Correctness		1	1	4		4			8		1	1		3		1
Note Uncertainty			5	2	1	4	3		1	1		6	1	2		1
Periodically Check If Reasonable	1			1		6			6	1	3	3	2	3		3
Consider If Answer Reasonable	1								3				2	1	1	
Check If Answered Question			1	1				1	9						1	1
Check For Mistakes	1			1			1	2	18			14	1	2	1	2
Check If Agreed with Prediction			1				1					2	8	2	1	1
Summarize Main Takeaways			12					2	2			10	2	11	5	4
Consider Changes for Future			3						1			4	3	3	5	1

Appendix 2.8: Metacognitive Strategies Survey: Undergraduate Students

Usage of Problem-Solving Strategies

Please indicate how frequently you use the following strategies when solving organic chemistry problems on homework assignments and on exams. Choose the option that best represents your **actual** behavior when solving problems on these assignments -- not what your behavior would have ideally been if you had more time, had studied more, etc.

I set goals (ex. "I need to make this bond," or "I want to make this functional group") before attempting a solution.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Before I start working on a problem, I sort through the information in the problem to determine what is relevant.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Before I start working on a problem, I look for any reactions I recognize.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I reflect upon things I know that are relevant to a problem before I start working.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I try to relate unfamiliar problems with previous problems I've encountered.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I jot down my ideas or things I know that are related to the problem before attempting a solution.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I make predictions about what will happen before I start working on a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I brainstorm multiple ways to solve a problem before I actually start solving it.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I consider whether my proposed steps are reasonable before I actually start solving a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

When I'm the middle of working on a problem, I pause to consider whether there is another way to solve it.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

While I'm working on a problem, I pause to consider whether I am making progress towards my goals.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I pause to consider whether what I am doing is correct while I'm working on a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I take note of what I am uncertain about as I work on a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

As I work on a problem, I periodically check back over what I have done so far to make sure my overall approach is reasonable.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I think about whether my answer is reasonable after I finish a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

I make sure that my solution actually answers the question.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

I check back over my work once I finish a problem to make sure I didn't make any mistakes.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

Once I reach an answer, I check to see that it agrees with what I predicted.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

Once I finish a problem, I summarize the main take-away lesson I have learned.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

After I finish a problem, I consider how I might change my approach for future problems.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

Course Background

Which organic chemistry course are you currently taking?

◯ CHEM 3A
◯ CHEM 3B

Had you previously taken CHEM 3A at UC Berkeley prior to the current semester?

◯ Yes
◯ No

Please indicate in which semester(s) you previously took CHEM 3A at UC Berkeley (check all that apply):

☐ Fall 2017

☐ Spring 2018
☐ Summer 2018
☐ Fall 2018
☐ Spring 2019
☐ Summer 2019
☐ Fall 2019
☐ Spring 2020
☐ Summer 2020
☐ [ ] Other: (Please specify)

Had you previously taken CHEM 3B at UC Berkeley prior to the current semester?

◯ Yes
◯ No

Please indicate in which semester(s) you took CHEM 3B at UC Berkeley (check all that apply):

☐ Fall 2017
☐ Spring 2018
☐ Summer 2018
☐ Fall 2018
☐ Spring 2019
☐ Summer 2019
☐ Fall 2019
☐ Spring 2020
☐ Summer 2020
☐ [ ] Other: (Please specify)

Did you take CHEM 3A at UC Berkeley?

◯ Yes
◯ No

Please indicate in which semester(s) you took CHEM 3A at UC Berkeley (check all that apply):

☐ Fall 2017
☐ Spring 2018
☐ Summer 2018
☐ Fall 2018
☐ Spring 2019
☐ Summer 2019
☐ Fall 2019
☐ Spring 2020
☐ Summer 2020
☐ [ ] Other: (Please specify)

Did you complete another organic chemistry course instead of CHEM 3A at UC Berkeley?

◯ Yes
◯ No

Please indicate the name of the course and at what institution it was offered.

Demographic and Background Information

Did you transfer to UC Berkeley from another college or university?

- ◯ Yes
- ◯ No

What is your major or intended major?

- ◯ Life Science
- ◯ Physical Science (other than chemistry)
- ◯ Chemistry/Chemical Biology
- ◯ Humanities
- ◯ Social Science
- ◯ Engineering
- ◯ Public Health
- ◯ Other: (Please specify)

How many units are you taking this semester?

What is the highest level of formal education obtained by either of your parents/guardians?

- ◯ Did not complete high school
- ◯ High school graduate
- ◯ Postsecondary school other than college
- ◯ Some college
- ◯ College degree
- ◯ Some graduate school
- ◯ Graduate degree
- ◯ Not sure
- ◯ Decline to state

Are you: (Mark all that apply)

- ☐ White/Caucasian
- ☐ African American/Black
- ☐ American Indian/Alaska Native
- ☐ Middle Eastern/North African (e.g., Moroccan, Egyptian, Saudi Arabian, Iranian)
- ☐ East Asian (e.g., Chinese, Japanese, Korean, Taiwanese)
- ☐ Filipino
- ☐ Southeast Asian (e.g., Cambodian, Vietnamese, Hmong)
- ☐ South Asian (e.g., Indian, Pakistani, Nepalese, Sri Lankan)
- ☐ Other Asian
- ☐ Native Hawaiian/Pacific Islander
- ☐ Mexican American/Chicano
- ☐ Puerto Rican
- ☐ Other Latino
- ☐ Decline to state

☐ [ ] Other: (please specify)

Are you an international student?

- ◯ Yes
- ◯ No

With which gender do you most identify?

- ◯ I identify as male
- ◯ I identify as female
- ◯ I identify as non-binary
- ◯ Not sure
- ◯ Decline to state
- ◯ [ ] Other:

Is English your first language?

- ◯ Yes
- ◯ No

Survey Conclusion

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!

After submitting your responses, you can protect your privacy by clearing your browser's history, cache, cookies, and other browsing data. (Warning: This will log you out of online services.)

Powered by Qualtrics

Appendix 2.9: Metacognitive Strategies Survey: Graduate Students

Usage of Problem-Solving Strategies

Please indicate how frequently you used the following strategies when solving organic chemistry problems on homework and on exams for the most recent course you have taken that was related to organic chemistry. Choose the option that best represents your **actual behavior** when solving problems on these assignments -- not what your behavior would have ideally been if you had more time, had studied more, etc.

I set goals (ex. "I need to make this bond," or "I want to make this functional group") before attempting a solution.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Before I start working on a problem, I sort through the information in the problem to determine what is relevant.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Before I start working on a problem, I look for any reactions I recognize.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I reflect upon things I know that are relevant to a problem before I start working.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I try to relate unfamiliar problems with previous problems I've encountered.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I jot down my ideas or things I know that are related to the problem before attempting a solution.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I make predictions about what will happen before I start working on a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I brainstorm multiple ways to solve a problem before I actually start solving it.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I consider whether my proposed steps are reasonable before I actually start solving a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

When I'm the middle of working on a problem, I pause to consider whether there is another way to solve it.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

While I'm working on a problem, I pause to consider whether I am making progress towards my goals.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I pause to consider whether what I am doing is correct while I'm working on a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I take note of what I am uncertain about as I work on a problem.

	Always	Most of the time	Sometimes	Rarely or Never

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

As I work on a problem, I periodically check back over what I have done so far to make sure my overall approach is reasonable.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I think about whether my answer is reasonable after I finish a problem.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I make sure that my solution actually answers the question.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

I check back over my work once I finish a problem to make sure I didn’t make any mistakes.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Once I reach an answer, I check to see that it agrees with what I predicted.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

Once I finish a problem, I summarize the main take-away lesson I have learned.

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	○	○	○	○
While working on exams	○	○	○	○

After I finish a problem, I consider how I might change my approach for future problems.

	Always	Most of the time	Sometimes	Rarely or Never

	Always	Most of the time	Sometimes	Rarely or Never
While working on homework	◯	◯	◯	◯
While working on exams	◯	◯	◯	◯

Educational Background

Background in Organic Chemistry

Which of the following areas of chemistry are most related to your graduate research? Please check all that apply.

- ☐ Materials Chemistry
- ☐ Organic Chemistry
- ☐ Inorganic Chemistry
- ☐ Chemical Biology
- ☐ Analytical Chemistry
- ☐ Physical Chemistry
- ☐ Other (please describe):

What year did you begin your graduate program?

- ◯ 2020
- ◯ 2019
- ◯ 2018
- ◯ 2017
- ◯ 2016
- ◯ 2015
- ◯ Other (please describe):

When was the last time you taught or tutored students in a course related to organic chemistry?

- ◯ During the 2020-2021 academic year
- ◯ During the 2019-2020 academic year
- ◯ During the 2018-2019 academic year
- ◯ During the 2017-2018 academic year
- ◯ Prior to the 2017-2018 academic year
- ◯ Not Applicable

When was the last time you took a course related to organic chemistry?

- ◯ During the 2020-2021 academic year
- ◯ During the 2019-2020 academic year
- ◯ During the 2018-2019 academic year
- ◯ During the 2017-2018 academic year
- ◯ Prior to the 2017-2018 academic year
- ◯ Not Applicable

Which of the following graduate courses related to organic chemistry have you taken at UC Berkeley? Please check all that apply.

- ☐ Chem 200 (Physical Organic Chemistry)
- ☐ Chem 214 (Heterocyclic Chemistry)
- ☐ Chem 260 (Physical Organic Chemistry)
- ☐ Chem 261A/B (Organic Reactions I/II)
- ☐ Chem 262 (Metals in Organic Synthesis)
- ☐ Chem 263A/B (Synthetic Design I/II)
- ☐ Chem 265 (NMR Theory and Application)
- ☐ Other course(s), either at UC Berkeley or another institution (please describe):

How often do you do organic chemistry problems that are *not* directly related to your research project? (e.g. on your own or during journal club, research group meetings, or other group problem-solving sessions)

- ◯ At least once per week
- ◯ Once or twice per month
- ◯ About once per semester
- ◯ Rarely or never

Demographic and Background Information

Demographic Information

What is the highest level of formal education obtained by either of your parents/guardians?

- ◯ Did not complete high school
- ◯ High school graduate
- ◯ Postsecondary school other than college
- ◯ Some college
- ◯ College degree
- ◯ Some graduate school
- ◯ Graduate degree
- ◯ Not sure
- ◯ Decline to state

Are you: (Mark all that apply)

- ☐ White/Caucasian
- ☐ African American/Black
- ☐ American Indian/Alaska Native
- ☐ Middle Eastern/North African (e.g., Moroccan, Egyptian, Saudi Arabian, Iranian)
- ☐ East Asian (e.g., Chinese, Japanese, Korean)
- ☐ Filipino
- ☐ Southeast Asian (e.g., Cambodian, Vietnamese, Hmong)
- ☐ South Asian (e.g., Indian, Pakistani, Nepalese, Sri Lankan)
- ☐ Other Asian
- ☐ Native Hawaiian/Pacific Islander
- ☐ Mexican American/Chicano

- [ ] Puerto Rican
- [ ] Other Latino
- [ ] Decline to state
- [ ] ____ Other: (please specify)

Are you an international student?

- ( ) Yes
- ( ) No
- ( ) Decline to state

With which gender do you most identify?

- ( ) I identify as male
- ( ) I identify as female
- ( ) I identify as non-binary
- ( ) Not sure
- ( ) Decline to state
- ( ) ____ Other:

Is English your first language?

- ( ) Yes
- ( ) No
- ( ) Decline to State

Survey Conclusion

We appreciate your feedback. Please fill in your **email address** here. This will allow us to verify that you are a student in the chemistry department as well as match your survey responses to your interview responses, if you do choose to participate in an interview.

____

Thank you for your participation! 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!

____

After submitting your responses, you can protect your privacy by clearing your browser's history, cache, cookies, and other browsing data. (Warning: This will log you out of online services.)

Chapter 3.

Design and Evaluation of the BeArS@home and Slugs@home Choose-Your-Own-Adventure-Style Online Laboratory Experiments

Portions of this chapter are adapted with permission from:

Blackford, K. A.; Calderon, A. A.; Gaillard, N. T.; Zera, A.; Droege, D.; Pitch, S. G.; Binder, C. M.; Marsden, P. C.; Fredriksen, L. L.; Shusterman, A. A.; Douskey, M. C.; Baranger, A. M. "Design and evaluation of the BeArS@home and Slugs@home choose-your-own-adventure-style online laboratory experiments" *J. Chem. Educ.* **2022,** *99*, 2351–2363.

Abstract

The COVID-19 pandemic has brought a new emphasis to the importance of designing effective methods for remote teaching. At the University of California, Berkeley, and the University of California, Santa Cruz, instructors and staff adapted to the necessity of remote laboratory instruction by creating choose-your-own-adventure-style video-based online experiments that have been introduced to thousands of students across 11 different courses. These experiments are designed to provide students with the opportunity to make and receive feedback on experimental decisions and learn from common mistakes that they may have encountered in hands-on laboratory instruction. Students' and instructors' impressions of the online experiments and student learning outcomes in both online and traditional laboratory courses were assessed using surveys, focus groups, and interviews via a mixed-methods approach that combined quantitative analysis and thematic coding. Though most respondents (79%) did not agree that online laboratory instruction was as effective as in-person laboratory instruction, the majority agreed that the online experiments were clear and easy to follow (75%), interesting and engaging (52%), and helpful for learning about laboratory techniques (70%) and the concepts underlying these laboratory techniques (77%). Many also mentioned several benefits of online laboratory instruction, including greater flexibility in scheduling and an increased focus on conceptual learning compared to traditional methods of instruction. Assessments of student learning also suggested that students who took the course online learned as much conceptually as students who had previously completed the course in person. The results of this study highlight the positive and negative aspects of this type of interactive online laboratory instruction, which could help inform the design of future laboratory experiences whether they take place in an online, hybrid, or fully in-person environment.

Introduction

Laboratory-based learning provides students with the opportunity to gain experience with experimental techniques and instrumentation as well as engage in critical thinking, scientific decision-making, and inquiry.[1,2] For these reasons, laboratory work, particularly that which is hands-on and takes place face-to-face in teaching laboratories, is viewed as an essential component of chemistry education. The American Chemical Society, for instance, requires 400 hours of laboratory experience beyond the introductory chemistry laboratory for its accredited bachelor's degree programs, and explicitly states that virtual laboratory experiences do not count toward these hours.[3] However, traditional hands-on laboratory experiences are not always possible or practical due to school closures, financial concerns, or safety issues; thus, educators have sought out alternative methods of laboratory instruction.[4–6]

The necessity of high-quality remote laboratory experiments was made abundantly clear during the COVID-19 pandemic, when schools across the world were forced to transition instruction to a format that could be completed outside of the classroom. While virtual laboratory experiences cannot fully replicate traditional laboratory instruction, many studies have reported positive outcomes associated with these digital laboratory courses.[7] Laboratory simulations are useful for introducing new concepts to students who are less familiar with laboratory work, because the cognitive load associated with simulations is smaller than the corresponding in-person experiments.[4] They can also allow students to visualize and manipulate variables that would not be observable in a physical laboratory, which can help students make connections between different representations with varying levels of abstraction.[7] Other strengths of online laboratory experiments include increased flexibility and autonomy for students, lower operating costs and waste production, and minimal safety concerns.[8]

Realism and interactivity are among the key characteristics of effective online experiments.[9] A realistic environment can be created using video-based instruction filmed in a manner that closely reflects what students would have encountered in the physical laboratory. Interactivity can be achieved by structuring experiments such that students make and receive feedback on experimental choices that reflect actions, including mistakes, that students completing an analogous experiment in-person would likely make. This ability to make experimental decisions increases the level of control and autonomy students have in their learning; according to Self-Determination Theory, the psychological need for choice and autonomy plays a key role in the promotion of intrinsic motivation.[10] Additionally, this cycle of experimental choices and feedback introduces elements of gamification to the learning experience that have been found to be associated with increases in intrinsic motivation and self-efficacy.[11] Receiving feedback allows students to monitor their progress and determine what they do and do not understand, which can help them self-regulate their learning.[12] Several virtual experiments created during the pandemic include student decision-making as a feature, including a text-based choose-your-own-adventure-style click-through story[13] and photo or video-based experiments in which students choose different paths that mimic actions students would perform during experiments related to titrations,[9] electrochemistry,[14] or organic reactions.[15]

In response to the COVID-19 pandemic, instructors and staff at the University of California, Berkeley and University of California, Santa Cruz created choose-your-own-adventure-style virtual laboratory exercises referred to as the BeArS@home and Slugs@home online experiments. The names of these online experiments were chosen based on the universities' mascots, Oski the Bear and Sammy the Slug. In designing these experiments, the goal was to maintain the curricula's emphasis on critical thinking and experimental design, while promoting interactivity by giving students the opportunity to make experimental decisions and learn from common mistakes. While there are many commercially available online laboratory simulations, these vary in quality and are not necessarily applicable to the existing chemistry curriculum at UC Berkeley and UC Santa Cruz. For this reason, we chose to create online versions of experiments that had already been designed for our student population and used during previous semesters. Though choose-your-own-adventure-style experiments have been reported previously, studies on their use have been limited to individual courses or have focused on only a few different experiments.[9,13,14] In contrast, this work covers the design and evaluation of over 70 online experiments created for use in 11 different courses across two universities, spanning a wide range of topics in both general and organic chemistry.

In evaluating the impact of these virtual experiments, we were guided by the following research questions:

1. What are students' and instructors' general impressions of the BeArS@home and Slugs@home online experiments?
2. What do students and instructors perceive to be the specific strengths and weaknesses of the online experiments?
3. How did students approach the online experiments, and did students with different approaches perform better in the course?
4. How do student learning outcomes and self-assessed gains in understanding compare between semesters in which experiments were conducted online vs. in person?

Design and Implementation of the BeArS@home and Slugs@home Online Experiments

The online experiments are designed to guide students through the process of setting up an experiment and collecting and analyzing data in a way that promotes student choice and autonomy. In creating these experiments, we endeavored to maintain the elements of active learning, collaboration, scientific inquiry, and authentic problem-solving present in the original in-person laboratory curriculum. We chose to use Google Sites to host each experiment because of ease of use, accessibility from computers and mobile devices, and a flexible format that would give instructors the freedom to tailor material to their specific needs. The experiment sites consist of text descriptions, tables of data, and embedded videos and photos of graduate students and instructional staff performing experiments using the same instruments and glassware that would have been used by students. Information about laboratory safety is also included in the introductory pages of each experiment site. Students click links on each page to navigate through the experiments in a specific order determined by students' experimental choices.

The "choose your own adventure" feature was implemented by offering multiple possible links to different pages of the experiment site (Figure 3.1). The flexibility of these websites gave instructors the ability to make different design choices based on specific skills they wished to emphasize, so the implementation of this "choose your own adventure" feature varied somewhat between courses. For UC Berkeley's organic chemistry courses, this feature was typically used to quiz students on the proper execution of a given laboratory technique by including a variety of common laboratory errors, such as leaving a TLC plate in the developing chamber for too long or increasing the temperature too quickly while attempting to measure a melting point, as possible choices. Students would be instructed through text or visuals about the result of their choice and, if their initial choice was incorrect, prompted to choose again until they chose the "correct" choice. Organic chemistry students at UC Santa Cruz had a particularly meaningful "choose your own adventure" experience: choices affected their final product yield, appearance, or composition in compounding ways. In some of the more inquiry-driven experiments in UC Berkeley's general chemistry courses, students were able to decide between different experimental design choices, which would lead to significantly different results. For more quantitative experiments, unique randomized datasets were also created for each student within a range of plausible data.

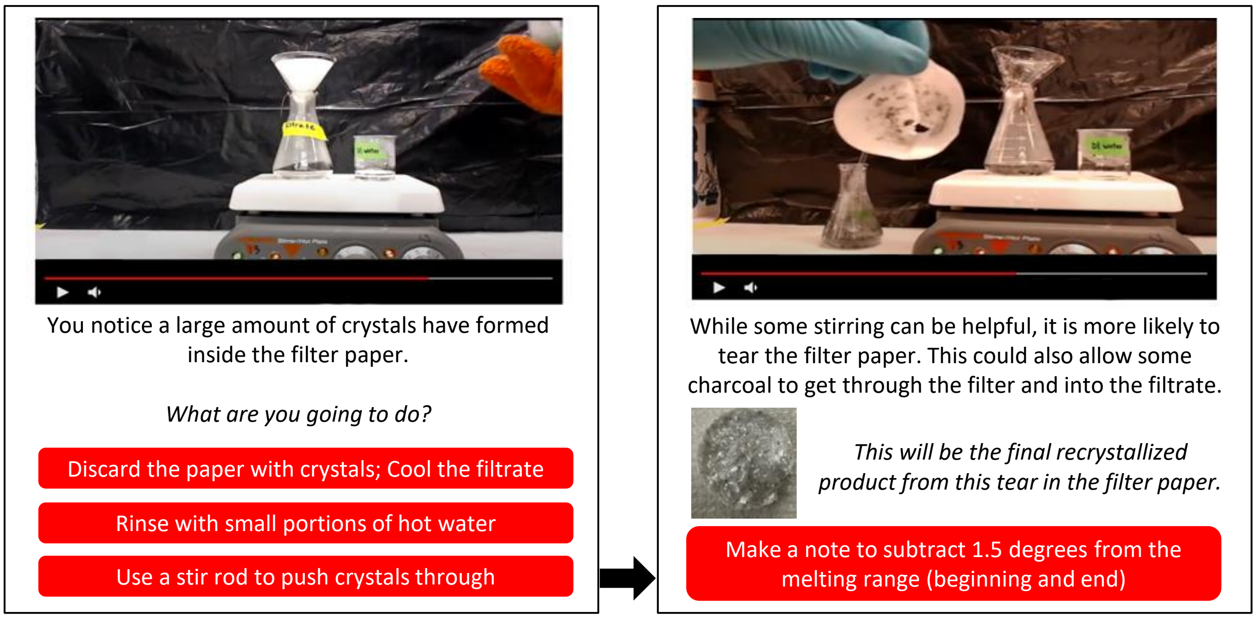


Figure 3.1. Example of a choose-your-own adventure sequence from an experiment used in Chem 8L at UC Santa Cruz. The box on the right shows the page to which students who choose the "use a stir rod to push crystals through" option are directed.

The online experiment sites were created in collaboration with a team of professors, lecturers, instructional staff, and other graduate students at UC Berkeley and UC Santa Cruz. We created an operational workflow that divided the work into five main stages: planning, filming, editing, compiling, and finalizing. At each stage, team members provided feedback to each other. In the planning stage, members of the team who were in charge of digitizing a specific experiment created and organized pages of a Google Site to form a storyboard indicating the flow of the experiment, from which a shot list could be written. A graduate student or instructional staff member then filmed themselves doing the experiment using the same instruments and glassware that would have been used by students. The filming staff often deviated from the procedure to represent common mistakes made by students during in-person experiments, or to highlight safety practices like cleaning up a chemical spill. Videos and photos were edited to remove unwanted audio, speed up or slow down certain actions, or add captions and other explanatory text. Each video represented logical subparts of the procedure or highlighted important landmarks for observation and other data gathering. Digital animations were also created for certain laboratory exercises. Individual videos were limited to 15 minutes in length, and the majority were five minutes or shorter. After editing was complete, media files were uploaded to Google Drive or YouTube and inserted into appropriate sections of the Google Site and captions and alt-text describing images and videos were added.

These experiments were used in 11 courses at UC Berkeley and UC Santa Cruz (Table 3.1). The specific implementation of the online experiments varied between courses. Typically, students completed prelaboratory assignments prior to synchronous laboratory sections. During weekly 2-4 hour synchronous laboratory sections, the teaching assistant (TA) first gave a brief lecture introducing key concepts and techniques; then, students navigated through the online experiments in groups in Zoom breakout rooms while recording observations and completing data analysis worksheets. Sometimes students would return to the main room for a class discussion moderated by the TA. In most of the courses, links to the experiment sites were posted ahead of time, so students had the option to start working in advance. Due dates for assignments ranged from the end of the synchronous laboratory section to the beginning of the following week's laboratory section depending on the course. In the courses at UC Berkeley, students were encouraged to work together, but their final answers to assignments had to be their own. Collaboration took place according to a more formalized process at UC Santa Cruz. Students turned in individual worksheets on the day of their synchronous laboratory sections; then, they submitted one laboratory report per pair of students one week after the experiment with a partner agreement indicating who was responsible for each portion of the report.

Table 3.1. Description of Laboratory Courses Using BeArS@Home and Slugs@Home Experiments

Course	Subject	Chemistry Majors?	Course Population	Period Offered (AY 2020-2021)
UC Berkeley				
Chem 1AL	General Chemistry I	No	1000 Fall, 500 Spring	Fall, Spring
Chem 1B	General Chemistry II	No	110	Spring
Chem 3AL	Organic Chemistry I	No	600	Fall, Spring
Chem 3BL	Organic Chemistry II	No	600	Fall, Spring
Chem 4A	General Chemistry I	Yes	250	Fall
Chem 4B	General Chemistry II	Yes	250	Spring
Chem 12A	Organic Chemistry I	Yes	250	Fall
Chem 12B	Organic Chemistry II	Yes	110	Spring
UC Santa Cruz				
Chem 8L	Organic Chemistry I	Mixed	200	Winter, Spring
Chem 8M	Organic Chemistry II	Mixed	200	Winter
Chem 110L	Organic Chemistry III	Yes	60	Spring

Methods

Data Collection

A mixed-methods approach was employed to evaluate the online laboratory platform, including surveys, interviews, and focus groups. All work was conducted at two large, research-intensive institutions in the University of California system: UC Berkeley and UC Santa Cruz.

This study was approved by both universities' Institutional Review Boards (IRBs), and informed consent was obtained from all participants. Copies of survey, interview, and focus group protocols are provided in Appendices 3.1-3.5.

Two surveys, referred to as the Learning Gains survey and the Online Laboratory survey, were administered as a part of this study. Both surveys were administered on Qualtrics. Student survey participants received a small amount of extra credit for their participation, while TAs were entered into a gift card drawing. As a part of the consent form completed prior to these surveys, students were additionally asked to grant the researchers access to their grades in the course.

The Learning Gains Survey was originally designed by Armstrong et al.[16] to evaluate a general chemistry curriculum focused on green chemistry and therefore contained, among other items, questions about student knowledge of chemistry and green chemistry concepts and techniques. The Learning Gains Survey was sent to Chem 1AL (General Chemistry I Laboratory at UC Berkeley) students at the beginning and end of the Fall 2019 and 2020 semesters, allowing for comparisons between students enrolled in the course in-person (2019) or online (2020). Response rates for this survey are displayed in Table 3.2.

Table 3.2. Learning Gains Survey Participants and Response Rates

Sample	Participants (Response Rate)		Population
	Pretest	Post-Test	
Chem 1AL Students, F19	770 (75%)	911 (88%)	1031
Chem 1AL Students, F20	723 (69%)	817 (78%)	1041

The Online Laboratory Survey was developed specifically for this study. It was designed by a team from UC Berkeley consisting of one STEM education consultant from the Center for Teaching and Learning, two graduate TAs and two undergraduate students who had previously taken or taught one of the laboratory courses listed in Table 3.1, and five instructors from the chemistry department. Each of these instructors had experience with developing or using online experiments in their courses, had previously taught one of the laboratory courses listed in Table 3.1 in person, and had previous experience with chemical education research projects. Members of this team began by brainstorming research questions, hypotheses, and possible survey items related to students' and TAs' experiences with online laboratory experiments. The survey was written and edited over the course of three cycles of feedback from the survey design team. Major modifications resulting from these cycles of feedback involved removing Likert items about attitudes toward chemistry that were not directly related to the online laboratory experience, adding Likert items about building community ties in online courses, and adding free response questions that asked participants to specify particularly positive and negative aspects of online laboratory instruction. Before sending this survey to participants from UC Santa Cruz, it was also reviewed by one chemistry instructor and two graduate TAs from that institution to ensure that the wording of all items made sense within the context of that institution.

The finalized version of the Online Laboratory Survey includes fixed and free response questions about student approaches to completing the online experiments, impressions of the online experiments, opinions of online experiments compared to in-person experiments, and demographic and educational background. This survey was sent to students and TAs in courses that made use of the online experiments near the end of each semester or quarter during the 2020–2021 academic year. Response rates for this survey are displayed in Table 3.3. After responses to the Online Laboratory Survey were collected, evidence for response process validity for this survey was gathered via interviews conducted over Zoom with 13 students and seven TAs who had taken or taught a variety of courses at UC Berkeley. These students volunteered to participate in interviews in May 2021. Five of the student interview participants identified as women and eight identified as men according to their Online Laboratory Survey responses. Demographic information was not collected on the version of the survey taken by TAs. During interviews, participants were asked to describe what they were thinking when they answered each item on the Online Laboratory Survey as well as more general questions about their experience with online laboratory experiments. In addition to providing evidence for the response process validity of the Online Laboratory Survey, these interviews were also designed to provide more in-depth explanations of student and instructor experiences.

Table 3.3. Online Laboratory Survey Participants and Response Rates

Sample	Participants (Response Rate)	Population
UC Berkeley Students, F20	2204 (79%)	2775
UC Berkeley Students, S21	1843 (88%)	2089
UC Santa Cruz Students, W21	83 (21%)	389
UC Santa Cruz Students, S21	104 (40%)	259
UC Berkeley TAs, F20	25 (27%)	93
UC Berkeley TAs, S21	33 (52%)	64
UC Santa Cruz TAs, W21	7 (54%)	13
UC Santa Cruz TAs, S21	1 (10%)	10

Focus groups were also conducted over Zoom and were recorded for later viewing and transcription. During each focus group, 2–5 students clicked through an online version of an experiment that they had previously completed in-person in Chem 1AL. These students were asked to compare this experience to their previous experience of completing the experiment in person. Ten UC Berkeley students participated in focus groups in November 2020. According to their responses to the Online Laboratory Survey, nine of the focus group participants identified as women and one identified as a man. One of the focus groups was mixed-gender and the others were composed only of students who identified as women.

Analysis of Survey Data

Fixed-response Likert items from the Online Laboratory Survey were assigned numerical values (1=Strongly Disagree to 5=Strongly Agree), and negatively worded items were reverse-coded. Based on the results of exploratory factor analysis, related survey items were combined into the three composite scales: general impressions of online experiments (Learning Experience), opinions regarding the usefulness of online experiments compared to in-person experiments (Comparing Usefulness), and opinions regarding community in online laboratory environments compared to in-person environments (Comparing Community). Composite scores were calculated by taking the mean of the individual item scores after reverse-coding any negatively worded items. Cronbach's alpha was greater than 0.7 for each of these composite scales, indicating acceptable internal consistency.[17] The individual Likert items which make up these three composite scales are listed in Table 3.4, and details of the factor analysis and reliability analysis are provided in Appendix 3.6.

Table 3.4. Survey Items Included in the Learning Experience, Comparing Usefulness, and Comparing Community Composite Scales of the Online Laboratory Survey

Learning Experience: General Impressions and Perceptions of Learning
The online labs helped me learn about various experimental techniques.
The online labs helped me learn about the concepts underlying various experimental techniques.
The online labs helped further my understanding of the chemistry concepts covered in the lecture component of my course.
The online labs were clear and easy to follow.
The online labs were interesting and engaging.
Comparing Usefulness: Comparison of Utility of Online and In-Person Laboratory Experiments
I think I learned more from the online lab experiments than I would have from the corresponding in-person lab experiments.
Online labs are not a reasonable substitute for in-person labs. *
I think the online labs were as effective as in-person labs would have been.
I think I prefer online labs to in-person labs.
Comparing Community: Comparison of Community in Online and In-Person Laboratory Environments
It was easier to connect with other students during online labs than it would have been in person.
It was more difficult to connect with my [teaching assistant] during online labs than it would have been in person. *
It was easier to find study partners in my online labs than it would have been in person.
It was more difficult to make friends in my online labs than it would have been in person. *
It was easier to ask for help during online labs than it would have been in person.

In analyzing the Learning Gains Survey, we focused on students' responses to (a) Likert items measuring self-reported understanding of chemistry concepts and techniques and (b) multiple-choice or select-all-that-apply items measuring general chemistry and green chemistry knowledge. These items, listed in Table 3.5,[16] were chosen because they allow for a comparison of student learning gains between semesters in which laboratory courses were conducted online or in person. Multiple-choice and select-all-that-apply items were graded for correctness according to rubrics developed by Armstrong and co-workers.[16] Answer choices and correct responses to each of these items are provided in Appendix 3.7. For each of the Likert and select-all-that-apply items that were analyzed, gain scores were computed by subtracting post-test scores from pretest scores, and these gain scores were compared for the Fall 2019 and Fall 2020 Chem 1AL classes.

Table 3.5. Learning Gains Survey Items Used in Analysis

Likert Items (Presently, how much do you understand about each of the following?)

1. Relationships between physical properties and molecular structures
2. Intermolecular interactions
3. Types of bonding (nonpolar covalent, polar covalent, ionic)
4. Calorimetry
5. Electrochemistry
6. Performing a titration using a pH probe
7. Performing a titration using indicators
8. Creating serial dilutions
9. Using a UV-vis spectrometer
10. Generating a calibration curve
11. Performing error analysis

Multiple-Choice Content Questions

1. **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?"
2. **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?"
3. **Intermolecular Forces:** "Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above."
4. **Titration:** "In lab you use hydrochloric acid (HCl) to titrate a mixture of sodium hydroxide (NaOH) and sodium acetate ($NaC_2H_3O_2$). 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 $NaC_2H_3O_2$. What would the titration curve for this sample look like compared to yours?"

Select-All-That-Apply Content Questions

1. **Atom Economy:** "The reaction below can be used to fill an automobile airbag. The atom economy for this reaction is 55%. This means that (Select all that are accurate.)"
2. **LD_{50} Definition:** "The reaction below can be used to fill an automobile airbag. The LD_{50} for the starting material, ammonium nitrate, is shown above. LD_{50} tells you (Select all statements that are accurate.)"
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."

Unfinished survey responses and responses from those who did not complete both the pre- and post-Learning Gains Surveys were dropped from the data set. IBM SPSS 27.0 was used for all statistical analysis. Because the variables under investigation violated assumptions of normality according to Kolmogorov–Smirnov and Shapiro–Wilk tests, nonparametric Mann–Whitney U tests or Kruskal-Wallis tests were used for comparisons between groups. Effect sizes are reported as $\frac{z}{\sqrt{n}}$. When multiple tests were performed, significance levels were determined using the Bonferroni correction in order to reduce the rate of false positives.

Free Response, Focus Group, and Interview Coding

We analyzed two free response questions from the Online Laboratory Survey:

1. **Positive Memory:** "Were there any particular online labs or parts of online labs that stuck in your memory in a positive way? Explain."
2. **Negative Memory:** "Were there any particular online labs or parts of online labs that stuck in your memory in a negative way? Explain."

Student and TA responses were coded using an approach that was both deductive and inductive in nature. Due to the large number of responses from UC Berkeley students, a random sample of 20% of the free responses was coded. All responses from TAs and UC Santa Cruz students were coded. Members of the research team first read over a random sample of 50 responses to each question and, using MaxQDA software, tagged them with one or more codes according to their subject. They then met to compare answers and decide on a preliminary coding scheme designed to encompass the major emerging themes. Each remaining free response was separately coded by two members of the team, then that pair met to discuss any disagreements until full agreement was reached. If at any point a response did not fit into an existing code, it was tagged with "other" and the scheme was modified until all responses could be categorized under at least one code. Definitions and examples of each code are provided in Appendix 3.8.

Audio transcripts of interviews and focus groups were coded using the same scheme and process. One code was added during interview analysis: "survey/interview mismatch." This code was used to denote occasions when participants changed their answer from the Online Laboratory Survey during the interview, stated that they had misunderstood a survey item, or provided a reason for selecting an answer choice that was not aligned with the intended meaning of the survey item. In total, 21 instances of this code across 11 interview transcripts were noted. Considering that each of the twenty interview participants was asked to explain their responses to approximately 20 survey items, this suggests that the interview participants rarely changed their answers or misinterpreted a survey item, providing evidence for the validity and reliability of the Online Laboratory Survey.

Following initial coding, statements coded with "Comparison of Laboratory Formats" were further analyzed to create a more detailed description of what students and TAs perceived as benefits and drawbacks of online laboratories. Members of the research team read over these responses and coded them as referring to perceived benefits or drawbacks of online laboratory experiments in comparison to in-person laboratory experiments.

Results and Discussion

Research Question 1: What Are Students' and Instructors' General Impressions of the BeArS@home and Slugs@home Online Experiments?

Responses to the Likert items that focused on the general impressions of online experiments (Learning Experience), opinions regarding the usefulness of online experiments compared to in-person experiments (Comparing Usefulness), and opinions regarding community in online laboratory environments compared to in-person environments (Comparing Community) on the Online Laboratory Survey were analyzed to gain insight into students' and teaching assistants' opinions of the BeArS@home and Slugs@home online laboratory exercises. The percentage of UC Berkeley and UC Santa Cruz students and teaching assistants who chose each of the five possible answer choices (strongly disagree to strongly agree) for each item is displayed in Figure 3.2.

For the Learning Experience items, most students and teaching assistants agreed that the online experiments were clear and interesting and helped them learn about concepts and laboratory techniques. Despite their generally positive impressions of the online experiments, survey respondents tended to disagree with all of the items that favorably compared online laboratories to physical laboratories. The most common answer choice among students when asked whether they preferred online experiments or whether they learned more from online experiments than they would have from a corresponding in-person experiment was "strongly disagree." Most respondents also disagreed that it was easier to find study partners, connect with other students, and make friends in the online laboratory environment than it would have been in person. Compared to UC Berkeley students, UC Santa Cruz students showed lower levels of disagreement with items that stated that it was easier to connect or collaborate with others in an online laboratory environment and higher levels of agreement with the Learning Experience items. This may be because collaboration between students was more formalized in the UC Santa Cruz courses, and interaction with peers in online courses has been found to be associated with increases in perceived learning and student satisfaction.[18,19] Overall, it is evident that students and teaching assistants believed in-person experiments to be better than online experiments, which is consistent with many other studies on remote learning during the COVID-19 pandemic,[20–28] but they still had generally positive impressions of the online experiments.

We have presented data on opinions of the online experiments pooled from all of the surveys collected at UC Berkeley and UC Santa Cruz, but it is also important to consider whether these experiments were a positive experience for all groups of students. Therefore, we were interested in investigating whether students with different backgrounds varied in their impressions of the online laboratory environment. Students' scores on the Learning Experience, Comparing Usefulness, and Comparing Community items were compared by gender, underrepresented minority (URM) status, first-generation status, and major using Mann–Whitney U tests (Table 3.6). Due to the small number of study participants from UC Santa Cruz, this analysis was conducted only with data from UC Berkeley students.

Figure 3.2 Distribution of UC Berkeley and UC Santa Cruz student responses to items from the Learning Experience, Comparing Usefulness, and Comparing Community composite scales of the Online Laboratory Survey (*N*=3839 UC Berkeley students, 181 UC Santa Cruz students, 58 UC Berkeley teaching assistants, 8 UC Santa Cruz teaching assistants).

Table 3.6. Mann–Whitney U Tests Comparing Student Learning Experience, Comparing Usefulness, and Comparing Community Scores by Gender, URM Status, First-Generation Status, and Major for UC Berkeley Students

	N	Mean	Mean Rank	U	p	Effect Size
Learning Experience						
Men	1212	3.64	1770.10	1,583,352.5	0.004	0.047
Women	2470	3.74	1876.53			
Non-URM	3052	3.72	1847.49	937,001.0	0.377	0.015
URM	628	3.66	1806.54			
Continuing Generation	2684	3.70	1845.65	1,397,962.5	0.413	0.013
First Generation	1024	3.72	1877.70			
Non-Chemistry Majors	3271	3.72	1909.51	894,644.0	0.015	0.039
Chemistry Majors	513	3.60	1784.05			
Comparing Usefulness						
Men	1212	2.34	1682.63	1,689,368.0	<0.001	0.105
Women	2470	2.56	1919.45			
Non-URM	3052	2.46	1822.23	1,014,076.5	0.021	0.038
URM	628	2.48	1929.27			
Continuing Generation	2684	2.42	1786.71	1,556,164.0	<0.001	0.103
First Generation	1024	2.65	2032.19			
Non-Chemistry Majors	3271	2.52	1927.01	951,884.0	<0.001	0.080
Chemistry Majors	513	2.28	1672.48			
Comparing Community						
Men	1212	2.40	1873.23	1,458,358.5	0.203	0.021
Women	2470	2.37	1825.93			
Non-URM	3052	2.37	1825.92	1,002,836.0	0.066	0.030
URM	628	2.43	1911.37			
Continuing Generation	2684	2.34	1804.03	1,509,658.0	<0.001	0.077
First Generation	1024	2.47	1986.78			
Non-Chemistry Majors	3271	2.37	1884.16	811,719.5	0.234	0.019
Chemistry Majors	513	2.39	1945.70			

Seventeen percent of survey respondents identified as a member of a URM group, defined as one of the following racial or ethnic groups: African American/Black, American Indian/Alaska Native, Native Hawaiian/Pacific Islander, Mexican American/Chicano, Puerto Rican, or Other Latino. First-generation college students, defined as students whose parents or guardians did not receive a four-year undergraduate degree, made up 28% of survey respondents. Approximately two-thirds (67%) of survey respondents identified as female, and the majority of respondents (86%) were not majoring in chemistry.

Because 26 tests were conducted in total, $p<0.004$ (0.05/12 tests) was considered to be statistically significant. Composite scores on the Learning Experience items were significantly higher among women, Comparing Usefulness scores were significantly higher among women, first generation students, and students not majoring in chemistry, and Comparing Community scores were higher among first-generation students. All other differences were non-significant. Overall, the few significant differences across demographic categories each had a small effect size and reflected a more positive response toward the online experiments among groups that are underrepresented in STEM fields.

Research Question 2: What Do Students and Instructors Perceive to Be the Strengths and Weaknesses of the Online Experiments?

To learn more about students' and TAs' opinions of the online experiments in their own words, data from survey free responses, focus groups, and interviews were coded. In completing this analysis, we focused on two sub-questions:

1. What aspects of the online experiments were viewed positively or negatively?
2. What aspects were viewed as advantages and disadvantages of online laboratory instruction as compared to in-person instruction?

Responses to the "Positive Memory" and "Negative Memory" free responses were used to answer the first sub-question. Certain codes, such as "Specific Experiments/Techniques" and "Videos/Photos," were referenced very frequently in responses to both questions (Table 3.7). Students often noted that they found specific experiments to be particularly engaging because they related to their interests or were interactive, and they mentioned enjoying videos that were clear, concise, and occasionally humorous. Unsurprisingly, students were bothered by experiment videos that had issues with blurriness or poor lighting because these issues sometimes made it difficult to observe parts of experiments, but respondents also mentioned benefits of video-based instruction, such as the ability to speed up, slow down, or rewatch videos as needed.

Other features of the online experiments were viewed particularly positively or negatively. For example, 90% of responses coded with "Ability to Revisit Content" or "Choose Your Own Adventure" were in reference to a positive memory. Students noted that being able to revisit certain webpages or parts of videos was helpful for collecting data; for instance, one stated that "being able to go back in the video to determine the exact temperature was a blessing, which would've been impossible in real-life." "Choose Your Own Adventure" sections of the online experiments helped students test their understanding of chemistry concepts and think critically: "I really like how the online labs give us both wrong and correct answer choices for certain lab procedures, which really solidified my understanding of certain underlying chemistry processes. In in-person labs, we would likely just go with the correct choice without truly understanding why we do what we do." The "Lack of Experience/Preparation" code was also notable in that it was much more commonly assigned to students' "Negative Memory" responses. These responses often mentioned that the lack of hands-on experience made the experiments uninteresting, or that students would not be prepared for future laboratory work. Examples of such responses include "I am completely unprepared to work in a lab…I haven't touched any of the lab equipment, I haven't actually done any of the labs" and "I just think the phrase 'online labs' is an oxymoron, the whole point of a lab is to do it. I feel like the assignments are just draining and uninteresting because I can't actually do the experiment." Taken together, responses to these items show which specific features of the online experiments were viewed positively and negatively, which can help guide the improvement of future experiments.

Table 3.7. Frequencies with Which Responses to the "Positive Memory" and "Negative Memory" Free Responses Were Tagged with Certain Codes.

Code Name	Frequency		
	Positive Memory	Negative Memory	Total
Specific Experiments/Techniques	300	291	591
Nothing/No	149	194	343
Videos/Photos	130	163	293
Ease of Use/Understanding	105	170	275
Interest/Engagement	173	89	262
Comparison of Laboratory Formats	88	53	141
Timing/Flexibility in Scheduling	69	60	129
Peers	71	48	119
Non-Website Features of Course	25	94	119
Lack of Experience/Preparation	3	91	94
Choose Your Own Adventure	81	9	90
Instructor	43	36	79
Workload	8	50	58
Ability to Revisit Content	41	4	45
Feelings of Stress	16	12	28
Focus on Theory	17	4	21
Tech Issues	0	12	12
Total Codes	**1320**	**1380**	**2700**
Free Responses Analyzed [a]	**819**	**851**	**1670**

[a] This includes 1247 responses from UC Berkeley Students, 337 responses from UC Santa Cruz students, 72 responses from UC Berkeley TAs, and 14 responses from UC Santa Cruz TAs.

Students' and TAs' perceptions of the benefits and drawbacks of online laboratory instruction compared to in-person instruction were investigated using the 164 free responses, interview transcripts, and focus group transcripts tagged with the "Comparison of Laboratory Formats" code. In total, participants made 395 explicit comparisons between online and in-person experiments in these responses. A list of the frequencies with which certain features were perceived as benefits or drawbacks of online experiments is included in Table 3.8.

Table 3.8. Frequencies with which Survey, Interview, or Focus Group Participants Noted Certain Codes as Benefits and Drawbacks of Online Experiments Compared to In-Person Experiments

Code Name	Number of Responses[a] Referring to Code	
	As a Benefit of Online Experiments	As a Drawback of Online Experiments
Timing/Flexibility in Scheduling	56	1
Ease of Use/Understanding	35	15
Lack of Experience/Preparation	0	46
Peers	13	33
Instructor	21	19
Focus on Theory	28	0
Interest/Engagement	1	24
Feelings of Stress	21	0
Revisiting	20	0
Videos/Photos	14	6
Specific Experiments/Techniques	10	6
Choose Your Own Adventure	9	0
Workload	8	0
Non-Website Features of Course	1	4
Tech Issues	0	1
Nothing/No	0	0
Timing/Flexibility in Scheduling	56	1
Total Codes	**240**	**155**

[a] Total number of responses analyzed: 1668 survey free responses, three focus group transcripts, and 20 interview transcripts

Several features were overwhelmingly perceived as advantages of online experiments: the relative amount of time spent, flexibility, and the ability to focus on conceptual learning rather than physically completing the experiment. Other reports about online laboratory courses have mentioned that students appreciated that the online format saved time[21] and allowed for a greater emphasis on theory.[15,29] Some participants also reported fewer feelings of stress associated with completing online experiments. This is likely because students were able to explore possible mistakes in a low-stakes manner using the choose-your-own-adventure feature and were able to revisit pages of the website, removing the stress of accidentally missing a crucial observation point.

The disadvantage of online experiments compared to in-person experiments most often cited by students and TAs was a lack of hands-on experience. These sentiments arose particularly often among the focus group participants, who had the unique perspective of completing the online version of an experiment that they had previously completed in-person. This is a common theme in studies where students and TAs are asked to give their feedback on remote chemistry laboratory experiences during the COVID-19 pandemic.[24,30,31] Not being able to conduct hands-on experiments led many students to report feeling less prepared for future laboratory work, less interested and engaged with course material, and less able to understand and interpret data that they did not collect themselves. These results are consistent with Kelley's Laboratory Action-Based (LAB) Theory,[5] which suggests that, without action-based laboratory work, students would not be able to fully achieve objectives associated with learning about materials and techniques used in the lab, being able to conduct and propose laboratory work, wanting to do work in the laboratory, and making sense of what was done in the laboratory.

Interestingly, participants were split on whether interactions with peers or instructors were better online or in-person. Those who described interactions with others as a benefit of online experiments tended to give three reasons: they were able to work with larger groups than would have been feasible in-person, it was easier to get the attention of TAs using Zoom's "Call for Help" feature, and it was more convenient to attend or hold office hours online. In the future, these benefits could be integrated into courses that primarily meet in-person by continuing to offer some office hours in an online format. Those who preferred in-person interactions with peers or instructors typically referred to the difficulty of finding partners who were willing to communicate over Zoom. One TA remarked in their interview that on Zoom "it's not hard for [students] to completely disengage and just mute their microphone, mute their camera, and then not even write in the chat when people are supposed to be working together," and many students described similar experiences. Issues with interpersonal aspects of online learning are well-documented; students taking online courses have reported feeling isolated[32] and uncomfortable with sharing their ideas[33] and have stated that it is more difficult to do group projects remotely.[23,34] Students clearly highly value active engagement with laboratory equipment and interaction with their peers, and these are key areas that instructors should focus on when designing both online and in-person laboratory experiences.

Research Question 3: How Did Students Approach the Online Experiments, and Did Students with Different Approaches Perform Better in the Course?

The implementation of the BeArS@home and Slugs@home laboratory platforms gave students the flexibility to approach the online experiments differently depending on their individual needs and preferences. We therefore asked students to answer several questions on the Online Laboratory Survey that were related to when, how, and with whom they navigated the experiment sites. Student responses to these questions, broken down by university, are summarized in Figure 3.3. In addition to wanting to know how students typically navigated the experiment sites, we also sought to determine whether students with different approaches differed in their course performance.

While students were encouraged to work with their classmates in breakout rooms, they were able to decide whether they preferred to click through the experiment site itself by themselves or with their peers. The proportion of students who chose to navigate the experiment site with their peers varied widely between the two universities. Most UC Santa Cruz students (72%) navigated the experiment sites with other students, compared to only 27% of UC Berkeley students. This is likely because pairs of UC Santa Cruz students were permitted to turn in a single laboratory assignment, incentivizing collaboration. Each individual UC Berkeley student was required to turn in their own assignment. Interview respondents communicated a variety of reasons for their choice to work alone, including technical issues associated with sharing their screen and streaming videos over Zoom, differences in pace between students, and a lack of friends in the course. Some students mentioned that they wanted to work with others, but they found it difficult to collaborate when members of their breakout room were mostly muted with their video off. Students who did navigate the experiment sites with peers stated that they found it helpful to click through the site at the same pace so they could more easily discuss the experiment with each other.

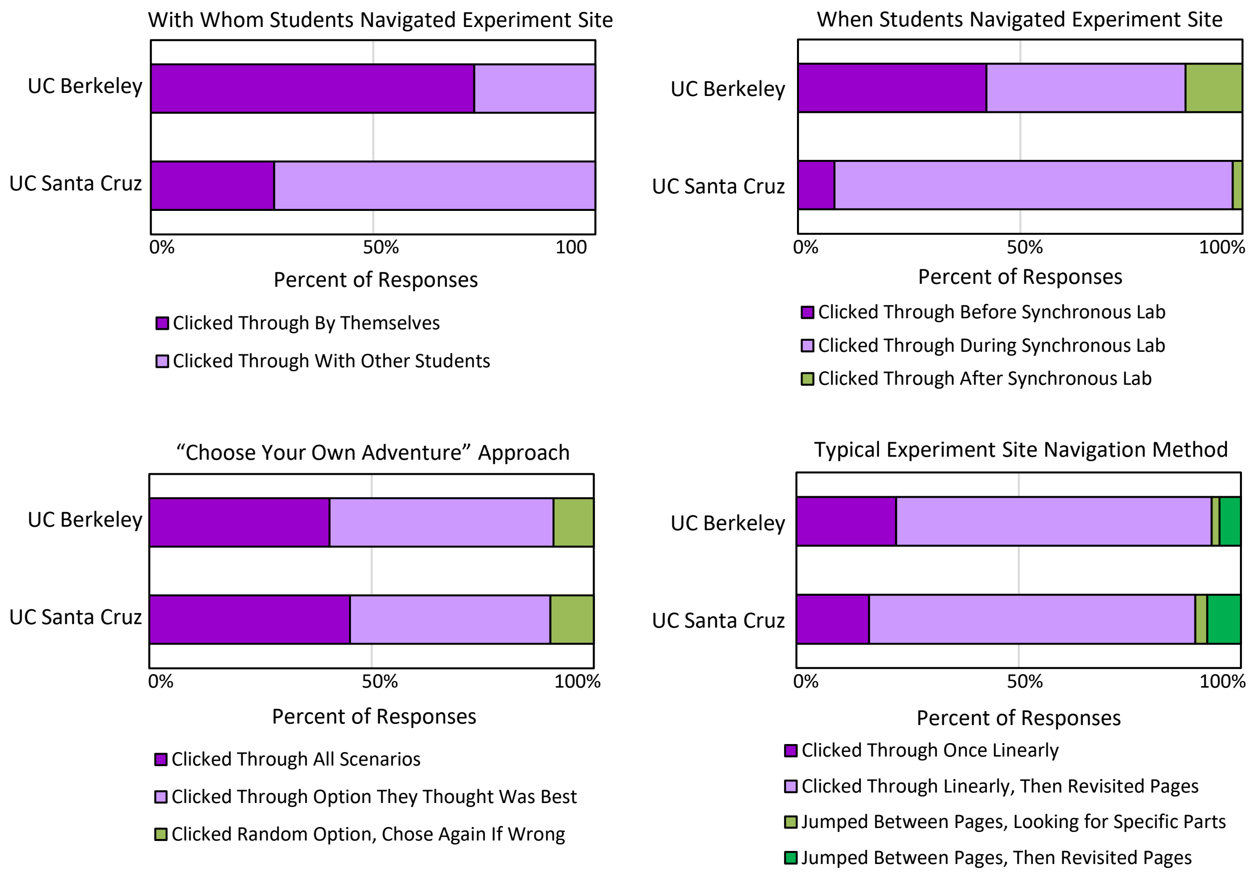


Figure 3.3. Percentage of survey respondents choosing various methods of navigating the experiment sites, broken down by university (*N*=3839 UC Berkeley students, 181 UC Santa Cruz students).

Students were also able to decide whether they preferred to click through the experiment site before, during, or after their assigned synchronous laboratory section. Student survey respondents from UC Berkeley typically navigated the experiment site before (42%) or during (45%) their synchronous laboratory section, though some students (13%) more often did so after the synchronous laboratory section. In comparison, nearly 90% of UC Santa Cruz students reported navigating through the experiment site during their synchronous laboratory section rather than before or after. We believe that much of this difference can be explained by differences in course policies: in several of the larger courses at UC Berkeley, students' laboratory assignments were due by the end of the synchronous laboratory section, which encouraged students to start working on their assignments ahead of time to ensure they met this deadline. In the UC Santa Cruz courses, no assignments were due any earlier than midnight on the day after a student's synchronous laboratory section. The policy allowing pairs of students to turn in a single assignment may have also encouraged UC Santa Cruz students to navigate the experiment sites during their synchronous laboratory section, since this was a scheduled time to meet with partners in breakout rooms.

In addition to choosing when and with whom they preferred to navigate the experiment sites, students could decide how to approach the "choose your own adventure" sections of the experiment sites. As displayed in Figure 3.3, the vast majority of students either reported that they explored all possible paths to see how the various scenarios played out or tried to figure out what the best option was and only clicked through that scenario, with responses approximately evenly split among these two approaches. Only 9% of students UC Berkeley students and 10% of UC Santa Cruz students chose a random option and then clicked through a different path if they chose incorrectly the first time, which indicates that most of the students were interacting with the "choose your own adventure" options in one of the ways we intended. Interview respondents who explored all possible paths typically chose this approach because seeing the results of multiple scenarios helped them better understand the concepts: "it really helps make things click." Students who only clicked through the option they thought was correct primarily stated that they chose this approach because it was faster, and they did not feel that it was necessary to click through multiple scenarios if they already understood the material. Responses did not significantly differ between UC Santa Cruz and UC Berkeley students.

As discussed in the previous section, one advantage of the online laboratory experiments that students often mentioned in their survey and interview responses was the ability to revisit parts of the experiment if needed. According to their responses to the Online Laboratory Survey, most students took advantage of this feature. Combining responses from UC Berkeley and UC Santa Cruz, 71% of students reported that they usually clicked through the experiment site once linearly, then went back to parts they needed to revisit at the end. An additional 5% of students reported that they revisited certain pages of the experiment site after having first jumped from page to page in order to look for specific pieces of information. Only a handful of students (2%) reported that their typical method of navigation was solely jumping around to look for specific parts of the websites. The remaining 22% of students reported that they usually clicked through the site only once linearly, from start to finish. Overall, more than three-quarters of students reported revisiting certain pages of the experiment site.

When designing the online experiments, we intended for students to navigate the experiment sites linearly, during their synchronous laboratory section, with other students. We also wanted students to engage with the choose-your-own-adventure scenarios by exploring either all possible paths or choosing the path they thought was the best choice, rather than choosing a path at random. However, based on responses to the Online Laboratory Survey, it is clear that students navigated the BeArS@home and Slugs@home online experiments in different ways, with some approaches more aligned with these expectations than others. We were therefore interested in whether students who did navigate the experiment sites as intended performed better in their laboratory course than those who did not. Because individual courses were graded on different scales, we converted students' final numerical grades to Z-scores standardized to the course mean. Table 3.9 presents descriptive statistics related to these Z-scores for different students, grouped according to their approach to navigating the experiment sites.

Table 3.9. Descriptive Statistics: Course Performance (Final Grade Z-Scores) Among Students with Different Approaches to Navigating the Experiment Sites

	N	Mean	Median	Standard Deviation
With Whom Students Navigated Experiment Site				
Clicked Through By Themselves	2386	0.11	0.26	0.73
Clicked Through With Other Students	1084	0.19	0.33	0.61
When Students Navigated Experiment Site				
Clicked Through Before Synchronous Lab	1458	0.18	0.31	0.65
Clicked Through During Synchronous Lab	1562	0.13	0.26	0.70
Clicked Through After Synchronous Lab	450	0.02	0.25	0.79
"Choose Your Own Adventure" Approach				
Clicked Through All Scenarios	1380	0.15	0.28	0.64
Clicked Through Option They Thought Was Best	1753	0.16	0.33	0.69
Clicked Random Option, Chose Again If Wrong	333	-0.05	0.14	0.85
Typical Experiment Site Navigation Method				
Clicked Through Once Linearly	741	0.12	0.28	0.68
Clicked Through Linearly, Then Revisited Pages	2472	0.15	0.30	0.68
Jumped Between Pages, Looking for Specific Parts	70	-0.03	0.18	0.89
Jumped Between Pages, Then Revisited Pages	181	-0.01	0.25	0.84

Comparing the final grade Z-scores of students who navigated the experiment sites in different ways using Kruskal-Wallis and Mann-Whitney U Tests revealed several significant differences (Tables 3.10 and 3.11). Students who navigated the experiment sites after their synchronous laboratory section received lower final grades than those who did so before or during their synchronous laboratory section. Students who approached choose-your-own-adventure scenarios by choosing a random option also performed less well than those who explored all options or only the "best" option. The students who navigated the experiment sites by themselves did not receive final grades as high as those who worked with their peers.

We did not observe differences in course performance between students who navigated the experiment sites before their synchronous laboratory section or during their synchronous laboratory section, or between those who explored all choose-your-own adventure options or only the option they believed was most correct. There were also no significant differences between students who navigated the sites linearly or by jumping around from page to page, regardless of whether they went back to revisit certain pages. This suggests that students can approach these experiments in a variety of ways and still succeed in the course. However, in each case where there was a significant difference in performance, students who navigated the experiment sites in the way we intended received slightly higher grades, on average, than those who did not. Students who navigated the experiment site alone or after their synchronous laboratory section despite being encouraged to do so in groups during the synchronous laboratory section, as well as students who chose a random option when presented with a choose-your-own-adventure scenario rather than considering the different options, may have been less engaged with the course material than other students, leading to the observed differences in course performance.

Table 3.10. Results of Kruskal-Wallis Tests (*N*=3470) Comparing Course Performance (Final Grade Z-Scores) Across Several Navigation Methods

Variable	Pairwise Comparison	Df	H	p	Effect Size
When Students Navigated Experiment Sites		2	15.853	<0.001	
	Before vs. During			0.054	0.033
	Before vs. After			<0.001	0.067
	During vs. After			0.008	0.045
How Students Navigated Experiment Sites		3	7.653	0.054	
Approach to Choose-Your-Own-Adventure		2	33.705	<0.001	
	All vs. Best Option			0.130	0.026
	All vs. Random Option			<0.001	0.081
	Best vs. Random Option			<0.001	0.099

Table 3.11. Results of Mann-Whitney U Tests (*N*=3470) Comparing Course Performance (Final Grade Z-Scores) Between Students Who Navigated the Experiment Sites Alone or With Others

	Mean Rank	U	P	Effect Size
Clicked Through By Themselves	1697.54	1,383,789.0	<0.001	0.056
Clicked Through With Other Students	1819.06			

Research Question 4: How Do Student Learning Outcomes and Self-Assessed Gains in Understanding in General Chemistry Laboratory Courses Compare between Semesters in Which Experiments Were Conducted Online vs In Person?

The Online Laboratory Survey, interviews, and focus groups that we conducted enabled us to learn about students' and TAs' impressions of the BeArS@home and Slugs@home online experiments. However, these assessments were conducted only after the transition to remote instruction, making direct comparisons to in-person instructional outcomes difficult. Comparing student performance on exams or other graded assignments is also problematic because in-person course assessments were closed-book and proctored, while all course assessments conducted over the 2020–2021 school year were unproctored take-home assignments. However, one source of data that does allow for some direct comparison of student learning outcomes and students' self-assessed gains in understanding is the Learning Gains Survey. The Learning Gains Survey was administered with Chem 1AL students at UC Berkeley at the beginning and end of both the Fall 2019 (in-person) and 2020 (online) semesters. The Fall 2019 and Fall 2020 Chem 1AL courses were taught by the same instructor, and the concepts and laboratory techniques covered in lectures, experiments, and assignments were very similar between these two semesters. The questions asked on the Learning Gains Survey and the method by which the survey was administered were identical for each of the four administrations (Fall 2019 pretest, Fall 2019 post-test, Fall 2020 pretest, Fall 2020 post-test.) Thus, this survey provides a reasonable comparison of student learning outcomes in online and in-person formats.

The first point of comparison in this survey involves students' self-assessment of their understanding of key general chemistry concepts and laboratory techniques, summarized below in Figure 3.3. Students were asked how well they understood 11 concepts or techniques at the beginning and end of the course. Question prompts for these survey items are included in Table 3.4 under the "Likert Items" subheading.

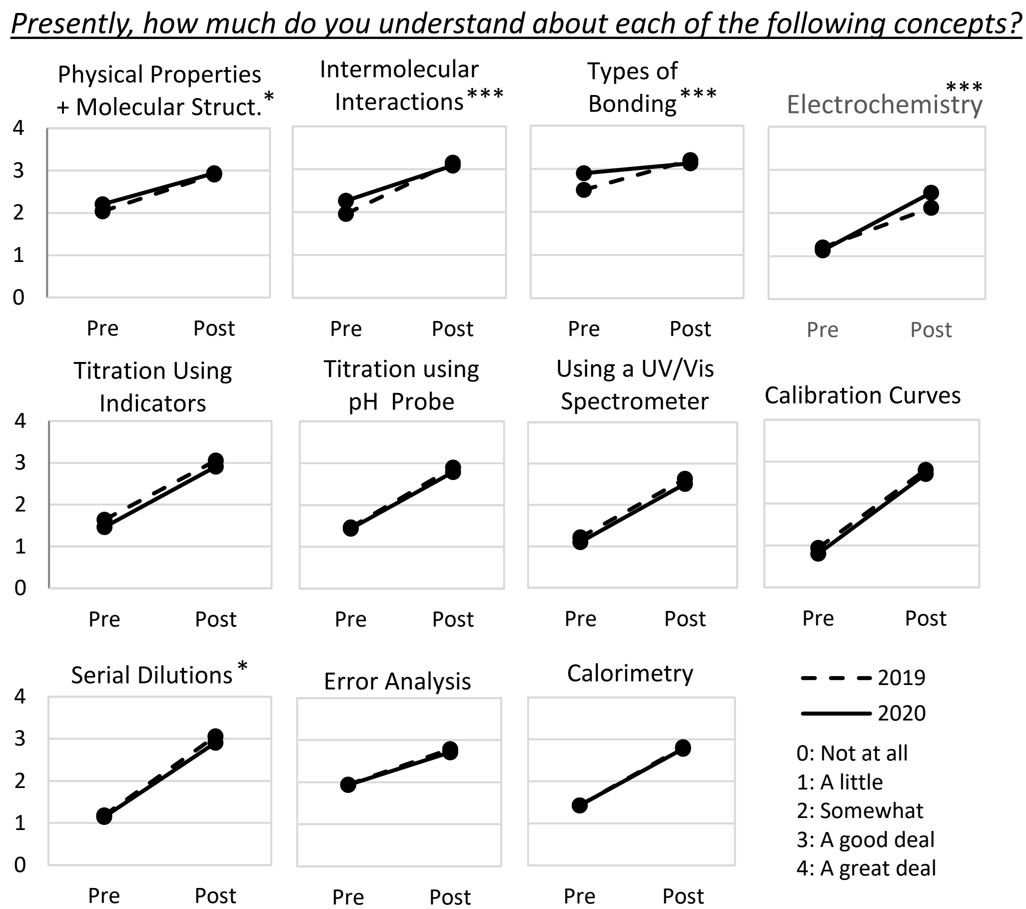


Figure 3.3. Chem 1AL students' self-reported understanding of chemistry concepts and techniques at the beginning and end of the semester. Mann–Whitney U Tests were used to compare gain scores for the Fall 2019 and Fall 2020 classes (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$; *N*=570 in 2019, 527 in 2020).

Comparing the increase in understanding reported by the Fall 2019 and Fall 2020 classes using Mann–Whitney U Tests yielded no significant differences for the technique items, but significant differences with $p<0.0045$ (0.05/11) were observed for three of the conceptual items

(Figure 3.3). Students taking the course in person reported larger pre–post gains in understanding intermolecular interactions (U=122,757.0, p<0.001, effect size=0.164) and types of bonding (U=116,954.5, p<0.001, effect size=0.204). These differences are due to higher pretest scores among students taking the course remotely; there were no significant differences in post-test scores on these items between semesters. For their self-assessed understanding of electrochemistry, however, students who took the course online in Fall 2020 reported higher gains in understanding (U=174,587.5, p<0.001, effect size=0.145), and there were significant differences in post-test scores rather than pretest scores.

Students taking Chem 1AL in Fall 2019 or Fall 2020 also answered seven multiple-choice or select-all-that-apply questions testing their knowledge of general chemistry and green chemistry concepts at the beginning and end of these semesters. Question prompts for these survey items are included in Table 3.4 under the "Multiple-Choice Content Questions" and "Select-All-That-Apply Content Questions" subheadings. The percentage of students who answered the four multiple-choice questions about absorbance spectra, bond energies, intermolecular forces, and titration curves correctly, incorrectly, or with "I don't know" is shown in Figure 3.4, and students' scores on the three select-all green chemistry items are shown in Figure 3.5. The atom economy question had two correct answers, giving a maximum score of two, while the remaining questions had a maximum score of one. Because one point was subtracted for each incorrect choice when scoring the select-all-that-apply items, negative scores were possible. For all seven items, scores were as high or higher at post-test for students who took the course online in Fall 2020 compared to those who took the course in-person in Fall 2019, and any differences in learning gains were primarily due to disparities in pretest scores.

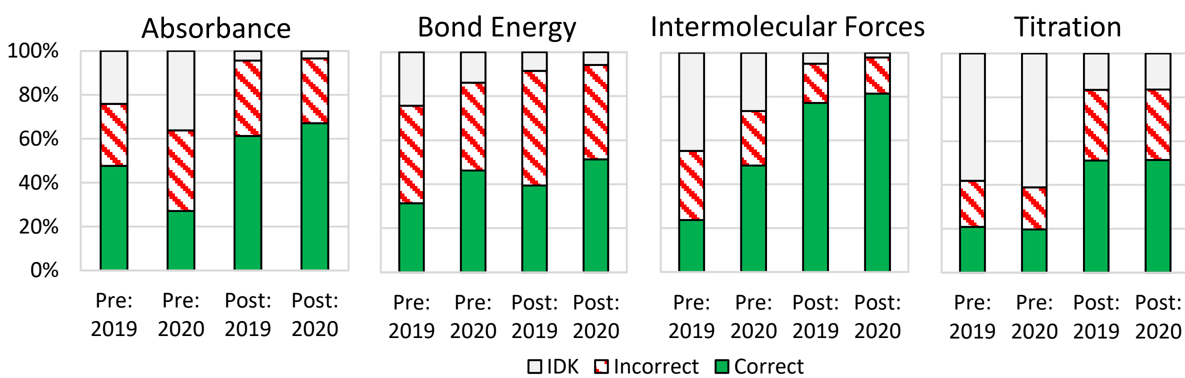


Figure 3.4. Percentage of Chem 1AL students who answered four multiple-choice chemistry content questions correctly, incorrectly, or with "I don't know" on the pretest and post-test during the Fall 2019 and Fall 2020 semesters. *N*=570 in 2019, 527 in 2020.

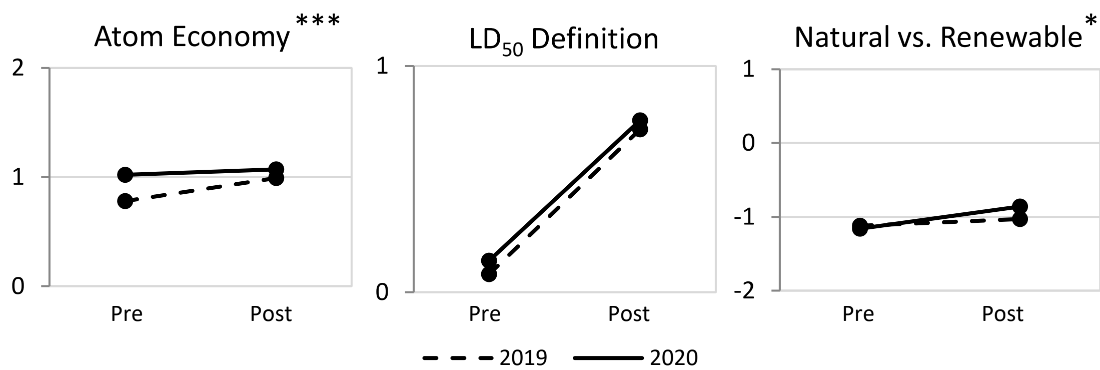


Figure 3.5. Chem 1AL students' mean scores on three select-all green chemistry content questions at the beginning and end of the semester. Mann–Whitney U Tests were used to compare gain scores for the Fall 2019 and Fall 2020 classes (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$; N=570 in 2019, 527 in 2020).

Some prior studies report lower[31] or comparable[20,35] performance for students who completed laboratory courses online. In other cases, students performed better on assignments related to virtual experiments, but these findings were tempered by concerns of academic integrity[36] or unequal assignment difficulty.[34] Because our analysis involved comparing scores on identical questions answered in the same online survey environment, differences in academic integrity and assessment difficulty were not a concern. It is therefore more appropriate to compare our results to studies that used identical pre–post assessments when comparing virtual and in-person instruction. In these studies, which were conducted prior to the COVID-19 pandemic, students who completed virtual experiments scored as well[37] or better[38,39] on conceptual questions related to the experiment as compared to students who completed the experiment in-person. This makes sense considering that online laboratory instruction can focus more on theory and conceptual understanding when students are not physically completing experimental procedures.

Limitations

There are several limitations to this study. The experiments described in this work were designed and evaluated during the COVID-19 pandemic. Student and instructor impressions would likely be different had they chosen to take the course online during a semester unaffected by the pandemic. Also, this study was conducted at large public universities, and the experiments were designed for those institutions' specific curricula. The Google Sites interface makes it easy to modify this type of experiment for courses at different institutions, but the findings reported herein may not be entirely generalizable to universities with different class sizes or instructional support. Although data from both universities is reported, some analyses were conducted only with UC Berkeley students, and the sample size and response rate for the Online Laboratory Survey were much lower at UC Santa Cruz than at UC Berkeley. This should be taken into account when interpreting comparisons between these institutions.

There are additional limitations associated with our use of the Learning Gains Survey in making comparisons in learning outcomes between online and in-person courses. Our comparison of students' performance on chemistry questions relied upon only a small number of multiple-choice and select-all-that-apply questions. These questions were identical on the pretest and post-test, which means that some of the pre–post gains observed could be explained by prior exposure to the pretest questions.[40] We also compared students' self-assessed understanding of chemistry concepts and techniques, but learners are known to commonly have predictive error in their self-evaluation of their understanding.[41] While issues with pretesting effects or predictive error would not necessarily differ in a systematic way between students who took the course online or in-person, it is still important to consider the limitations of the data collected. Furthermore, while we were able to make comparisons involving conceptual knowledge and self-reported understanding of laboratory techniques, we have not yet investigated learning outcomes related to physical performance of laboratory techniques.

Conclusions and Implications

The COVID-19 pandemic presented many challenges to the education system, but it also provided a unique opportunity to explore new modes of instruction and evaluate their impact. We created interactive online laboratory websites for a wide range of courses at two institutions. The websites are easy to adapt for use in different courses, and their creation and use do not require specialized technology or proprietary software. Compared to commercially available virtual laboratory simulations, these experiment websites allow instructors much more freedom to tailor instruction according to the aims of their individual courses.

Students responded positively despite their preference for in-person experiments. Importantly, assessments of student learning in one of the courses that used these online experiments suggested that students who took the course online learned as much conceptual knowledge as students who had previously taken the course in person. However, there were two areas for improvement. Intrinsically, the experiment websites did not provide students with hands-on experience. For fully remote laboratory courses, supplementing with at-home hands-on experiments involving kitchen chemistry (examples: refs 31,42–49) or home laboratory kits (examples: refs 50–56) is a possible solution. Difficulties in collaboration between students was another clear disadvantage of online laboratory courses. Comparing student impressions of community and connection at UC Berkeley and UC Santa Cruz suggests that one way to encourage collaboration between students is to allow students to submit work in pairs according to a formal partner agreement.

These experiment websites remain useful resources even as we return to in-person instruction. In situations where a student would typically miss class due to illness, family emergencies, or school closures, they are now able to complete the experiment online. The BeArS@home and Slugs@home websites can also serve as supplemental prelaboratory activities. Navigating through the various choose-your-own-adventure scenarios prior to completing the physical experiment could give students the opportunity to learn from common mistakes in the low-stakes environment, leading to a less stressful in-person experience. Previous research indicates that supplementing in-person laboratory work with preparatory simulations or instructional videos can lead to increased confidence and conceptual understanding,[57–59] as well as decrease the amount of time spent and the number of experimental errors made while completing the corresponding physical experiment.[60] For these reasons, we have continued to make these experiment sites available to students. It would be valuable in the future to investigate ways that these online experiments can effectively be used to supplement in-person laboratory instruction.

References

(1) Hofstein, A.; Lunetta, V. N. *Sci. Educ.* **2003**, *88*, 28–54.
(2) Reid, N.; Shah, I. *Chem. Educ. Res. Pract.* **2007**, *8*, 172–185.

(3) Committee on Professional Training. *Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*; American Chemical Society: Washington, D. C., 2015.
(4) Kennepohl, D. *Can. J. Chem.* **2021**, *99*, 851–859.
(5) Kelley, E. W. *J. Chem. Educ.* **2021**, *98*, 2496–2517.
(6) Chan, P.; Van Gerven, T.; Dubois, J.-L.; Bernaerts, K. *Comput. Educ. Open* **2021**, *2*, 100053-1–100053-17.
(7) de Jong, T.; Linn, M. C.; Zacharia, Z. C. *Science* **2013**, *340*, 305–308.
(8) Achuthan, K.; Murali, S. S. A Comparative Study of Educational Laboratories from Cost & Learning Effectiveness Perspective. In *Software Engineering in Intelligent Systems*; Silhavy, R., Senkerik, R., Oplatkova, Z. K., Prokopova, Z., Silhavy, P., Eds.; Advances in Intelligent Systems and Computing; Springer International Publishing: Cham, 2015; pp 143–153.
(9) Groos, L.; Maass, K.; Graulich, N. *J. Chem. Educ.* **2021,** *98*, 1919–1927.
(10) Evans, M.; Boucher, A. R. *Mind Brain Educ.* **2015**, *9*, 87–91.
(11) Banfield, J.; Wilkerson, B. *Contemp. Issues Educ. Res.* **2014**, *7*, 291–298.
(12) Butler, D. L.; Winne, P. H. *Rev. Educ. Res.* **1995**, *65*, 245–281.
(13) D'Angelo, J. G. *J. Chem. Educ.* **2020**, *97*, 3064–3069.
(14) Warning, L. A.; Kobylianskii, K. *J. Chem. Educ.* **2021**, *98*, 924–929.
(15) Mistry, N.; Shahid, N. *J. Chem. Educ.* **2021**, *98*, 2952–2958.
(16) Armstrong, L. B. The Green (Chemistry) Environment: Developing and Assessing Green Chemistry Curricula and Student Outcomes in the General Chemistry Laboratory. Ph.D., University of California, Berkeley, United States -- California, 2021.
(17) Bland, J. M.; Altman, D. G. *BMJ* **1997**, *314* (7080), 572.
(18) Sher, A. *J. Interact. Online Learn.* **2009**, *8*, 102–120.
(19) Swan, K. Learning Effectiveness Online: What the Research Tells Us. In *Elements of Quality Online Education, Practice and Direction*; Moore, J. C., Bourne, J., Eds.; Sloan Center for Online Education, 2003; pp 13–45.
(20) Scruggs, A. W.; Leamy, K. A.; Cravens, S. L.; Siegel, S. J. *J. Chem. Educ.* **2020**, *97*, 2981–2986.
(21) Rodríguez-Rodríguez, E.; Sánchez-Paniagua, M.; Sanz-Landaluze, J.; Moreno-Guzmán, M. *J. Chem. Educ.* **2020**, *97*, 2556–2564.
(22) Serafin, J. M.; Chabra, J. *J. Chem. Educ.* **2020**, *97*, 3007–3010.
(23) Villanueva, O.; Zimmermann, K. *J. Chem. Educ.* **2020**, *97*, 3114–3120.
(24) Wang, L.-Q.; Ren, J. *J. Chem. Educ.* **2020**, *97*, 3002–3006.
(25) Woelk, K.; Whitefield, P. D. *J. Chem. Educ.* **2020**, *97*, 2996–3001.
(26) Youssef, M.; McKinstry, E. L.; Dunne, A.; Bitton, A.; Brady, A. G.; Jordan, T. *J. Chem. Educ.* **2020**, *97*, 3048–3054.
(27) Bassindale, T.; LeSuer, R.; Smith, D. *J. Forensic Sci. Educ.* **2021**, *3*, 1–10.
(28) Anstey, M. R.; Blauch, David. N.; Carroll, F. A.; Gorensek-Benitez, A. H.; Hauser, C. D.; Key, H. M.; Myers, J. K.; Stevens, E. P.; Striplin, D. R.; Holck, H. W.; Montero-Lopez, L.; Snyder, N. L. *J. Chem. Educ.* **2020**, *97*, 2800–2805.
(29) Dietrich, N.; Kentheswaran, K.; Ahmadi, A.; Teychené, J.; Bessière, Y.; Alfenore, S.; Laborie, S.; Bastoul, D.; Loubière, K.; Guigui, C.; Sperandio, M.; Barna, L.; Paul, E.; Cabassud, C.; Liné, A.; Hébrard, G. *J. Chem. Educ.* **2020**, *97*, 2448–2457.
(30) Dickson-Karn, N. M. *J. Chem. Educ.* **2020**, *97*, 2955–2959.

(31) Schultz, M.; Callahan, D. L.; Miltiadous, A. *J. Chem. Educ.* **2020**, *97*, 2678–2684.
(32) Boling, E. C.; Hough, M.; Krinsky, H.; Saleem, H.; Stevens, M. *Internet High. Educ.* **2012**, *15*, 118–126.
(33) Alawamleh, M.; Al-Twait, L. M.; Al-Saht, G. R. *Asian Educ. Dev. Stud.* **2020**, *11*, 2046–3162.
(34) Gao, R.; Lloyd, J.; Kim, Y. *J. Chem. Educ.* **2020**, *97*, 3028–3032.
(35) Marincean, S.; Scribner, S. L. *J. Chem. Educ.* **2020**, *97*, 3074–3078.
(36) Tran, K.; Beshir, A.; Vaze, A. *J. Chem. Educ.* **2020**, *97*, 3079–3084.
(37) Hawkins, I.; Phelps, A. J. *Chem. Educ. Res. Pract.* **2013**, *14*, 516–523.
(38) Tatli, Z.; Ayas, A. *J. Educ. Technol. Soc.* **2013**, *16*, 159–170.
(39) Winkelmann, K.; Keeney-Kennicutt, W.; Fowler, D.; Macik, M. *J. Chem. Educ.* **2017**, *94*, 849–858.
(40) Hartley, J. *Instr. Sci.* **1973**, *2*, 193–214.
(41) Lindsey, B. A.; Nagel, M. L. *Phys. Rev. Spec. Top. - Phys. Educ. Res.* **2015**, *11*, 020103-1–020103-11.
(42) Maqsood, S.; Kilpatrick, S. M.; Truong, C. D.; Lefler, S. R. *J. Chem. Educ.* **2021**, *98*, 858–865.
(43) Andrews, J. L.; de Los Rios, J. P.; Rayaluru, M.; Lee, S.; Mai, L.; Schusser, A.; Mak, C. H. *J. Chem. Educ.* **2020**, *97*, 1887–1894.
(44) Al-Soufi, W.; Carrazana-Garcia, J.; Novo, M. *J. Chem. Educ.* **2020**, *97*, 3090–3096.
(45) Ibarra-Rivera, T. R.; Delgado-Montemayor, C.; Oviedo-Garza, F.; Pérez-Meseguer, J.; Rivas-Galindo, V. M.; Waksman-Minsky, N.; Pérez-López, L. A. *J. Chem. Educ.* **2020**, *97*, 3055–3059.
(46) Doughan, S.; Shahmuradyan, A. *J. Chem. Educ.* **2021**, *98*, 1031–1036.
(47) Destino, J. F.; Cunningham, K. *J. Chem. Educ.* **2020**, *97*, 2960–2966.
(48) Nguyen, J. G.; Keuseman, K. J. *J. Chem. Educ.* **2020**, *97*, 3042–3047.
(49) Caraballo, R. M.; Saleh Medina, L. M.; Gomez, S. G. J.; Vensaus, P.; Hamer, M. *J. Chem. Educ.* **2021**, *98*, 958–965.
(50) Burchett, S.; Hayes, J. L. Online Chemistry: The Development and Use of a Custom In-House Laboratory Kit. In *Online Approaches to Chemical Education*; ACS Symposium Series; American Chemical Society, 2017; Vol. 1261, pp 57–70.
(51) Kelley, E. W. *J. Chem. Educ.* **2021**, *98*, 1622–1635.
(52) Miles, D. T.; Wells, W. G. *J. Chem. Educ.* **2020**, *97*, 2971–2975.
(53) Orzolek, B. J.; Kozlowski, M. C. *J. Chem. Educ.* **2021**, *98*, 951–957.
(54) Pitre, D.; Stokes, S.; Mlsna, D. *J. Chem. Educ.* **2021**, *98*, 2403–2410.
(55) Schmuck, V. D. E.; Romine, I. C.; Sisley, T. A.; Immoos, C. E.; Scott, G. E.; Zigler, D. F.; Martinez, A. W. *J. Chem. Educ.* **2022**, *99*, 1081–1086.
(56) Ambruso, K.; Riley, K. R. *J. Chem. Educ.* **2022**, *99*, 1125–1131.
(57) Limniou, M.; Papadopoulos, N.; Giannakoudakis, A.; Roberts, D.; Otto, O. *Chem. Educ. Res. Pract.* **2007**, *8*, 220–231.
(58) Campbell, J.; Macey, A.; Chen, W.; Shah, U. V.; Brechtelsbauer, C. *J. Chem. Educ.* **2020**, *97*, 4001–4007.
(59) Altowaiji, S.; Haddadin, R.; Campos, P.; Sorn, S.; Gonzalez, L.; Villafañe, S. M.; Groves, M. N. *Chem. Educ. Res. Pract.* **2021**, *22*, 616–625.
(60) Burewicz, A.; Miranowicz, N. *Chem. Educ. Res. Pract.* **2006**, *7*, 1–12.

Chapter Contributions

The work described in this chapter would not have been possible without the contributions of Adrienne Calderon, Alex Zera, Alexis Shusterman, Anne Baranger, Caitlin Binder, Daniel Droege, Laura Fredriksen, Michelle Douskey, Nelson Gaillard, Peter Marsden, and Stephanie Pitch. Peter Marsden, Laura Fredriksen, Alexis Shusterman, Michelle Douskey, and Anne Baranger, and Daniel Droege, Stephanie Pitch, Caitlin Binder, and I all participated in the design of various online experiments used at UC Berkeley or UC Santa Cruz. I designed the Online Laboratory Survey, with helpful feedback from Adrienne Calderon, Alex Zera, Peter Marsden, Alexis Shusterman, Michelle Douskey, and Anne Baranger. I distributed surveys to UC Berkeley study participants, while Daniel Droege and Stephanie Pitch distributed surveys to UC Santa Cruz study participants. Adrienne Calderon, Nelson Gaillard, and Alex Zera helped me with developing the free response coding scheme and analyzing free response data from the Online Laboratory Survey. I performed all other data collection, data analysis, and additional research activities described in this chapter.

Appendices

Appendix 3.1: Student/TA Individual Interview Protocol

Introduction

- What year are you in school?
- What are your future plans (research, career?)
- Students Only:
  - What is your major?
  - What science courses have you taken that have used online experiments?
  - What other science laboratory courses have you taken or plan to take?
- TAs Only:
  - What course(s) have you taught that used these online experiments?
  - What other teaching experience do you have? Had you taught online prior to teaching this course?

Survey Response Explanations:

For each multiple-choice question on the survey:

- On the survey, you said this: ________. Why did you answer in this way? Explain your thought process.

General Questions:

- Describe your typical experience in your synchronous laboratory section. How did you approach the online experiments? What interactions did you have with students or instructors?
- In your opinion, what are the major strengths of the online experiments?
- What are the major negative aspects of online experiments?
- What suggestions/best practices do you have for teaching online experiments?

Appendix 3.2: Focus Group Guide

General questions about Chemistry 1AL:

- What laboratory experiences (chemistry or otherwise) have you had since taking Chemistry 1AL?
- What are some skills that you associate with learning during Chemistry 1AL?
- What skills from Chemistry 1AL do you currently use in either other laboratory courses or research laboratories?

At this point, the member of the research team who is facilitating the focus group will give them a brief description of the experiment in case they don't remember the details.

Questions related to Polymers Lab:

Before going through online version of experiment:

- What was the most memorable part of doing this experiment in person?
- What were the main concepts and techniques you remember learning from doing this experiment in person?

The group of students will then work on the online experiment together for 20 minutes while sharing their browser window on Zoom.

After going through online version of experiment:

- What is your general impression of this online experiment?
  - Is it clear?
  - Is it engaging?
- What is at least one benefit and at least one drawback of doing this experiment in person?
- What is at least one benefit and at least one drawback of doing this experiment online?
- Do you think you would have learned the concepts as effectively when doing this experiment online?
- What were the main concepts and techniques you think students would learn from doing this experiment online?
- What aspects would you change about this online experiment if you could?

Appendix 3.3: Online Laboratory Survey: Students

Online Laboratory Survey: Students

Course Taken

Which of the following laboratory courses did you take this semester/quarter?

- ○ Chem 1AL
- ○ Chem 1B
- ○ Chem 3AL
- ○ Chem 3BL
- ○ Chem 4A
- ○ Chem 4B
- ○ Chem 8M
- ○ Chem 8L
- ○ Chem 12A
- ○ Chem 12B
- ○ Chem 110L

Synchronous Lab Attendance

How often did you attend your assigned lab section synchronously this semester/quarter?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Most of the time
- ○ Always

Why did you decide to attend your assigned lab section synchronously at least some of the time? Please check all that apply.

- ☐ Attending synchronously allowed me to learn from my GSI's prelab lecture
- ☐ Attending synchronously allowed me to ask my GSI questions in real time
- ☐ Attending synchronously gave me the ability to work together with other students in real time

- ☐ Attending synchronously provided me with a structured environment for getting my work done
- ☐ [ ] Other (please specify):

Why did you sometimes or always decide against attending your assigned lab section synchronously? Please check all that apply.

- ☐ Time zone conflicts
- ☐ Other time conflicts
- ☐ Technology issues
- ☐ I did not find attending synchronously to be helpful
- ☐ [ ] Other (please specify):

Navigating Through Online Labs

When and with whom did you most often navigate the online labs?

- ○ I usually clicked through by myself, before my lab section.
- ○ I usually clicked through by myself, during my lab section.
- ○ I usually clicked through by myself, after my lab section.
- ○ I usually clicked through with one or more other students, before my lab section.
- ○ I usually clicked through with one or more other students, during my lab section.
- ○ I usually clicked through with one or more other students, after my lab section.

How did you typically navigate through the online labs?

- ○ I usually clicked through once linearly, from start to finish.
- ○ I usually clicked through once linearly, and then went back to parts I needed to revisit at the end.
- ○ I usually jumped around, looking for specific parts.
- ○ I usually jumped around, looking for specific parts, and then went back to parts I needed to revisit at the end.

How did you typically approach "choose your own adventure" labs where you were able to choose different paths?

○ Whenever there was a choice, I clicked all of the different options to see how the various scenarios played out.

○ I tried to figure out what the best option was, and I only clicked through that scenario.

○ I randomly chose a path without considering what the best option was, then clicked through a different path if I chose incorrectly the first time.

Impressions of Online Labs

Please indicate how much you agree with the following statements about the online labs:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
The online labs helped me learn about various experimental techniques.	○	○	○	○	○
The online labs helped me learn about the concepts underlying various experimental techniques.	○	○	○	○	○
The online labs helped further my understanding of the chemistry concepts covered in the lecture component of my course.	○	○	○	○	○
The online labs were clear and easy to follow.	○	○	○	○	○
The online labs were interesting and engaging.	○	○	○	○	○
I think I learned more from the online lab experiments than I would have from the corresponding in-person lab experiments.	○	○	○	○	○
Online labs are not a reasonable substitute for in-person labs.	○	○	○	○	○
I think the online labs were as effective as in-person labs would have been.	○	○	○	○	○
I think I prefer online labs to in-person labs.	○	○	○	○	○
Once in-person labs resume, I would continue to use the online labs as an additional resource for myself.	○	○	○	○	○
I think the online labs will prepare me well for the next chemistry laboratory course I will take.	○	○	○	○	○
I do not think the online labs will prepare me well for my future plans (e.g. med school, grad school, job - write plans below): [ ]	○	○	○	○	○

What was your favorite experiment?

What was your least favorite experiment?

Were there any particular online labs or parts of online labs that stuck in your memory in a positive way? Explain.

Were there any particular online labs or parts of online labs that stuck in your memory in a negative way? Explain.

Building Community in Online Labs

Please indicate how much you agree with the following statements about forming connections with others during online and in-person labs.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was easier to connect with other students during online labs than it would have been in person.	○	○	○	○	○
It was more difficult to connect with my GSI during online labs than it would have been in person.	○	○	○	○	○
It was easier to find study partners in my online labs than it would have been in person.	○	○	○	○	○
It was more difficult to make friends in my online labs than it would have been in person.	○	○	○	○	○
It was easier to ask for help during online labs than it would have been in person.	○	○	○	○	○

What have you found to be most helpful in building community with your classmates and/or instructors in your online lab course? Please select up to four choices.

- ☐ Synchronous lab sections
- ☐ Study groups
- ☐ Piazza
- ☐ Discord groups
- ☐ Slack channels
- ☐ Facebook groups
- ☐ Other (please specify): ______

Technology Issues

How often have you encountered technological issues while completing the online labs?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Most of the time
- ○ Always

What technology-related issues have you encountered while completing the online labs? Please check all that apply.

- ☐ Problems with internet connectivity or speed
- ☐ Problems with printing
- ☐ Problems with scanning
- ☐ Problems with downloading and/or uploading assignments
- ☐ Problems with accessing Google sites
- ☐ Problems with annotating PDFs on a tablet or other device
- ☐ Other (please specify):

Free Response

What else would you like to recommend or make sure that the instructional team knows about your experience with online labs?

Course Background and Demographics

How would you characterize your previous college-level lab coursework?

- ○ None
- ○ Online, at my current institution
- ○ Online, at another institution
- ○ In person, at my current institution
- ○ In person, at another institution
- ○ Mixture of online and in person, at my current institution
- ○ Mixture of online and in person, at another institution

Did you transfer to your current institution from another college or university?

- ◯ Yes
- ◯ No

What is your major or intended major?

- ◯ Life Science
- ◯ Physical Science (other than chemistry)
- ◯ Chemistry/Chemical Biology
- ◯ Humanities
- ◯ Social Science
- ◯ Engineering
- ◯ Public Health
- ◯ [ ] Other: (Please specify)

How many college credit units are you taking this semester/quarter?

[ ]

What is the highest level of formal education obtained by either of your parents/guardians?

- ◯ Did not complete high school
- ◯ High school graduate
- ◯ Postsecondary school other than college
- ◯ Some college
- ◯ College degree
- ◯ Some graduate school
- ◯ Graduate degree
- ◯ Not sure
- ◯ Decline to state

What do you most closely identify as? Mark all that apply.

- [ ] White/Caucasian
- [ ] African American/Black
- [ ] American Indian/Alaska Native
- [ ] Middle Eastern/North African (e.g., Moroccan, Egyptian, Saudi Arabian, Iranian)
- [ ] East Asian (e.g., Chinese, Japanese, Korean, Taiwanese)
- [ ] Filipino
- [ ] Southeast Asian (e.g., Cambodian, Vietnamese, Hmong)
- [ ] South Asian (e.g., Indian, Pakistani, Nepalese, Sri Lankan)
- [ ] Other Asian
- [ ] Native Hawaiian/Pacific Islander
- [ ] Mexican American/Chicano
- [ ] Puerto Rican
- [ ] Other Latino
- [ ] Decline to state
- [ ] Prefer to self-describe: ____

Are you an international student?

- ○ Yes
- ○ No

With which gender do you most identify?

- ○ I identify as a man
- ○ I identify as a woman
- ○ I identify as non-binary
- ○ Not sure
- ○ Decline to state
- ○ Prefer to self describe: ____

Is English your first language?

- ○ Yes
- ○ No

Survey Conclusion

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!

After submitting your responses, you can protect your privacy by clearing your browser's history, cache, cookies, and other browsing data. (Warning: This will log you out of online services.)

Appendix 3.4: Online Laboratory Survey: Teaching Assistants

Online Laboratory Survey: Teaching Assistants

Course Taught

Which of the following laboratory courses did you teach this semester/quarter?

Chem 1AL
Chem 1B
Chem 3AL
Chem 3BL
Chem 4A
Chem 4B
Chem 8M
Chem 8L
Chem 12A
Chem 12B
Chem 110L

Impressions of Online Labs

Please indicate how much you agree with the following statements about the online labs:

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
The online labs helped my students learn about various experimental techniques.	○	○	○	○	○
The online labs helped my students learn about the concepts underlying various experimental techniques.	○	○	○	○	○

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
The online labs helped my students further their understanding of the chemistry concepts covered in the lecture component of the course.	○	○	○	○	○
The online labs were clear and easy to follow.	○	○	○	○	○
The online labs were interesting and engaging.	○	○	○	○	○
The online labs allowed me to give my students more specific, individualized attention compared to in-person labs.	○	○	○	○	○
It was difficult for me to track my students' learning during online labs.	○	○	○	○	○
Online labs are a reasonable substitute for in-person labs.	○	○	○	○	○
I think the online labs were as effective as in-person labs would have been.	○	○	○	○	○
Once in-person labs resume, I would continue to use the online labs as an additional resource for myself and/or my students.	○	○	○	○	○
After completing the online labs, most of my students would be able to safely perform a similar experiment in person.	○	○	○	○	○

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
After completing the online labs, most of my students would be well-prepared for their next chemistry lab class.	○	○	○	○	○

Were there any particular online labs or parts of online labs that stuck in your memory in a positive way? Explain.

Were there any particular online labs or parts of online labs that stuck in your memory in a negative way? Explain.

Previous Teaching Experience

How would you characterize your previous semesters/quarters of teaching laboratory courses?

None

Online, at my current institution

Online, at another institution

In person, at my current institution

In person, at another institution

Mixture of online and in person, at my current institution

Mixture of online and in person, at another institution

Please indicate how much you agree with the following statements comparing your experience with online and in-person instruction.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Teaching online labs requires more work than teaching in-person labs.	○	○	○	○	○
I prefer teaching online labs to in-person labs.	○	○	○	○	○

Building Community in Online Labs

Please indicate how much you agree with the following statements about forming connections with others during online and in-person labs.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was easier for my students to connect with other students during online labs than it would have been in person.	○	○	○	○	○
It was more difficult for me to connect with my students during online labs than it would have been in person.	○	○	○	○	○
It was easier for my students to find study partners in the online lab than it would have been in person.	○	○	○	○	○

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
It was more difficult for my students to make friends in the online labs than it would have been in person.	○	○	○	○	○
It was easier for my students to ask for help during online labs than it would have been in person.	○	○	○	○	○

What have you found to be most helpful in building community with your student and/or fellow instructors in the online lab course you are teaching? Please select up to four choices.

Synchronous lab sections
Piazza
Discord groups
Slack channels
Facebook groups
Other (please specify):

Suggestions for Teaching Online Labs

What do you recommend for assigning groups in breakout rooms? (For example, some teaching assistantss are organizing by level of engagement, putting people that want to talk a lot together, etc.)

What do you recommend for using the Google sites during the synchronous lab session? (For example, one member of the group sharing their screen, students each going through the Google site at their own pace, etc.)

What other suggestions do you have for teaching online labs?

Free Response

What else would you like to recommend or make sure that the instructional team knows about your experience with online labs?

Survey Conclusion

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!

After submitting your responses, you can protect your privacy by clearing your browser's history, cache, cookies, and other browsing data. (Warning: This will log you out of online services.)

Appendix 3.5: Learning Gains Survey

Green Chemistry Practices

Please indicate your level of agreement with the following statements:

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
Energy usage is not a major concern during chemistry experiments.	○	○	○	○
Chemistry should focus on advancing research and chemical understanding. The impact these advances have on humans and the environment is a secondary concern.	○	○	○	○
I think about how my decisions impact the environment.	○	○	○	○
I buy products that I consider 'green.'	○	○	○	○
Cleaning up or treating chemical waste is a good alternative to minimizing the amount of experimental waste.	○	○	○	○
I don't worry about how much waste I create; one person can't make much of a difference.	○	○	○	○
I talk with friends about problems related to green chemistry.	○	○	○	○
When choosing a new product I think about what was required to make it (starting materials, safety, waste, etc.).	○	○	○	○
Chemistry experiments should use nonrenewable materials if this leads to lower costs or better results.	○	○	○	○
We don't need to make chemistry experiments safer - that's why we use goggles, lab coats, and gloves.	○	○	○	○

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.

Green Chemistry Attitudes

Please indicate your level of agreement with the following statements about **green chemistry**:

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I want to acquire more green chemistry knowledge.	○	○	○	○
I think green chemistry is important in advancing knowledge.	○	○	○	○
I can do green chemistry.	○	○	○	○
I think green chemistry is important for advancing society.	○	○	○	○
Green chemistry plays an important role in my life because I use many products of the chemical industry.	○	○	○	○
I think about the green chemistry I experience in everyday life.	○	○	○	○

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I find green chemistry interesting.	○	○	○	○
Learning green chemistry changes my ideas about how the world works.	○	○	○	○
I think green products are very important.	○	○	○	○
Green chemistry is **NOT** useful for other fields I am interested in.	○	○	○	○
I believe that I can understand green chemistry.	○	○	○	○
The subject of green chemistry has little relation to what I experience in the real world.	○	○	○	○
Green chemistry has connections to my daily life.	○	○	○	○

Green Chemistry Multiple Choice

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 LD_{50} for the starting material, ammonium nitrate, is shown above. LD_{50} tells you:
(Select all statements that are accurate.)

- [ ] 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 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 cancer in an entire test population
- [ ] 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.

- [ ] Renewable products are likely to be safe for humans and the environment.
- [ ] Natural products or processes are preferable to lab-made ones.
- [ ] Natural products are likely to be safe for humans and the environment.
- [ ] Natural products are sustainable.
- [ ] Renewable products are sustainable.
- [ ] The terms "natural" and "renewable" are interchangeable.
- [ ] I don't know.

Green Chemistry Principles Ranking Task

For the following three questions, please choose the top three 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)?

Items	Top three principles that apply (ranked from most to least applicable):
Waste Prevention	
Atom Economy	
Less Hazardous Chemicals/Syntheses	
Designing Safer Chemicals	
Safer Solvents	
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	

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)?

Items	Top three principles that apply (ranked from most to least applicable):
Waste Prevention	
Atom Economy	

Less Hazardous Chemicals/Syntheses

Designing Safer Chemicals

Safer Solvents

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

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)?

Items	Top three principles that apply (ranked from most to least applicable):
Waste Prevention	
Atom Economy	
Less Hazardous Chemicals/Syntheses	
Designing Safer Chemicals	
Safer Solvents	
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

Green Chemistry Understanding

Please indicate your level of agreement with the following statements:

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I can define green chemistry principles (e.g. atom economy, catalysis, renewable feedstocks).	◯	◯	◯	◯
I understand what happens to waste after it leaves the laboratory.	◯	◯	◯	◯
I can identify factors that make a reaction 'green'.	◯	◯	◯	◯
I can identify hazards associated with a reaction or experiment.	◯	◯	◯	◯
I understand how to minimize chemical waste.	◯	◯	◯	◯
I know what the term green chemistry means.	◯	◯	◯	◯
I can suggest improvements to make a reaction greener.	◯	◯	◯	◯
I can suggest ways to make a reaction or experiment less hazardous.	◯	◯	◯	◯

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
Creating serial dilutions	◯	◯	◯	◯	◯
Performing a titration using indicators	◯	◯	◯	◯	◯
Relationships between physical properties and molecular structures	◯	◯	◯	◯	◯

	not at all	a little	somewhat	a good deal	a great deal
Types of bonding (non-polar covalent, polar covalent, ionic)	○	○	○	○	○
Using a UV/Vis spectrometer	○	○	○	○	○
Intermolecular interactions	○	○	○	○	○
Electrochemistry	○	○	○	○	○
Generating a calibration curve	○	○	○	○	○
Calorimetry	○	○	○	○	○
Performing error analysis	○	○	○	○	○
Performing a titration using a pH probe	○	○	○	○	○

Chemistry Attitudes

Please indicate your level of agreement with the following statements about **chemistry**:

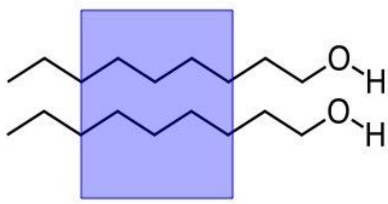
	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I can do chemistry.	○	○	○	○
I find chemistry interesting.	○	○	○	○
I believe that I can understand chemistry.	○	○	○	○
I talk with friends about problems related to green chemistry.	○	○	○	○
I think about the chemistry I experience in everyday life.	○	○	○	○
I think chemical products are very important.	○	○	○	○
Learning chemistry changes my ideas about how the world works.	○	○	○	○
Chemistry plays an important role in my life because I use many products of the chemical industry.	○	○	○	○
I think chemistry is important in advancing knowledge.	○	○	○	○
Chemistry is **NOT** useful for other fields I am interested in.	○	○	○	○
I want to acquire more chemistry knowledge.	○	○	○	○

	Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree
I think chemistry is important for advancing society.	○	○	○	○
Chemistry has connections to my daily life.	○	○	○	○
The subject of chemistry has little relation to what I experience in the real world.	○	○	○	○

Chemistry Multiple Choice Questions

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."

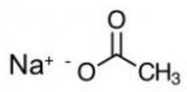


Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above.

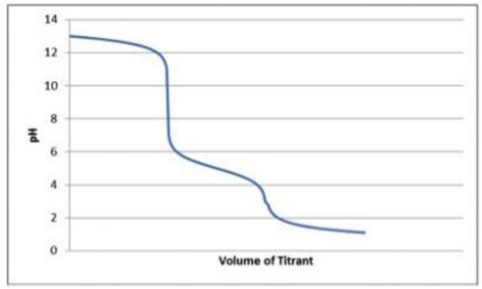
- ○ Ionic interactions
- ○ Hydrogen bonding interactions
- ○ London dispersion interactions (induced dipole-induced dipole interactions)
- ○ I don't know.

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 ($NaC_2H_3O_2$). You measure the pH during the titration, and the titration curve shown below is the result.



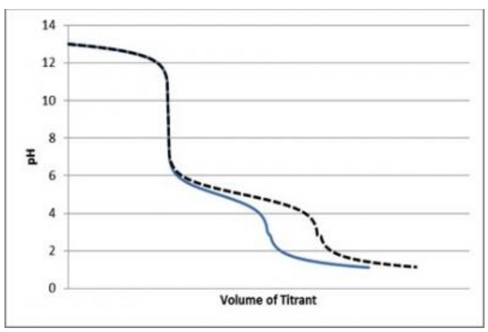
sodium acetate

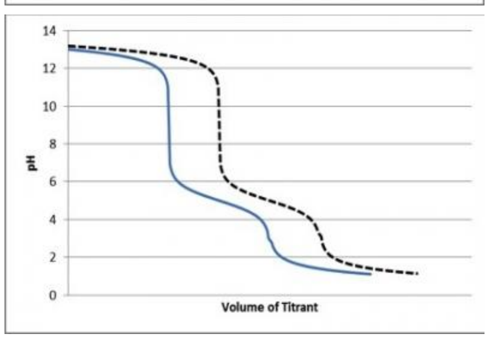


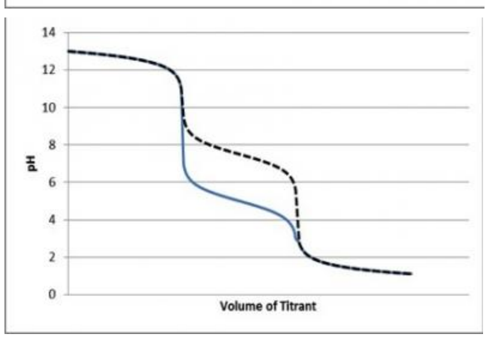
Your lab partner has a different sample, one with a greater amount of NaOH and the same amount of $NaC_2H_3O_2$.

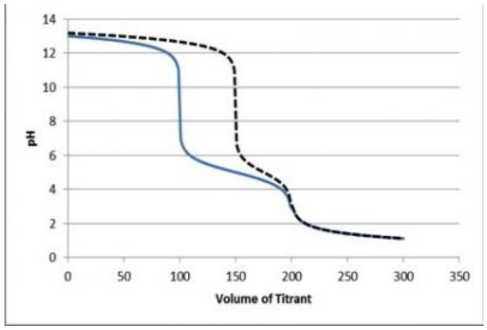
— Your data
--- Your lab partner's data

What would the titration curve for this sample look like compared to yours?

○ 

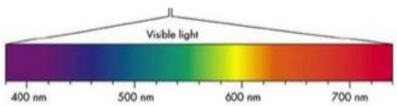
○ 

○ 

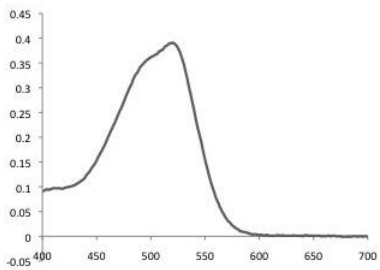


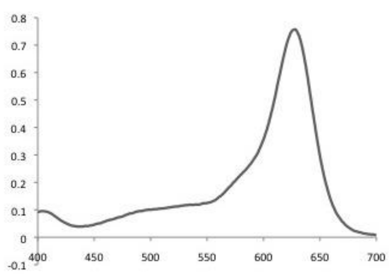
I don't know.

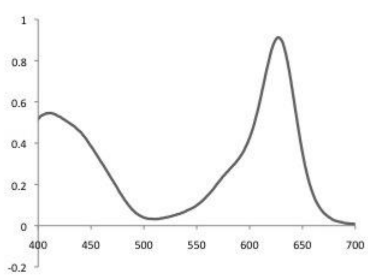
For the next question, refer to the spectrum provided below:



Which absorbance spectrum (absorbance versus wavelength in nm) would correspond to a green solution?







I don't know.

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.

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 will not be able to return to this page once you have pressed the NEXT button. Please make sure your answers are complete before you progress.

Appendix 3.6: Factor Analysis and Reliability Analysis

The sample of UC Berkeley Online Laboratory Survey respondents was determined to be adequate for factor analysis using the Kaiser-Meyer-Olin Measure of Sampling Adequacy (KMO=0.86; >0.5 is considered suitable) and Bartlett's Test of Sphericity ($p=0.000$, $p<0.05$ is considered suitable). Exploratory unrestricted factor analysis was conducted using principal-axis factoring due to the non-normality of the data, and direct oblimin oblique rotation was chosen because some degree of correlation was expected among the factors. This resulted in a three-factor solution with eigenvalues greater than one, accounting for 48% of the total variance. Items were considered to load onto a factor when the absolute value of the standardized loading greater than 0.35. As seen in Table A3.6.1, all items loaded unambiguously on only one factor. The correlations between the subscales were -0.498 between factors 1 and 2, 0.548 between factors 1 and 3, and -0.314 between factors 2 and 3.

Based on inspection of the items that clustered together, we named these factors:

Learning Experience: Items that indicated students' general impressions of the online experiments and their perceptions of learning in an online laboratory environment

Comparing Usefulness: Items that indicated students' opinion of the utility/effectiveness of online experiments in comparison to in-person experiments

Comparing Community: Items that indicated students' opinion of community in online laboratory environments compared to in-person environments

Table A3.6.1. Factor Loadings for Online Laboratory Survey Likert Items. Affiliation to a Factor is Indicated by Bold Text.

Survey Item	**Factor 1** Comparing Usefulness	**Factor 2** Learning Experience	**Factor 3** Comparing Community
The online labs helped me learn about various experimental techniques.	0.097	**-0.692**	-0.028
The online labs helped me learn about the concepts underlying various experimental techniques.	-0.102	**-0.860**	-0.011
The online labs helped further my understanding of the chemistry concepts covered in the lecture component of my course.	-0.052	**-0.825**	-0.018
The online labs were clear and easy to follow.	0.060	**-0.469**	0.041
The online labs were interesting and engaging.	0.140	**-0.592**	0.075
I think I learned more from the online lab experiments than I would have from the corresponding in-person lab experiments.	**0.806**	-0.017	0.026

Online labs are not a reasonable substitute for in-person labs. *	**0.413**	-0.055	0.005
I think the online labs were as effective as in-person labs would have been.	**0.844**	-0.027	-0.021
I think I prefer online labs to in-person labs.	**0.794**	0.071	0.020
It was easier to connect with other students during online labs than it would have been in person.	0.065	0.067	**0.728**
It was more difficult to connect with my [TA] during online labs than it would have been in person. *	-0.013	-0.100	**0.464**
It was easier to find study partners in my online labs than it would have been in person.	-0.001	0.060	**0.746**
It was more difficult to make friends in my online labs than it would have been in person. *	-0.032	0.032	**0.583**
It was easier to ask for help during online labs than it would have been in person.	0.028	-0.072	**0.514**

* Items were reverse-coded for the purpose of analysis.

For each composite scale, Cronbach's alpha was used to assess the reliability of the set of items. All three composite scales had Cronbach's alpha values greater than 0.7, which is considered to indicate acceptable internal consistency (Table A3.6.2).

Table A3.6.2. Cronbach's Alpha Values for the Learning Experience, Comparing Usefulness, and Comparing Community Composite Scales (*N*=3784)

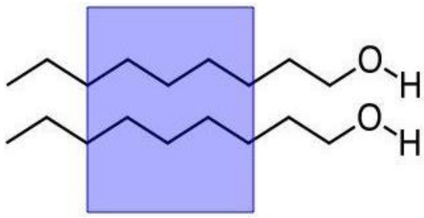
Composite Scale	Number of Items	Cronbach's Alpha
Learning Experience	5	0.830
Comparing Usefulness	4	0.808
Comparing Community	5	0.746

Appendix 3.7: Correct Answers to Learning Gains Survey Content Questions

Note: Correct answers are highlighted in yellow.

Chemistry Multiple-Choice Questions

1. **Intermolecular Forces:**



Indicate which of the following intermolecular interactions is occurring in the area shaded in the diagram above.

- o Ionic interactions
- o Hydrogen bonding interactions
- o London dispersion interactions (induced dipole-induced dipole interactions)
- o I don't know.

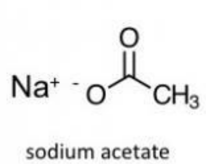
2. **Bond Energy:** Heat is given off when hydrogen burns in air according to the equation:

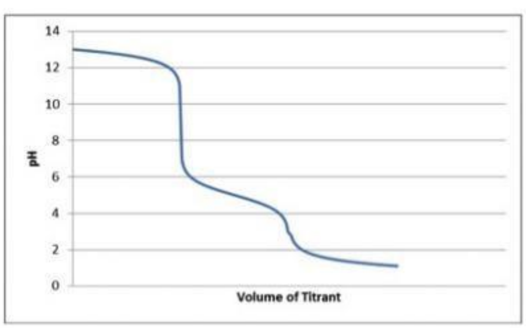
$2\ H_2 + O_2 \rightarrow 2\ H_2O$

Which of the following is responsible for the heat?

- o A. Breaking bonds between hydrogen atoms gives off energy.
- o B. Breaking bonds between oxygen atoms gives off energy.
- o C. Forming bonds between hydrogen and oxygen atoms gives off energy.
- o Both answers A and B are correct.
- o Answers A, B, and C are correct.
- o I don't know

3. **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.



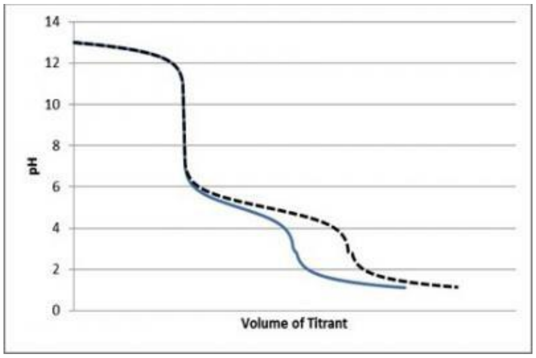


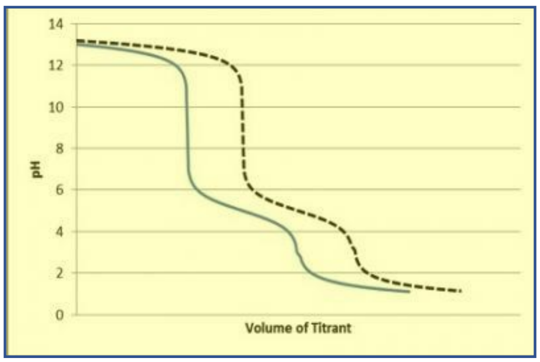
Your lab partner has a different sample, one with a greater amount of NaOH and the same amount of NaC2H3O2.

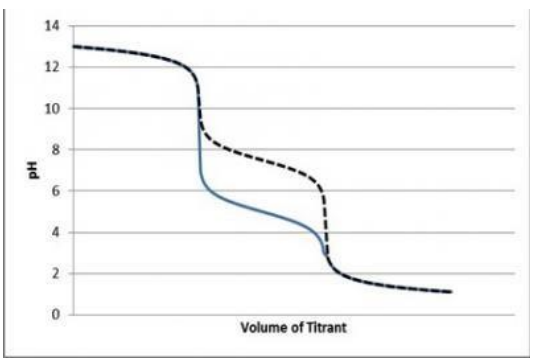
Your data

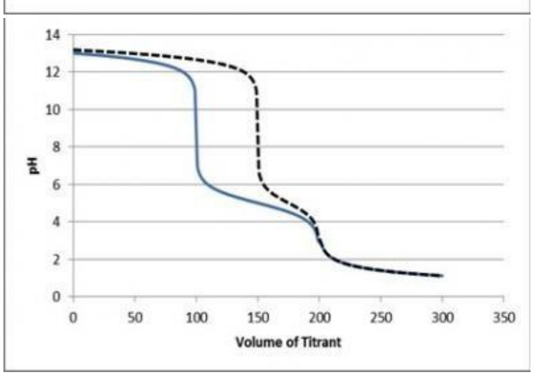
Your lab partner's data

What would the titration curve for this sample look like compared to yours?



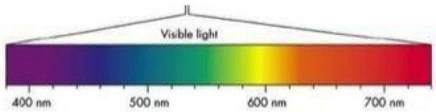




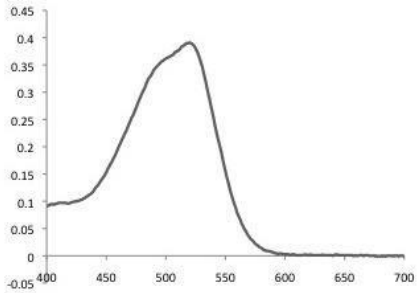


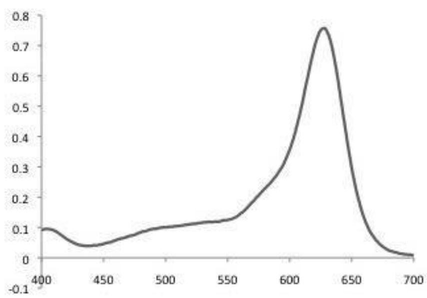
I don't know.

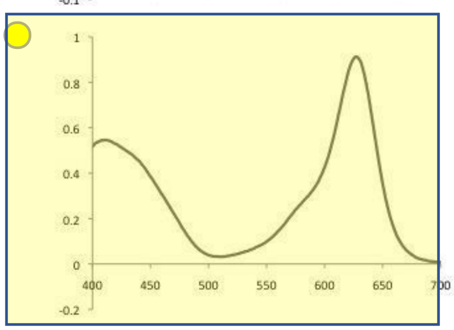
4. **Absorbance:** For the next question, refer to the spectrum provided below:



Which absorbance spectrum (absorbance versus wavelength in nm) would correspond to a green solution?







I don't know.

Green Chemistry Select-All-That-Apply Questions

1. **Atom Economy:** 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.

2. **LD_{50} Definition:** The LD_{50} 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.

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.

- ☐ 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 preferable to lab-made ones.
- ☐ I don't know.

Appendix 3.8: Coding Scheme

Table A3.8.1. Names and Definitions of Codes Used in Analysis of Survey Free Responses, Interviews, and Focus Groups

Code	Definition: Response mentions...	Example Quote(s)
Ability to Revisit Content	Being able go back over experiment content or rewatch videos	"It was nice to be able to replay videos so students could review parts that they may have missed. You can't replay a chemical reaction in person."
Choose Your Own Adventure	"Choose your own adventure" portions of online experiments	"It was helpful when we were given a few different choices for variables or chemicals in the experiment that each yielded different results. If I went through the experiment for one variable and was still confused, I could press another option and see that part of the experiment again (in a different way)."
Comparison of Laboratory Formats	A comparison of online and in-person laboratories, often giving an advantage or disadvantage of one format	"Labs were easy to follow, as we were walked through all the steps. I found that for some labs I learned more than I probably would have in-person."
Ease of Use/Understanding	That something about the online experiments is easy or difficult to use or understand	"There were definitely labs that were somewhat confusing when trying to match certain parts of it to the lab reports but other than that it was actually very clear."
Feelings of Stress	Feelings of stress, worry, or anxiety	"The structure of the online labs made me less stressed that I might mess up and ruin the experiment."
Focus on Theory	That online experiments focus on conceptual knowledge	"One bright side to online labs was that I could focus more on understanding the chemistry concepts than completing a lab in a time period."
Instructor	An instructor associated with the course, or interactions between students and instructors	"I liked how [our TA] was more freely available to answer our questions, compared to during in-person labs. Online, [our TA] could pop into our breakout rooms frequently"

Interest/Engagement	Whether something is fun, interesting, or engaging	"Clicking through can feel monotonous at times and can detract from the appeal of learning and engaging with science."
Lack of Experience/ Preparation	That students lack hands-on experience or preparation	"Online labs have a fault in that they cannot replicate the physical touch of the tools used so I still feel inadequate."
Non-Website Features of Course	Features of the course that do not involve the experiment sites, such as assignments, grading, or lectures	"I thought some of the deadlines for work were a little harsh or rigid."
Nothing/No	"No," "none," "N/A," or similar non-response	"Not really," "Not that I can remember," "No online lab stuck out in a negative way."
Peers	Other students in the course, or interactions between students	"I think the most frustrating part of online lab was getting a communicative group to work with."
Time Spent/Flexibility	Amount of time spent on laboratory work or flexibility in scheduling	"Some positives about online labs are the convenience of being able to do it whenever you want, even in multiple sittings if necessary…and the fact that they probably take less time than in person labs."
Specific Experiments/ Techniques	A specific experiment or laboratory technique, e.g. chromatography	"The online lab that was centered around Smells (Nose Lab) due to the fact it was very engaging and descriptive and the videos delineating the smells with the cartoon characters were very helpful"
Tech Issues	Problems associated with technology	"The lab website was sometimes slow or did not work on my computer making the labs frustrating at times."
Videos/Photos	Videos and photos used on experiment sites	"Some labs had unclear images so collecting data was difficult."
Workload	Amount of work involved in completing experiments	"Hydration of alkenes seemed like way too much work but I was probably just tired that week."