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A Specifications-Graded, Spice-Themed, General Chemistry Laboratory Course Using an Argument-Driven Inquiry Approach

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Abstract:

This paper describes the creation of a second quarter of a two-quarter sequence of argument-driven-inquiry general chemistry laboratories. The course contains four projects investigating the chemistry of spices (vanilla, cinnamon, spearmint, and cloves) and incorporates a structured review and hands-on applications of fundamental concepts necessary to transition between general and organic chemistry (colligative properties, TLC, synthesis, characterization tests, and unknown determination). The inquiry-based curriculum was designed to give students increasing responsibility and freedom to develop experimental design skills. Specifications grading is used to increase concept iteration and encourage teamwork amongst students. Survey results for student learning style, feelings about chemistry, and perception of the course format are compared for first and second quarter courses. Changes in survey responses show higher average positive responses in many categories for the second quarter course.

Graphical Abstract

Keywords

Undergraduate / General, Laboratory Instruction, Curriculum, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Specifications Grading

Introduction

Herein, we describe the thematically connected curriculum for the second quarter general chemistry laboratory course (GCL-II) at the University of California, Irvine (UCI). We previously described the creation of the first quarter large-scale general chemistry laboratory course (GCL-I) using the same methodology.[1]

Course Scale and Structure

UCI's non-chemistry-major two-course general chemistry laboratory sequence (GCL-I and GCL-II) spans two 10-week quarters. Weekly four-hour laboratory sessions with 24 students are supervised by one graduate student teaching assistant (GTA). The first quarter of lab (GCL-I) is taken with the last quarter of general chemistry lecture (GC-III) and the second quarter of lab (GCL-II) is typically taken with the first quarter of organic chemistry lecture (OC-I) (Table 1). The high-enrollment (1300+ students) GCL-I course offering occurs each spring, followed by a high-enrollment (1000+ students) GCL-II course offering each fall. Summer session and alternate quarter course offerings for both courses typically have enrollments of approximately 200 with students who either did not initially pass prerequisite lecture courses or completed the course sequence off track. On-sequence high-enrollment GCL-I and GCL-II courses typically require 50 lab sessions and 25 GTAs. Off-sequence low-enrollment courses require 8 lab sessions and 4 GTAs. (SI Section IX contains GCL-II student demographics).

Table 1: Structure of On-Sequence and Off-sequence General Chemistry Courses[1]

Year	Fall Quarter	Winter Quarter	Spring Quarter
First-Year On-Sequence	General Chemistry Lecture I (GC-I) *(No Laboratory Course)*	General Chemistry Lecture II (GC-II) *(No Laboratory Course)*	General Chemistry Lecture III (GC-III) **General Chemistry Laboratory I (GCL-I)**
First-Year Off-Sequence		General Chemistry Lecture I (GC-I) *(No Laboratory Course)*	General Chemistry Lecture II (GC-II) *(No Laboratory Course)*
Second-Year On-Sequence	Organic Chemistry Lecture I (OC-I) **General Chemistry Laboratory II (GCL-II)**		
Second-Year Off-Sequence	General Chemistry Lecture III (GC-III) **General Chemistry Laboratory I (GCL-I)**	No Lecture Course **General Chemistry Laboratory II (GCL-II)**	Organic Chemistry Lecture I (OC-I) *(No Laboratory Course)*

UCI's offset of lower division lab from lecture, specifically the coupling of the large enrollment on-sequence GCL-II with OC-I, permits the incorporation of organic chemistry content in GCL-II, resulting in a transitional course bridging general and organic chemistry. Because GCL-II relies on theories connected to intermolecular forces introduced in GC-II, students in the off-sequence GCL-II can still connect conceptually with course content and benefit from the exposure to introductory organic techniques once enrolled in organic chemistry laboratory.

Originally, the 8 weeks of traditional expository-type experiments in GCL-II addressed diverse topics derived from general chemistry lecture and the corequisite organic chemistry lecture course (e.g., solubility and miscibility, vapor pressure, analysis of a chelated iron salt, aspirin, and chlorophyll). During the laboratory, students worked in pairs to complete procedures outlined in the laboratory manual. After completing the experimentation, each student worked independently to answer post-laboratory questions including calculations with collected data or answering conceptual questions.

Theme

Instead of a broad expository coverage of topics, the new GCL-II course still takes advantage of the corequisite organic lecture (OC-I), but is structured around four spice-themed projects following the argument-driven inquiry (ADI) format developed for GCL-I. Theme-based instruction in general chemistry laboratory courses has been used to contextualize course content for students.[2–8] Thematic connections between experiments provide students a conceptual framework,[9] make course content more relevant,[4,9] and increase student understanding[10,11] and engagement[4,5,9,11,12]. Because of this and the positive student response to the Gatorade theme in GCL-I, we also adopted a theme for GCL-II.[1] Spices were chosen because their organic nature resonates with students concurrently enrolled in OC-I while still utilizing concepts from GC-II to remain accessible to off-sequence students. Furthermore, their benign nature eliminates most chemical hazards and waste.

In the first project of GCL-II, students use freezing point depression and melting point to determine the identity of an unknown spice compound. In the second project, students identify spice compounds in an essential oil through thin layer chromatography (TLC). The final two projects require students to use techniques learned in GCL-I and the previous projects in the GCL-II to synthesize and determine the product of vanillin oxidation and to synthesize and determine the better sunscreen product from ketone and cinnamaldehyde reactions.

Argument-Driven Inquiry (ADI)

The previous version of GCL-II used confirmation-type experiments which provided detailed procedures and post-laboratory questions. Such an approach encourages students to engage in basic science process skills: observation, measurement, and data interpretation. There is support in the education community for going beyond this type of confirmation style experiments.[13–16]

In comparison, Argument Driven Inquiry (ADI) experiments now used in GCL-II provide general procedural guidance and use the claim-evidence-justification framework.[11] Students engage both in the above skills and in additional science process skills: hypothesis (claim) formulation, experimentation, and communication (through argumentation).[15,17–20] The *inquiry* approach engages students more authentically in experimentation by requiring them to develop their own procedures.[14,21] Furthermore, *argumentation* requires students to defend their claims and critique those of others. By combining inquiry and argumentation, ADI has been shown to increase student ability to use evidence and reasoning, create a more positive student attitude toward chemistry, and improve performance on summative assessments.[17,20,22,23]

Additionally, the encouraging results of the Laboratory Course Assessment Survey (LCAS) given to GCL-I students led us to continue the ADI approach in GCL-II.[1] The LCAS measures student perception of peer collaboration, knowledge discovery, and iteration (revision and repetition) for course-based undergraduate research experiences (CUREs).[24] We incorporated the survey because it also probes student perception of relevant ADI activities and, hence our course learning outcomes (Table 2): planning and conducting investigations (LO2 & LO3), collecting and analyzing data (LO3 & LO4), working with others (LO1 & LO4), and presenting and revising work (LO5).

Table 2. GCL-II Learning Outcomes (LOs)

Students will be able to:

LO1: Broadly, engage in scientific inquiry and argumentation with a team of peers.

LO2: Develop fundamental laboratory skills and design experimental procedures. (Skills: recordkeeping, safety/waste disposal, UV-Vis spectroscopy, separations, chromatography, melting and freezing point, and synthesis)

LO3: Collect data, determine and perform data analysis on characterization test results.

LO4: Determine what data are evidence that can be used as justification to support a claim. Defend scientific reasoning to peers.

LO5: Produce an independent report defending their team's claim using scientific reasoning, experimental design, and data analysis. Utilize the revision process to correct misconceptions.

LO6: Demonstrate laboratory skill proficiency and argumentation abilities in the final practical exam.

LO7: Demonstrate a basic understanding of lab safety through safety moments, weekly quizzes, and the safety exam.

Method

GCL-II's ADI course structure like, GCL-I[1] contains four 2-week projects. The learning outcomes (Table 2) are inseparable from the seven-step ADI process (Figure 1):

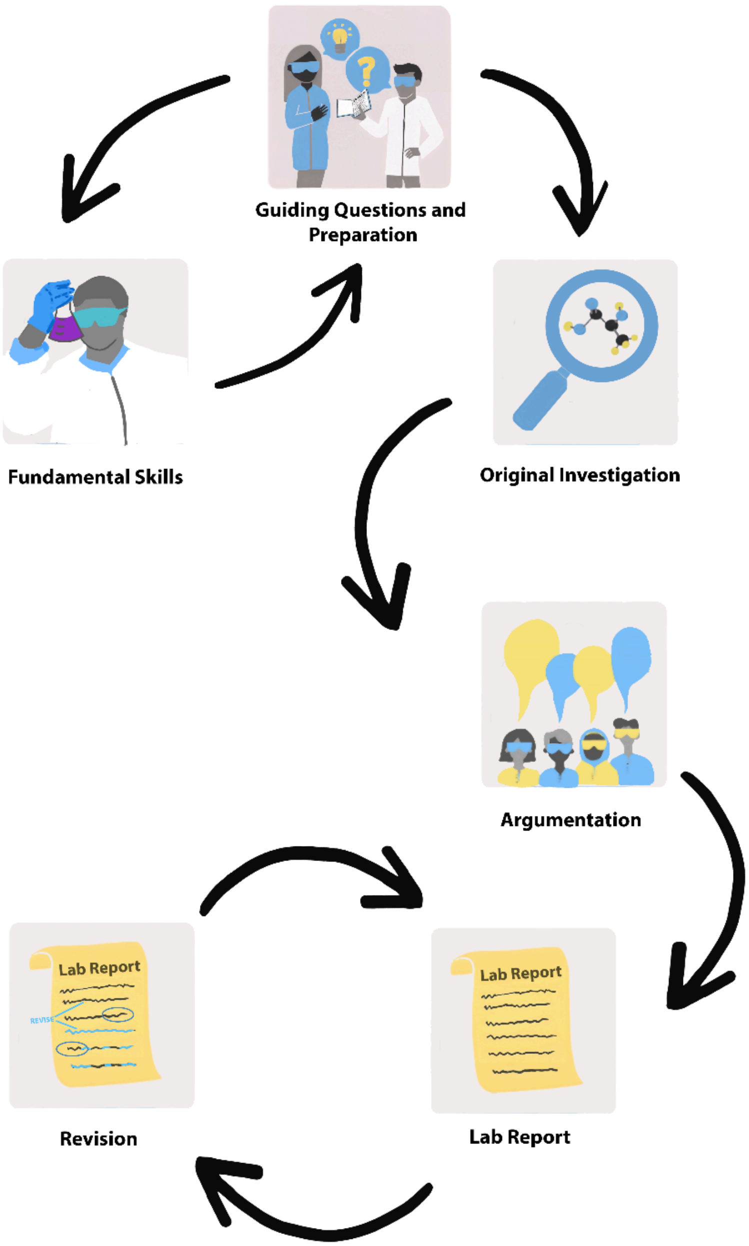


Figure 1. ADI Process

1. **Guiding Question** (LO1)**:** To prepare for a project's first laboratory session (the fundamental skills (FS) session), students are given an initial guiding question (Table 3, second column) and provided general technique information. Before entering the lab, students independently complete a pre-laboratory quiz and prepare their electronic laboratory notebook (ELN) with an objective, safety and chemical tables (LO7), and a draft of procedures to follow in lab.
2. **Fundamental Skills** (LO2 & LO3)**:** During the FS session, a team of 3 to 4 students, (randomly formed during the first course meeting), practice the general technique, collect data, and perform data analysis to answer the guiding question. The team then creates a

procedural plan to approach a second guiding question (Table 3, third column) for the original investigation (OI) in the following laboratory session.

3. **Plan for Original Investigation** (LO2)**:** To prepare for a project's second laboratory session (the OI session), students independently complete a pre-laboratory quiz and prepare their ELN as they did for the first lab session.
4. **Original Investigation** (LO3)**:** During the OI session, the team follows their procedural plan to collect more data, performs data analysis, then provides a justification of their claim (the second guiding question's answer).
5. **Argumentation** (LO1 & LO4)**:** Using chalk paint on their benchtop, the team creates a poster with their claim, evidence, and justification. One team member stays with the poster to defend the team's argument to other teams, while the remaining team members travel to other posters and critique their claims.
6. **Laboratory Report** (LO5)**:** After the OI lab session, students individually write a report based on their experimental work, data analysis, and feedback received during the argumentation session.
7. **Revise and Resubmit** (LO5)**:** Students may revise work based on GTA feedback in exchange for tokens earned through the specifications grading system (see SI).

Table 3. Guiding Questions for GCL-II

Project	**Fundamental Skills (FS)**	**Original Investigation (OI)**
1	What is the average freezing point depression constant for menthol? What is the melting point of the solute? Students measure the freezing point of pure menthol and a menthol solution to determine the freezing point depression constant. Students also measure the solute melting point.	What is the identity of the unknown spice chemical? Students measure the melting point of an unknown and the freezing point of a menthol solution containing a known amount of that unknown. The unknown's molecular mass is determined by freezing point depression.
2	What are the R_f values of the spice compounds? Which heptane:acetone ratio is the best eluent? Students run multiple TLCs of known compounds in various eluent mixtures.	Which spice compounds are present in the essential oil? Students run a TLC of an essential oil with an eluent mixture chosen from the previous work and compare the R_f values to the standards.
3	What is the percent yield of the synthesis if the product is divanillin? If the product is vanillic acid? Students perform an oxidation of vanillin and measure the product's yield.	What is synthesized, divanillin or vanillic acid? Is the product pure? Students use product solubility, melting point, TLC, and UV-Vis absorbance to characterize their product.
4	What are the characteristics of the products observed so far make for a good sunblock? Students synthesize, crystallize, and begin characterization	When combined with **cinnamaldehyde**, which reagent (acetophenone or acetone) makes the best sunblock? Why? Students complete

	tests.	characterization tests on both products.

Our seven ADI steps incorporate scientific inquiry processes: problem identification, making observations, posing questions, collecting data, using scientific concepts to analyze data, and finally, summarizing and communicating results.[25] While most undergraduate laboratory curriculum contains the above steps, the amount students can control experimentation (the inquiry level) is on a continuum. Experiments can range from confirmation type experiments (in which all experimentation parts are dictated) to authentic inquiry (where the student is responsible for the entire process - from the problem investigated to the conclusion derived from the results). Structured, guided, and open inquiry span the difference between these two extremes (Figure 2).[21,26–29]

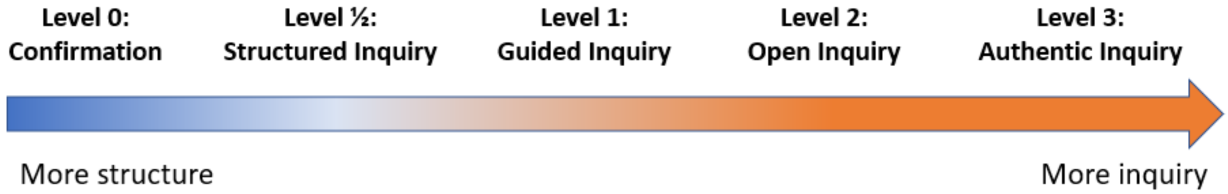


Figure 2. Spectrum of Inquiry Instruction[21]

A primary goal in designing the GCL-I and GCL-II curriculum was to increase the trajectory of inquiry during the courses. An iterative approach throughout the course sequence reinforces understanding of laboratory skills and data analysis techniques while providing students a tool chest to use in each progressive experiment. This is especially evident in GCL-II. Students must employ basic laboratory techniques (such as solution preparation, digital balance use, and visible spectroscopy) from GCL-I with little prompting as well as repurpose skills introduced in each progressive GCL-II project to answer the guiding questions. Another design goal was to allow for student result variability to enable robust argumentation (ADI course structure, step 5). The social sense-making of argumentation is short-circuited if all students come to the same conclusion. In conjunction with this, the ability to use scientific reasoning and apply laboratory skills to new problems is more important than finding one right answer.[18,19,30,31]

An analysis of GCL-I and GCL-II experiments using Bruck et al's *Rubric to Guide Curriculum Development*[27] is shown in Table 4. In the first week of each GCL-I project (the FS session), the question, background, procedures, and data analysis are provided. Therefore, the inquiry level for the FS sessions is structured. The second week of each GCL-I project (the OI session) provides:

- A new guiding question (Table 3);
- General instructions about poster creation for argumentation including claim, evidence, and justification;

- Lab report content questions regarding concepts investigated, procedures used, and claim justification. Students have access to a rubric, which is specific to each project and provides the student some direction as they prepare their report. (Rubric examples, SI Section II.)

Because results analysis/interpretation is not provided in the OI sessions, the inquiry level is guided.

Like GCL-I, the first two projects of GCL-II start with structured inquiry FS sessions, followed by guided inquiry OI sessions. The third and fourth projects of GCL-II rely on the techniques learned in GCL-I and the first two projects of GCL-II to characterize products. Students are reminded of the techniques learned thus far and a few experimental directions (potential solvents, dilution factors, and synthesis procedures). This reduces cognitive load and ensures lab work can be completed during the 4 hour time block. Therefore, the inquiry level in the FS sessions has increased to guided inquiry in the last two projects of GCL-II. While the question, background and procedures are given, no indication of how to analyze the data is provided. The OI sessions for these two projects increase inquiry further toward open inquiry by not providing procedures/design. By project #4, the only information available to provide guidance in answering the OI guiding question is a list of the characterization tests learned during the course sequence with a few experimental details so students can accomplish the work within the allotted laboratory time.

Table 4. Level of Inquiry by Laboratory Session.

Characteristic	**GCL-I FS 1-4**	**GCL-I OI 1-4**	**GCL-II FS 1 & 2**	**GCL-II OI 1 & 2**	**GCL-II FS 3 & 4**	**GCL-II OI 3 & 4**
Problem /Question	P[a]	P	P	P	P	P
Theory /Background	P	P	P	P	P	P
Procedures /Design	P	P	P	P	P	NP
Results Analysis	P	NP	P	NP	NP	NP
Results Communication	NP[b]	NP	NP	NP	NP	NP
Conclusion	NP	NP	NP	NP	NP	NP
Level of Inquiry	Structured (0.5)	Guided (1)	Structured (0.5)	Guided (1)	Guided (1)	Open (2)

[a] P = provided

[b] NP = not provided

For an ADI course, content that predictability results in naturally-occurring variability is often chosen. (Note: this is the opposite of confirmation-type curriculum which relies on the students finding one correct answer.)[13,32] Therefore, an experiment that does not consistently provide good data for novices may work well for ADI. Another important aspect of ADI experiment design is the type of guiding question. Choosing a guiding question focusing on distinguishing (or identifying) instead of obtaining mathematical values supports variation in experimental design and data interpretation.[19]

While GCL-II's FS guiding questions often ask students to obtain specific mathematical values (such as melting points, retention factors, and percent yields), the OI guiding questions (which are central to the argumentation process) do not (Table 3). Furthemore, while the OI guiding questions of GCL-II's first three projects do have correct, scientifically sound answers, flaws in student extrapolation of FS procedure and data analysis in the OI sessions lead to varied data and result in differing claims between student teams. Finally, the last GCL-II project (#4) starts with a guiding question with only conditional answers. One team's product might be better because it is pure, while another team's product has a higher yield, and so on. Another benefit of this variability is that small experimental details are interchangeable in a way that does not affect project structure or documentation (learning outcomes, the manual, the answer key).

Projects

GCL-II is a transitional course bridging general and organic chemistry with a mixture of concepts and techniques from the two sub-disciplines. The course is designed so major concepts and techniques, such as TLC, reoccur throughout projects. Projects also have enough variability to increase inquiry and foster discussion. TLC eluent, for example, is not dictated, and students can choose characterization tests when determining product identity. Furthermore, some conclusions depend on techniques learned (Project 1 and 2) while others allow students to choose techniques they wish to perform (Projects 3 and 4).

Project #1: Menthol and Freezing Point Depression

Project 1 focuses on determining an unknown's identity with freezing and melting points. Many freezing-point depression experiments are known;[29,33–37] herein, we use menthol as a solvent and spice compounds as the solute. In the FS session, student teams measure menthol and cinnamic acid melting points using a melting point apparatus. Students also set up, measure, and analyze the cooling curves for menthol and cinnamic acid-menthol solutions to determine freezing points and calculate their team's K_f and average K_f of menthol for the lab section.

For the OI, students are provided an unknown: cinnamic acid, 4-hydroxybenzaldehyde or vanillin. Students identify the unknown by measuring melting point and finding the molar mass using freezing point depression. Because the collection of the cooling curve requires proper technique (vigorous mixing), freezing point depression data are more varied compared to melting point data (Figure 3). As seen in Figure 3, the ability to determine the freezing point (based off of the graph's inflection point, or the plateau that follows) is more difficult with incorrect technique.

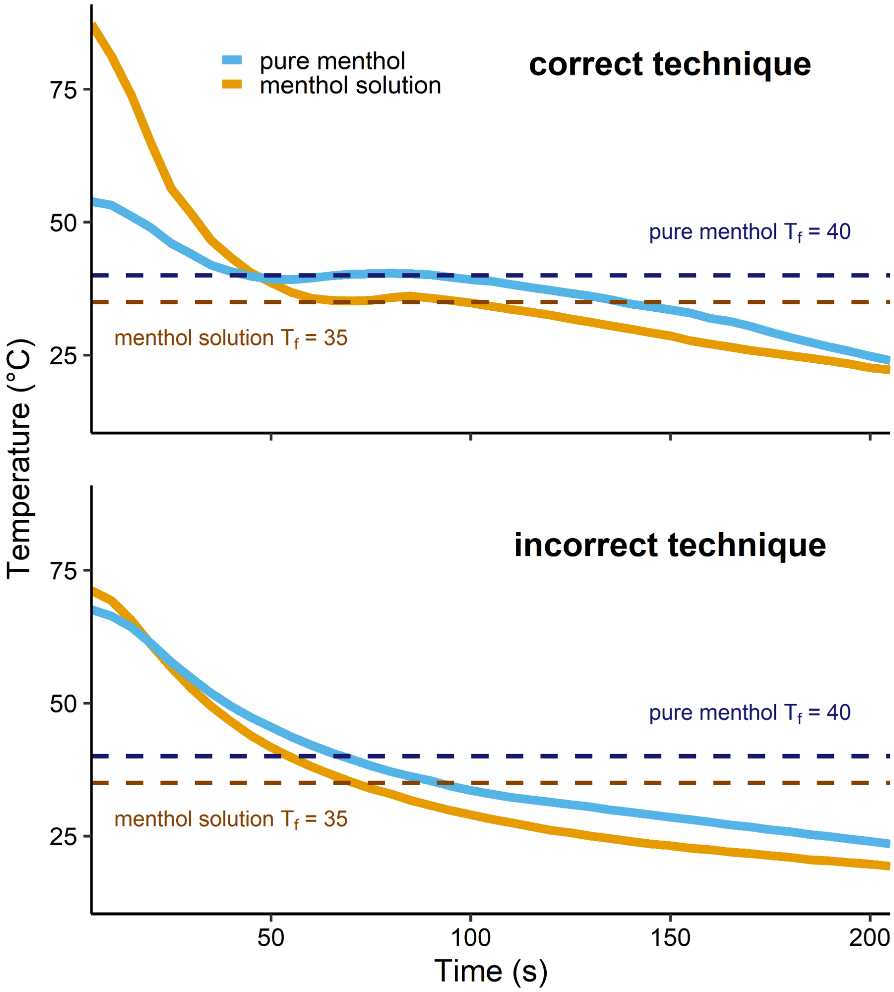


Figure 3. Cooling curves of pure menthol and menthol solution acquired by using correct (top) and incorrect (bottom) technique.

As part of argumentation, students must decide if they would use freezing point depression or melting point to characterize an unknown. A majority of students decide freezing point depression is less useful. For future projects, most students choose melting point over freezing point depression.

Project #2: Essential Oils and TLC

Project 2 focuses on thin-layer chromatography (TLC) and serves as a building block for later experiments. TLC is a separation technique widely employed in industry and laboratory courses.[38–40] Food-based analytes such as essential oils have been used for undergraduate TLC experiments since they are common, inexpensive, and often contain a mixture of organics for separation.[41,42] Inquiry-based TLC experiments have also been utilized, though these experiments are generally limited to factors modulating TLC performance.[38,43,44]

In the FS session, students are tasked to determine the best eluent to achieve good TLC separation of the provided standards: carvone, cinnamaldehyde, dihydrocarveol, eugenol, limonene, and vanillin. The eluents are of variable polarity, consisting of 1:1, 1:2, 2:3, or 3:2 heptane:acetone. (This procedure has since been improved; see SI). Students work within a team, with each student developing TLC plates of all standards for a particular eluent ratio. All standards appear colorless, so UV light and permanganate dip techniques are employed to visualize aromatics/conjugated systems and oxidizable groups respectively. While the various eluent ratios produce varied separation between standards, results are also affected by student technique. Once all plates are developed, teammates compare R_f values to determine the best eluent ratio. (The eluent ratio with the most distinct standard R_f values is 3:2 heptane:acetone, Figure 4.) These R_f values are also used in the OI.

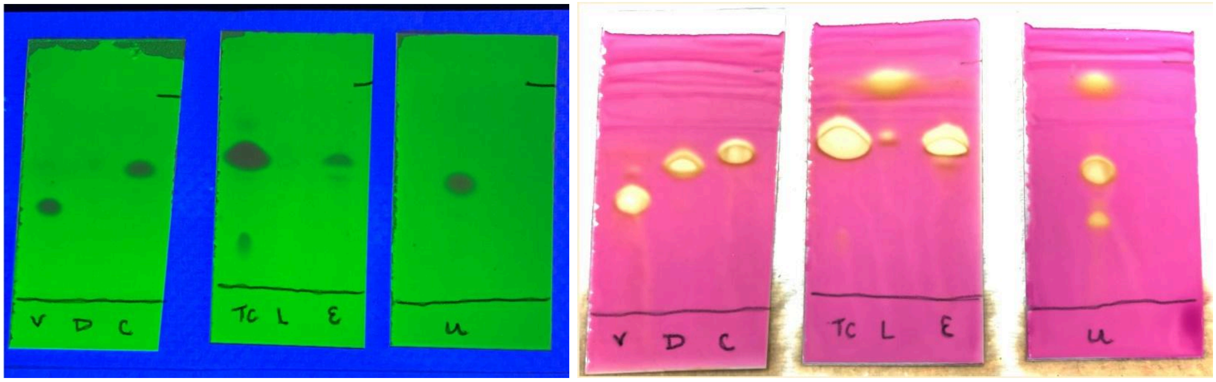
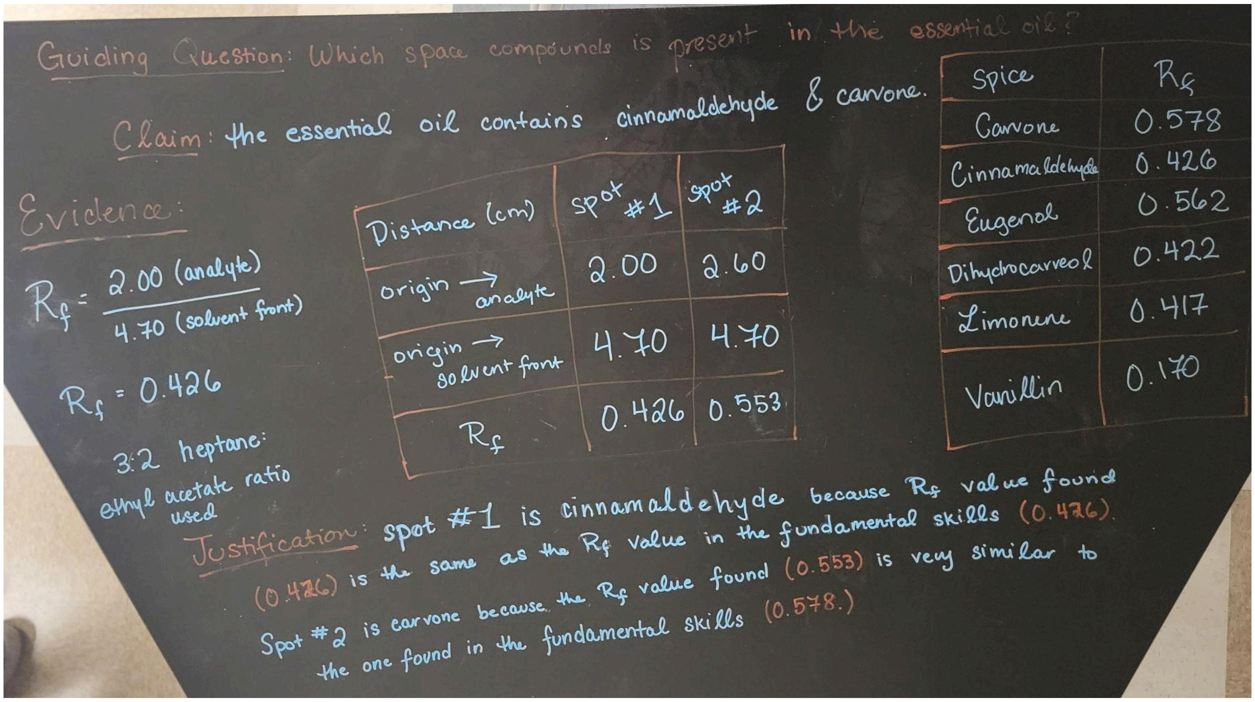


Figure 4. TLCs of essential oil standards under UV light and after a permanganate dip (left to right: vanillin (V), dihydrocarveol (D), carvone (C), *trans*-cinnamaldehyde (TC), limonene (L), eugenol (E)) and the unknown spearmint oil (U) (rightmost) in 3:2 heptane:acetone eluent mixture.

In the OI, teammates work together to determine the chemicals present in an unknown essential oil. Ideally, students select the best eluent ratio from the FS session to run TLC on their unknown, then compare R_f values between standard and unknown plates to determine the unknown components. Other approaches may include running multiple plates with different eluent ratios, and/or rerunning standard plates from the FS session. The unknown sample is the same for all students (spearmint oil), and contains only carvone, limonene, and dihydrocarveol. One of the unknown components (carvone) is UV-active, while the other two are visible after the permanganate dip. During argumentation, student results tend to vary both in eluent ratio selected and in the unknown components determined. For example, student claims vary from one to three unknown chemicals. Sample student responses (Table 5) and an argumentation poster example (Figure 5) are provided and 39% of students sampled (n =157) found 2 of the 3 right unknown compounds, and 56% of students used the best ratio (3:2 heptane:acetone).



Guiding Question: Which space compounds is present in the essential oil?

Claim: the essential oil contains cinnamaldehyde & carvone.

Evidence:

$R_f = \frac{2.00 \text{ (analyte)}}{4.70 \text{ (solvent front)}}$

$R_f = 0.426$

3:2 heptane: ethyl acetate ratio used

Distance (cm)	spot #1	spot #2
origin → analyte	2.00	2.60
origin → solvent front	4.70	4.70
R_f	0.426	0.553

Spice	R_f
Carvone	0.578
Cinnamaldehyde	0.426
Eugenol	0.562
Dihydrocarveol	0.422
Limonene	0.417
Vanillin	0.170

Justification: spot #1 is cinnamaldehyde because R_f value found (0.426) is the same as the R_f value in the fundamental skills (0.426).

Spot #2 is carvone because the R_f value found (0.553) is very similar to the one found in the fundamental skills (0.578.)

Figure 5. Example of a Project #2 Argumentation Poster. Poster has been rewritten from a student poster by the authors for increased legibility.

Table 5. Representative Sample of Project #2 Student Claims and the Eluent Ratios they used

Claim: Which essential oils are present in the unknown?	Eluent Ratio (heptane:acetone)
Carvone and limonene	2:3
Carvone and eugenol	2:3
Carvone	3:2
Carvone, dihydrocarveol and limonene	3:2

Project #3: Vanillin Oxidation and Melting Point

Projects 3 and 4 are adapted from literature[45–47] and focus on performing a synthesis during the FS session and then using characterization techniques of the student's choice during the OI session.

In Project 3, vanillin is reacted with hydrogen peroxide in the presence of horseradish peroxidase. The procedure is adapted from Vosburg[45], with one modification: students are instructed to cool the reaction to room temperature before adding acetic acid and horseradish peroxidase solution (0.05 mg/mL). The FS session is the students' first exposure to organic synthesis and vacuum filtration. During the OI session, students are expected to determine the major product after the synthesis: vanillic acid, divanillin, or recovery of vanillin starting material. While students can choose from characterization techniques they have used before, melting point analysis between product and the provided standards of vanillin and vanillic acid allows for conclusive determination that divanillin is the synthesized product. Other techniques used to determine the identity of the product include solubility, UV-Visible spectroscopy (which students used in GCL-I) and TLC (sample data, Table 6). Because students successively build upon concepts learned in the course, no explicit procedure is provided for TLC or UV-Vis spectroscopy.

Table 6. Representative Sample of Student Data for Project #3 Chemicals.

	vanillin	**vanillic acid**	**divanillin**
Yield	n/a	n/a	57.8%[a]
Solubility	EtoAc, EtOH, water	EtOH, water	EtOH
Melting Point (°C)	81-83	210	315
R_f (in 7:3 ethyl acetate:heptane)	0.64	0.46	0.15

[a] Averaged from student data, *n* = 102, after excluding students who calculated above 100% yield

Project #4: Cinnamon Sunscreen and UV-Vis Spectroscopy

Project 4 focuses on the synthesis of two aldol products from cinnamaldehyde and either acetone or acetophenone. At this point in OC-I (typically taken with GCL-II), the students have not learned aldol condensation and do not know the mechanism; therefore, the experimental focus is product characterization (sample data, Table 7).

Table 7. Representative Sample of Student Data for Project #4 Chemicals.

	acetophenone aldol	**acetone aldol**
Yield	30-70%	40-50%
Solubility	EtOH (partial), EtOAc (partial)	EtOH, EtOAc
Melting Point (°C)	100-102	142-143
R_f (in 3:2 ethyl acetate:heptane)	0.57	0.46

The procedure was adapted from Jaworek-Lopez and Dicks, but with only acetone or acetophenone as the ketone partner to cinnamaldehyde.[46,47] The FS session focuses on the synthesis of either the cinnamaldehyde-acetone or cinnamaldehyde-acetophenone product; students work in teams of four, with each pair performing one synthesis. During the procedure, students are introduced to recrystallization to purify products. The OI session focuses on the student's choice of three previously used characterization techniques to determine which product is the more effective sunscreen. The main technique for determination is designed to be UV-Vis spectroscopy (Figure 6), but this characterization test is not required and is performed only at the student's prerogative. A conclusion can be made using whatever characterization tests are performed.

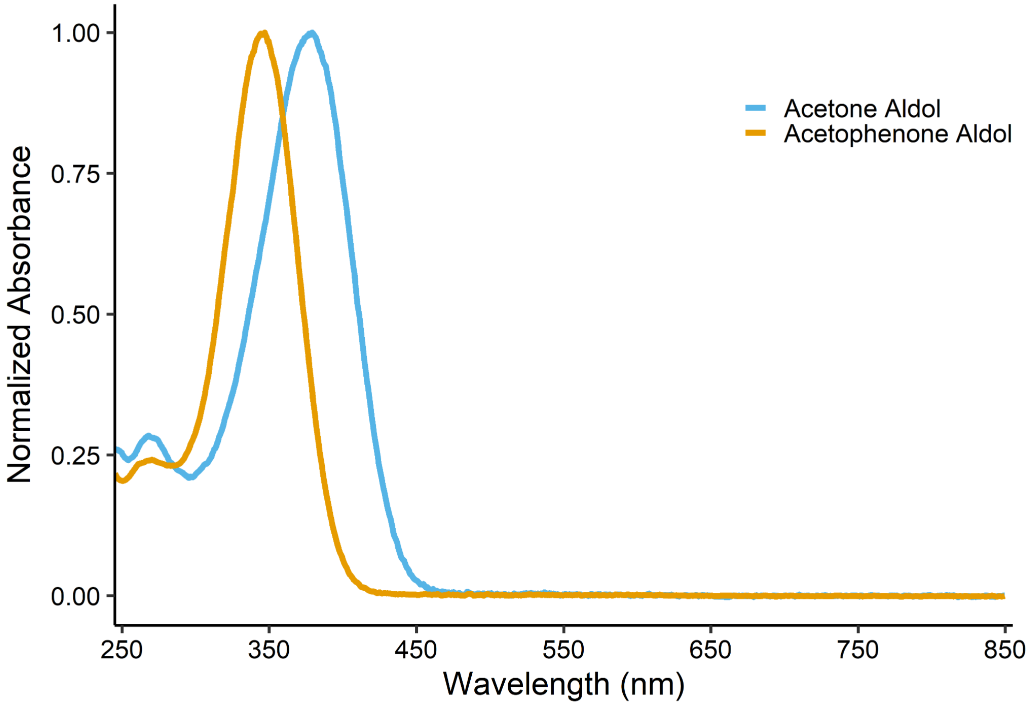


Figure 6. UV-Vis Spectra of Acetophenone and Acetone Aldol

Both products could be argued to be the most effective based on a myriad of factors, from the respective absorbances in the UV region to the color of each purified product (Table 8).

Table 8. Sample Project #4 Student Claims and Justifications

Claim: Which product is a better sunscreen?	**Sample Justification**
Acetophenone Aldol Product	"It is insoluble in water . . . so it will be effective as a water resistant sunscreen. In addition, it had a higher yield, and will therefore be more cost-effective."
Acetone Aldol Product	"[The] acetone [product] is a better sunscreen ingredient because it had a higher melting point than the [acetophenone product] . . and we want a sunscreen that will only melt at high temperatures."
Acetone Aldol Product	"[The acetone product] makes a better sunscreen . . . proven by the broader peak and the higher absorbance [relative to the acetophenone product] of the UV-Vis spectra."

Acetophenone Aldol Product	“The amount of UV light that the [acetophenone aldol product] absorbed was the determining factor. The peak is larger and broader than that for the [acetone aldol product]. From this, we can conclude that the acetophenone product absorbs a larger amount of UV light.”

Hazards

While many chemicals used (vanillin, cinnamaldehyde, eugenol, carvone, etc.) are flammable, skin and/or eye irritants/sensitizers in concentrated or pure form, all chemicals are used in either small quantities or are provided in dilute forms. The organic solvents used (acetone, heptane, ethanol, and ethyl acetate) have the same hazards, with the addition of central nervous system toxicity. Heptane is used in place of hexane because of its lower volatility. Horseradish peroxidase (project #3) is a respiratory and skin sensitizer. Sodium hydroxide (3M, project #4) is corrosive to the skin and can cause eye damage.

If required, waste is neutralized with citric acid and sodium bicarbonate. Glass TLC spotters are collected and disposed of by the GTAs to minimize contamination and injury.

Required laboratory attire for GCL-II includes safety goggles, lab coats, long thick pants covering ankles, sturdy water-resistant closed toed shoes and nitrile gloves. These steps protect against exposure (to irritants, sensitizers, and corrosives) and cuts from broken glassware. All heating is done with hotplates and water baths to reduce the risk of ignition of flammable substances. Volatile organic solvents are used in the fume hood. No open flame is present in the laboratory.

Student Assessment & Specifications Grading

In specifications grading, assignments or rubric items are combined into bundles and the level to pass each bundle for a particular grade is specified. Each rubric item and bundled assignments are assessed as satisfactory or unsatisfactory. This grading method was first introduced by Linda Nilson in 2014[48]. Examples of specifications grading have been reported for general chemistry, biochemistry, biology, math, anatomy and physiology, engineering, and physics lectures, as well as scientific writing courses, general, and organic chemistry laboratory.[1,49–62]

The specifications grading structure of GCL-II is the same as GCL-I[1]. For each project, three types (or grading bundles) of assignments are due: (1) the in-laboratory work done during the FS session; (2) the in-laboratory work done during the OI session; and, (3) the lab report completed after the OI session. All assignments have student facing rubrics with each assignment type (bundle) containing the same general rubric item categories (Table 9). A final assignment bundle is the laboratory practical consisting of: safety, technique, and argumentation. The practical contains all but two of the same general categories: (1) The safety part of the practical includes the safety rubric item; (2) the technique part includes procedure, observations, and data analysis rubric items; and, (3) the argumentation part includes data analysis, but focuses on argumentation rubric items (claim, justification, and evidence).

Table 9. General Rubric Items by Assignment Type

General Rubric Items	**Fundamental Skills (FS)**	**Original Investigations (OI)**	**Lab Reports**	**Final Exam**
Safety	✓	✓		✓
Objective or Purpose	✓	✓	✓	
Concepts	✓		✓	
Procedure	✓	✓	✓	✓
Observations	✓	✓		✓
Data Analysis	✓	✓	✓	✓
Argumentation	✓	✓	✓	✓

The goal of specifications grading is to focus students on the specific skills / knowledge needed to meet course learning outcomes.[48,50,54,63,64] The repetition of general rubric items throughout the courses is central to this effort. To ensure this repetition is obvious to students, rubric items are titled with a general rubric item name and then have a description specific to each assignment (SI Section II). Each rubric item is pass or no pass; no partial credit is given. To further encourage students to meet course learning outcomes,[58] students can revise and resubmit graded work in exchange for tokens earned by completing introductory course assignments, educational study surveys (described below), and mid-quarter GTA student evaluations (SI Section VII). (Note: Completion rate for token earning opportunities (including educational surveys) typically exceeded 98% of course enrollment.)

For a given course grade, students must pass a given number of each of the assignment bundles (Fundamental Skills, Original Investigation, Laboratory Reports) and practical exam sections. Performance on the pre-laboratory quizzes dictates the assignment of + or - to the letter grade. This requirement is the same as published for GCL-I[1] (SI Section VII).

Because specifications grading is a non-competitive grading process, teams work together in a collaborative manner, supporting the ADI process.[50,54,65] Furthermore, token earning and exchange permits revision on 5 of the 12 assignments (4 FS + 4 OI + 4 LR = 12). Token exchange for revision replaces the peer-review step often present in ADI.

Results

Attitude toward the Subject of Chemistry Inventory

Because the **Attitude toward the Subject of Chemistry Inventory** (ASCI(V2)) has shown the impact of a curriculum change, we choose to use the survey to measure students' attitude toward chemistry midway through each quarter of GCL-I and GCL-II.[66–69] In general, students indicate general chemistry laboratory is hard, tense, challenging work that is beneficial and somewhat interesting and worthwhile regardless of their enrollment in GCL-I or GCL-II. (Figure 7).

Going from GCL-I to GCL-II, a statistically positive shift occurred in 9 of 20 items surveyed (demonstrated by bold green average shift values, Figure 7). While on the negative side of the center value (4), GCL-II is more relaxed, more organized, more secure, and clearer, than GCL-I. Furthermore, GCL-II is more exciting, with an increase of 0.17. It cannot be discounted, with increased time in the lab, students will become more comfortable, which may influence the positive trends seen.

The only significant negative attitude shift is students perceive GCL-II as less safe than GCL-I, with an average shift of -0.19. The increase in hazards between the GCL-I and GCL-II courses is a potential source. The hazards in the Gatorade themed GCL-I are limited to dilute solutions of acids, bases and bleach. No chemical reactions require heating and no vacuum is used. However, in GCL-II, the organic nature of many of the chemicals require the use of volatile organic solvents (and, therefore, fume hood use), oxidizers, reaction heating, et cetera in combination with safety curriculum covering these hazards.

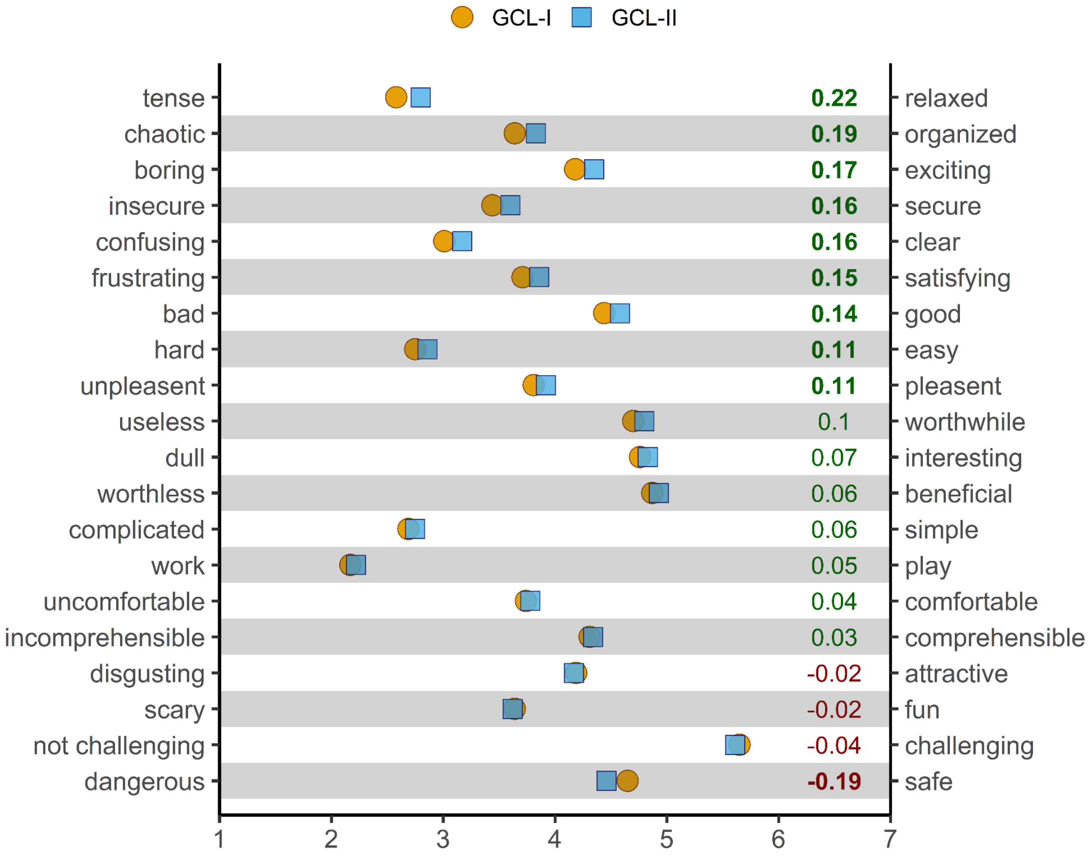


Figure 7. Attitude toward the Subject of Chemistry Inventory (ASCI (V2)) Results for GCL-I and GCL-II, Large On-Sequence Courses. Positive adjectives are shown on the right, their corresponding negative values on the left, reported as a continuum from 1-7. Average responses for GCL-I are shown in orange (◙) and GCL-II in blue (▣). Changes that are statistically significant ($p < 0.05$ with Mann-Whitney U test) are denoted in bolded text. Numerical data can be found in the SI.

Laboratory Course Assessment Survey

A modified version of the **Laboratory Course Assessment Survey** (LCAS) was given to GCL-I and GCL-II while students were engaged in the fourth and final project. LCAS, a 17-item survey designed to measure the effectiveness of course-based undergraduate research experiences (CUREs)[24], contains three sections: assessing student perception of peer collaboration, generation of new knowledge, and work revision and repetition. In addition to the above mentioned activities, the LCAS tool measures student perception of course activities central to ADI: experimental design, data collection / analysis and argumentation. Conclusions from survey data are offered with the caveat that no control group was used for comparison.

Table 10. Modified LCAS Results Comparisons between GCL-I and GCL-II.

Course (Enrollment)	GCL-I (1224)		GCL-II (927)	
	Avg	*SD*	Avg	*SD*
Collaboration	22.1	*0.6*	22.2	*0.7*
C1. Discuss elements of my investigation with classmates and instructors	3.8	*0.8*	3.8	*0.6*
C2. Reflect on what I was learning	3.6	*0.8*	3.7	*0.7*
C3. Contribute my ideas and suggestions during class discussions	3.6	*0.7*	3.6	*0.8*
C4. Help other students collect or analyze data	3.7	*0.7*	3.7	*0.7*
C5. Provide constructive criticism and challenge each other's interpretations	3.7	*0.6*	3.6	*0.7*
C6. Share the problems and seek input on how to address them	3.7	*0.7*	3.7	*0.7*
Discovery / Relevance	18.4	*0.9*	19.0	*1.1*
D1. Generate novel results that could be of interest the community	3.0	*1.2*	3.2	*1.2*
D2. Conduct an investigation to find something previously unknown	3.6	*1.1*	3.7	*1.19*
D3. Formulate my own research question or hypothesis to guide an investigation	4.0	*1.0*	4.0	*1.07*
D4. Develop new arguments based on data	4.1	*1.0*	4.2	*0.91*
D5. Explain how my work has resulted in new scientific knowledge	3.8	*0.9*	3.9	*1.14*
Iteration	20.9	*1.0*	22.7	*1.1*
I1. Revise and repeat work to account for errors or fix problems	3.2	*1.3*	3.6	*1.2*
I2. Change methods of investigation if it was not unfolding as predicted	3.1	*0.9*	3.5	*1.2*
I3. Share and compare data with other students	4.0	*1.0*	4.3	*0.9*
I4. Collect and analyze additional data to	4.1	*1.0*	3.8	*1.2*

address new questions				
I5. Revise and repeat analyses based on feedback	4.1	*1.0*	3.8	*1.2*
I6. Revise drafts of papers or presentations based on feedback	3.5	*1.0*	3.8	*1.1*

Collaboration was measured on a four point scale: weekly (4), monthly (3), 1 or 2 times (2) and never (1). Both Discovery / Relevance and Iteration were modified from the six point scale in the earlier work to a five point scale: (5) strongly agree, (4) somewhat agree, (3) neither, (2) somewhat disagree, and (1) strongly disagree. The sum of the averages for each of the three categories is reported in the gray box in the average (Avg) column.

The responses in the Collaboration (C1-C6) section are consistently high (Table 10). On average most activities occur almost weekly for both GCL-I and GCL-II. This consistent response indicates the ADI team structure results in the perception of collaboration (C1-C6).

The Discovery/Relevance (D1-D5) section contains survey items closely connected with the inquiry processes of the course: designing experimentation, forming a hypothesis, creating an argument and communicating work. Overall, the averaged response shows small increases in agreement strength from GCL-I to GCL-II, indicating students perceive these inquiry processes are occurring repeatedly throughout the course sequence (Table 10). The agreement with the item about new argument creation based on data (D4) is the highest agreement level of all survey items. Furthermore, the agreement to this item increases slightly from GCL-I to GCL-II, suggesting the argumentation sessions (which occur with each project) play a prominent role in the students' perception of the curriculum. Conversely, the "generate novel results… of interest to the community" item (D1) garnered a neutral response in both GCL-I and GCL-II. The theme-based nature of the courses could explain this response. GCL-II's spice theme (like GCL-I's Gatorade theme) was used to provide students with a familiar connection to the course content, but also reduces the "novelty" of the subject matter.

Multiple survey items showed significant increases in agreement in the Iteration section (I1-I6), specifically in items related to revision (I1 and I2, Table 10). Rather than the period-long techniques in GCL-I, GCL-II provides students with multiple small characterization tests which can be repeated. The time barrier that restricted multiple tries of a single technique is not as prevalent in the GCL-II, which is likely tied to the increase in agreement to I1 and I2. This can also be seen in the previously presented ASCI (V2) survey results, which indicate students in GCL-II felt more organized and more relaxed than in GCL-I.

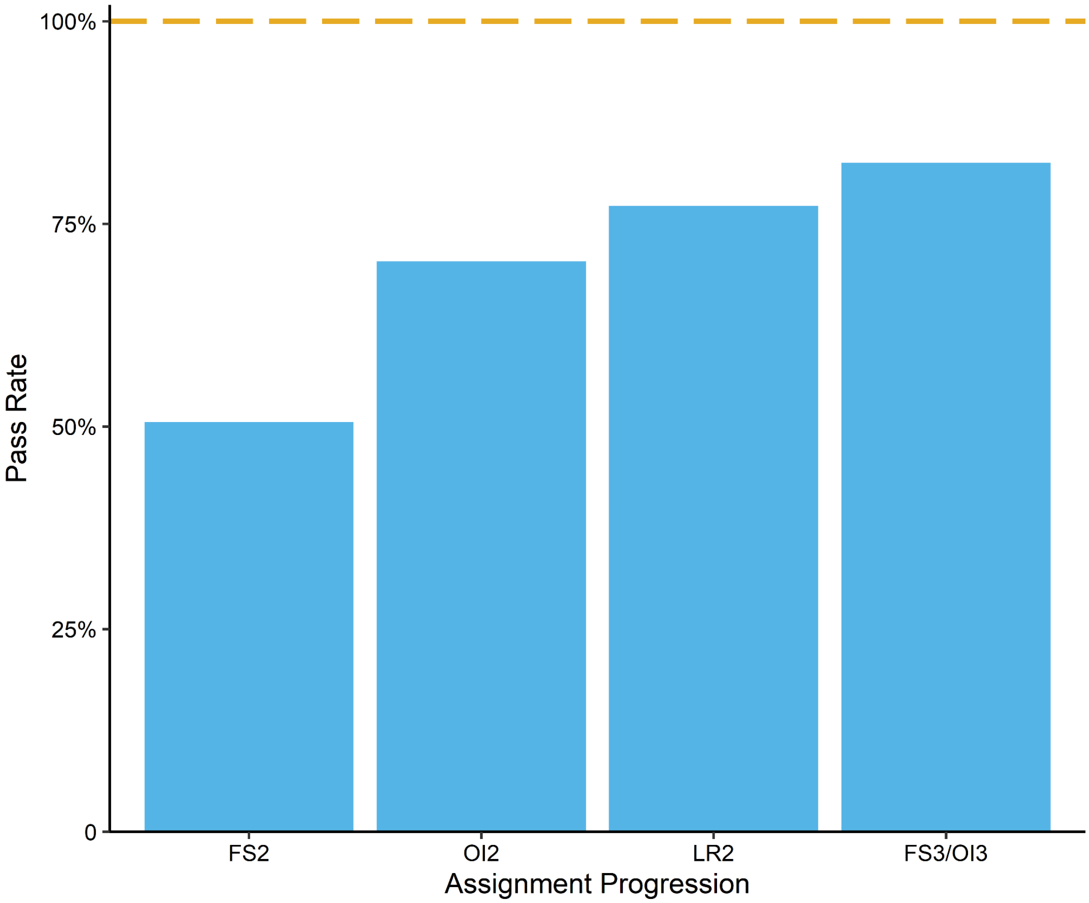


Figure 8. Student pass rates on rubric items concerning TLC technique throughout GCL-II.

The effect of iteration is shown in students' mastery of TLC. TLC is repeated throughout GCL-II: in the FS of Project #2, then in the OI and LR of Project #2, and finally in Project #3 with only basic eluent information provided. The pass rate for TLC (Figure 8) increases from an initial 50.5% pass rate to a 77.2% pass rate within Project #2, and increases again to a 82.5% pass rate during Project #3, indicating increasing retention of TLC techniques and concepts.

Summary and Future Work

Herein, we have presented a theme-based, specifications-graded, ADI-focused lab for GCL-II. The thematic connection was well-received in GCL-I and was continued to connect projects and increase the relevance of the content.[1] Furthermore, the iterative application of methods and skills from previous projects gives student teams increasing responsibility and freedom to collaboratively develop experimental design skills.

The modified LCAS results indicate the GCL-II course results in varying student engagement compared to GCL-I, mostly showing small to significant increases, especially for iteration. The designed repetition of fundamental concepts and techniques results in increased comprehension, as shown in increasing pass rate on related rubric items as the course proceeds. From GCL-I to GCL-II, the ASCI (V2) results show a positive attitude shift, notably with students considering GCL-II to be more relaxed, more organized, and more exciting than GCL-I.

Since the results presented here, adjustments have been made to Project #2 (detailed in the SI). Future adjustments are being made to the specifications grading tools, such as switching to general rubric items from assignment bundles to ensure a passing score reflects proficiency for course objectives. Technique videos are also being developed and implemented to enhance retention and iteration.

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Associated Content

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [Publisher will fill this URL in.]

IRB Statement, Project Manual Links, Survey Questions, Posters, Sample Quiz and Exam Questions, Specifications Use and Letter Grade Requirements and Modifications to Project 2 are available in the SI.

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