Chapter 11

Active Learning Exercises Involving Building and Design

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Chemical analysis relies on calibrated glassware and sophisticated instrumentation. This chapter describes three approaches to student-built models of these tools. In the first, students participate in a semester-long activity to develop quantitative chemical containers (QCCs) to allow those with autism spectrum disorder to work in a laboratory setting. Students determine accuracy, precision, and uncertainty for each container and create technical specifications documents that describe the prototype and its ability to maintain its structure and its volume. Students pitch their designs, use Tinkercad and other software to create their QCCs, print the prototypes on 3D printers, and troubleshoot the robustness of their container. In the second approach, students receive a parts kit for a home-built spectrophotometer. The kit allows for construction of different instruments at varying degrees of sophistication. After design and construction, students characterize the performance of their instrument and/or demonstrate its applicability in an analysis problem. In the third approach, students develop, evaluate, and revise scientific models to explain and predict physical-chemical phenomena in instrumental analysis. The activity promotes understanding at the macroscopic and molecular levels. Different strategies to implement model-based learning are presented, including hand-made models, animated videos, and do-it-yourself instrument prototypes. The flexible activities presented in this chapter may be implemented in classroom or laboratory sections, using different levels of inquiry according to the time and resources available. Additionally, these strategies actively engage students in group work and social interactions that improve motivation and appreciation for the chemical sciences.

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Introduction

This chapter describes three projects, suitable for either a classroom or laboratory course, that engage students in learning through building and design. These projects draw on the principles of design-based and model-based learning. Design-based learning is a pedagogical method in which students work together to design a solution to a real-world problem (*1*, *2*). A review of the literature on design-based learning in engineering education found that the design tasks were "open-ended, hands-on, authentic, and multidisciplinary" (*1*). In model-based learning (MbL), the focus is on developing students' mental models (*3–6*), but instructional strategies may include tasks in which students' prepare and test physical representations of their mental models (*7–10*). These pedagogical methods share a number of advantages. Both approaches encourage students to revise their thinking and take an iterative approach to improving their models or designs (*1*, *2*, *7*, *10*). These methods help students grasp abstract concepts by making them concrete and often help to contextualize new course material within students' prior knowledge (*2*, *8*). Finally, both methods tap into students' creativity. The analytical chemistry curriculum lends itself to these pedagogical approaches, as evidenced by past work (*11*, *12*) and the examples provided here, which include student-designed 3D-printed containers for end users with autism, student-built spectroscopy instrumentation, and multi-modal models of instrumentation.

A 3D Printing Active Learning Activity for Analytical Chemistry

There is precedent that students who engage in Makerspace Activities and the process of "making" have an enhanced experience in STEM (*13*). Moreover, integrative STEM education increases the retention of information for students learning challenging and complex concepts (*14–16*). In this problem-based learning (PBL) activity, fairly simple and often overlooked concepts – accuracy, precision, and uncertainty–in analytical chemistry are explored to substantiate their importance in every unit throughout the course. PBL gives students a real-world problem for which they must use prior knowledge, new knowledge, and collaboration to develop a strategy to solve the problem (*17*). Students are tasked with creating specialized lab equipment (SLE), referred to as Quantitative Chemical Containers (QCCs), for a cosmetics company that is looking for better ways to help their employees with autism develop their laboratory skills to create products. Through this activity, students learn how tolerances of glassware are derived and how to apply the concepts of accuracy, precision, and uncertainty to their own system. The semester-long activity that I (MLM) will describe uses the 3D printers housed in our school's Makerspace in order to develop a prototype QCC.

Analytical Chemistry at Morehouse College is a 200-level course and the only prerequisite to take this course is completion of two semesters of General Chemistry. However, students in their second year usually take Organic Chemistry and in their third year, Physical Chemistry. Therefore, most chemistry majors do not take this course until their fourth year in the chemistry program. In 2017, there was an initiative at the college for faculty to develop curricular activities that involve the use of the Morehouse Makerspace Exploration Center. Thus, I began to have analytical chemistry students utilize the space to 3D print accurate and precise measuring containers. In the summer of 2018, I developed this concept into a series of active learning activities which span the semester, take place in the classroom and laboratory, and incorporate many analytical chemistry topics from precision, accuracy and uncertainty to quality assurance and statistics. The students complete these activities alongside a series of more traditional analytical laboratory experiments. The modules for this activity build upon one another and culminate in a final presentation by the students of their prototype and the accompanying documentation. In the fall of 2018, the PBL case was fully developed into modules that students worked through and were assessed on. Depending on the size of the class, which has spanned from 3 to 15 students over the last few years, students work alone or in pairs on this project. To accommodate larger class sizes, students could work in groups of 3-4.

The activity consists of six modules. One is an introduction and the other five are as follows: 1) Pitch, 2) Prototype, 3) Quality Assurance, 4) Specifications Sheet Development, and 5) Process Document Presentation. Each of the modules aligns with the Analytical Chemistry curriculum, and modules take place from the beginning to the end of the semester. The introductory module consists of a PowerPoint presentation and a handout that gives the project description and purpose of the activity. Students are also informed of the scenario, tasks, assessment criteria, and the deliverables necessary to effectively complete the project. This part of the activity is reviewed together in class as a whole group. However, each module is student-centered, and I am a facilitator of the information, which is typical in PBL (*18*).

Module 1: Pitch

In this stage, students generate, compare, and begin to sketch out their ideas for QCCs. First, students brainstorm on how a person with autism may misread or misunderstand how to measure liquid quantities using typical chemical laboratory glassware. I give students a lecture on autism spectrum disorder and sensory processing disorders that can affect their ability to use glassware appropriately. I am an autism mom to a son on the spectrum, and I also sit on the National Community Advisory Council for Autism Speaks and am an Advocacy Ambassador in the State of Georgia for autism. Instructors who are less familiar with autism and want to give background on the disorder can reach out to the following organizations to obtain resources and connect with guest speakers: Autism Speaks, TACA (The Autism Community in Action), Marcus Autism Center, Emory Autism Center, CDC, NIMH-NIH, and the Mayo Clinic. Students also do their own research on ways that their designs can help those with autism thrive in a laboratory setting. Students begin thoughtfully sketching designs of their QCCs on paper (Figure 1). Students then pitch their idea to their partners, and the group will choose the best design based on the rationale and ease with which the volume can be determined.

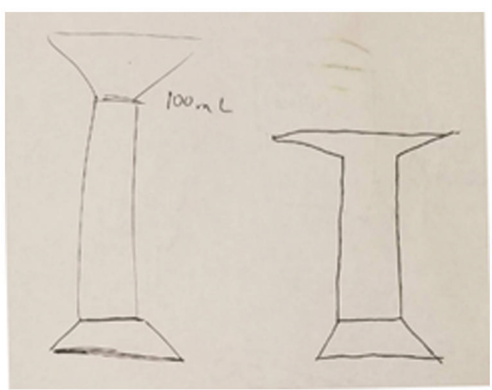

Figure 1. 2D Sketch of a QCC. Example of a student's preliminary sketch of the QCC with an adaptation for easy pouring into and out of the container.

Next, students create their designs using a wide range of 3D design software, depending on their prior experience. For some students, this first task is the most challenging. Students who have never used any 3D design software before search for containers in Thingiverse (Thingiverse.com) by Makerbot and then manipulate the dimensions using Autodesk Tinkercad (Tinkercad.com) (Figure 2A). Students with some proficiency using 3D design software design their original QCCs using Tinkercad first. For example, the 2D sketch students pitch and discuss in the first half of Module 1 would be recreated in Tinkercad. The dimensions would be calculated for the QCC based on its shape to account for the expected volume. Students often base their designs on a 100 mL graduated cylinder where their QCC has a fixed volume. Using the equations for the volume of a cylinder, the dimensions are tabulated. Students with high levels of skill working with 3D design software use Tinkercad but include some type of increased functionality to the QCC, such as that seen in Figures 1 and 2C, where the funnel was added to the top of a fixed interval graduated cylinder. Still others who are comfortable using the design software chose to use Blender (blender.org) to start and then use UpStudio (the software accompanying the 3D printers) to convert to the right dimensions (Figure 2B).

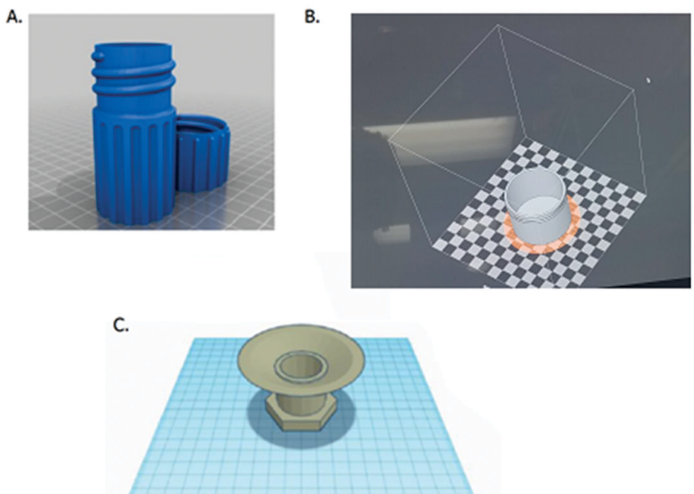

Figure 2. 3D design types. A. Design adapted from the Thingiverse library and then manipulated on Tinkercad. B. Design uploaded to UpStudio software for printing. C. Design adapted with a funnel on Tinkercad workplane.

Module 2: Prototype

In the second module, students produce physical prototypes of their digital designs by 3D printing. Prototype designs are 3D printed using ABS (Acrylonitrile Butadiene Styrene) Filament on an UP Plus 2 3D Printer (Figure 3). The UpStudio 3D Printing Software is used to ensure that the prototypes are printed with the correct dimensions (Figure 2B). The students learn to perform every step in the 3D printing process from transferring their designs into the software, to loading the filament, removing their 3D printed prototypes from the hotbed, and removing the scaffolding from the inside and outside of the 3D printed object carefully after the print has fully cooled. Students have three weeks to get a good print, and I let them know early on to consider doing three prints of the container in this period of time. Students can be easily frustrated if their prints fail, which is understandable because depending on the size, prints can take several hours. Since students are not required to watch the entire process but leave the container to print in the Makerspace, they may not know that it failed until the next day. Half of the students have flawless first prints, while there are others who have to print more than once (Figure 3C). However, I have never had a student print more than three prototypes since the inception of this project.

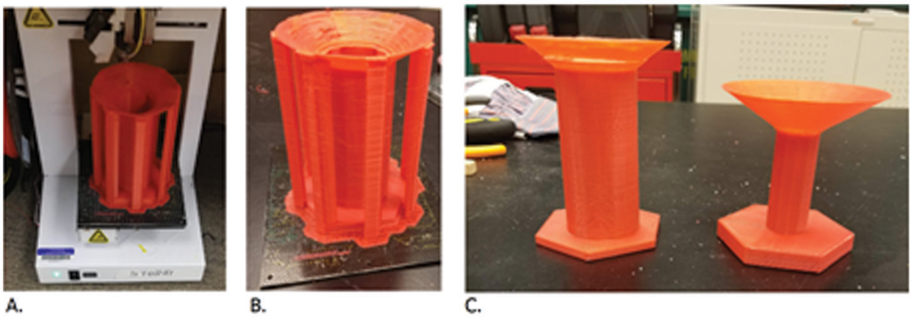

Figure 3. 3D Printed Prototype Samples. A. 3D printed design in progress on the Up Plus 2 3D Printer with scaffolding. B. Hotbed with the 3D printed object taken off printer to be removed. C. 3D prints of QCCs with varying volumes. The print on the left was flawed and had to be reprinted while the print to the right printed as expected.

Module 3: Quality Assurance

In this module, the precision and accuracy for the 3D printed prototype QCCs are determined. Precision is determined by massing the QCC filled to the capacity of its fixed interval with water several times and calculating the standard deviation for the measurements. Accuracy is determined for each container based on % error with the true value being the predicted volume each QCC could hold. The accuracy goal is to get the percent error for the desired quantity to be less than 5%. Robustness of the QCCs is determined using varying temperatures and/or varying pH solutions and then reevaluating whether the accuracy and precision have changed. Another check for robustness is done to determine the number of times the object can be dropped from varying distances without compromising the volume it could hold or the shape. While no formal assessment is done at this stage, I assist students in learning to use statistical programs to input data and code their own functions for calculating standard deviations and relative standard deviations and troubleshoot their QCCs if they do not meet the required benchmarks. There are times when students will make it through the activities for Modules 1-3 only to discover that they have to go back to Module 1 and recreate the 3D design, especially if there is a flaw in the prototype caused by the design, resulting in poor performance. In other cases, a student may only have to go back to Module 2 from 3 and reprint the prototype because it was leaking or had a printing flaw.

Modules 4 and 5: Technical Specifications and Process Documents

In Modules 4-5, the students prepare two documents and a presentation on the work. First, students are tasked with putting together a technical specifications document in the form of a brochure, pamphlet, or informational leaflet to accompany the prototype QCC. In these technical specifications documents, students must report the dimensions of their printed QCC along with data on its accuracy, precision, uncertainty, and robustness. This is a 1-2 page document that would be packaged with the prototype during production. Next, on the last day of lab, the students give a PowerPoint presentation to the class, including the rationale for their design and a flow chart detailing every stage of the project. Finally, students prepare a process document that details the entire process from Modules 1-4. In this process document, students detail every aspect of the project including the pitfalls and limitations at each stage, resulting in a reflective component for this final report.

Assessment

The project itself is worth 20% of the overall grade in Analytical Chemistry. Rubrics are used for students to know how they are assessed at each stage of the process (Figures 4 and 5). The deliverables due throughout the semester include the 2D and 3D designs with rationales for the design from Module 1, the 3D printed prototype from Module 2, the technical specifications brochure to accompany the 3D printed prototype from Module 4 and the process document with presentation from Module 5. The data from Module 3 is compiled into the technical specifications document and is not assessed separately. The final Makerspace Activity project grade is weighted as shown in Table 1.

CATEGORY	4	3	2	1
Research	Group researched the subject and integrated 3 or more \"tidbits\" from their research into their pitch.	Group researched the subject and integrated 2 \"tidbits\" from their research into their pitch.	Group researched the subject and integrated 1 \"tidbit\" from their research into their pitch.	Either no research was done or it was not clear that the group used it in the pitch.
Accuracy of Facts	All supportive facts are reported accurately (3 of 3).	Almost all facts are reported accurately (2 of 3).	One fact is reported accurately.	No facts are reported accurately OR no facts were reported.
Graphics	Graphics include some original material and are clearly related to the material being preesented. The designs are legibly labeled.	Graphics are clearly related to the material being preesented, but none are original.	Graphics include some original material but are only somewhat related to the material being preesented.	Graphics are not related to the material being presented.
Point of View - Purpose	Pitch establishes a purpose at the beginning and maintains that focus throughout! Cohesive pitch.	Establishes a purpose at the beginning, but occasionally wanders from that focus.	The purpose is somewhat clear but many apects of the newscast seem only slightly related.	It was difficult to figure out the purpose of the newscast.
Posture and Eye Contact	Stands or sits up straight and looks confident and relaxed. Establishes eye contact with audience during most of newscast.	Stands or sits up straight. Establishes eye contact with audience during most of newscast.	Slouches or appears too casual but establishes good eye contact with audience during most of newscast.	Slouches or appears too casual AND establishes little eye contact with audience during newscast.
Enthusiasm	Facial expression and body language show a strong interest and enthusiasm about the topic throughout the newscast, but it is not overdone.	Facial expression and body language show a strong interest and enthusiasm about the topic throughout the newscast, but it is somewhat overdone.	Facial expression and body language show some interest and enthusiasm about the topic throughout the newscast.	Facial expression and body language depict apathy or boredom with the topic.

Figure 4. Rubric for Module 1: Pitch. This rubric is used to assess the students' pitch for their QCC.

CATEGORY	4	3	2	1
Writing - Organization	Each section in the brochure has a clear beginning, middle, and end.	Almost all sections of the brochure have a clear beginning, middle and end.	Most sections of the brochure have a clear beginning, middle and end.	Less than half of the sections of the brochure have a clear beginning, middle and end.
Content - Accuracy	All facts in the brochure are accurate.	99-90% of the facts in the brochure are accurate.	89-80% of the facts in the brochure are accurate.	Fewer than 80% of the facts in the brochure are accurate.
Attractiveness & Organization	The brochure has exceptionally attractive formatting and well-organized information.	The brochure has attractive formatting and well-organized information.	The brochure has well-organized information.	The brochure\\\'s formatting and organization of material are confusing to the reader.
Graphics/Pictures	Graphics go well with the text and there is a good mix of text and graphics.	Graphics go well with the text, but there are so many that they distract from the text.	Graphics go well with the text, but there are too few and the brochure seems \\\"text-heavy\\\".	Graphics do not go with the accompanying text or appear to be randomly chosen.
Knowledge Gained	All students in the group can accurately answer all questions related to facts in the brochure and to technical processes used to create the brochure.	All students in the group can accurately answer most questions related to facts in the brochure and to technical processes used to create the brochure.	Most students in the group can accurately answer most questions related to facts in the brochure and to technical processes used to create the brochure.	Several students in the group appear to have little knowledge about the facts or technical processes used in the brochure.

Figure 5. Rubric for Technical Specifications Brochure for Module 4.

Table 1. Weighted Grading for Project

Deliverable[a]	***% of Project Grade***
Module 1: Pitch	10
Module 2: Prototype	10
Module 4: Technical Specifications Document	30
Module 5: Process Document (Presentation)	50
Total Project Grade[b]	**100**

[a] Each module is graded separately. [b] Overall, the QCC Project is worth 20% of the Analytical Chemistry final grade.

Observed Outcomes

Based on in-class discussions, working on this project gave some of my students a different perspective of the work that they do. First, this project makes students aware of differences in abilities between individuals and allows them to engage with this difference in a meaningful way. Students work with design software and are able to articulate how they create novel lab equipment that is specialized for a sensitive and vulnerable population of people with autism who will be in the workplace. The development of compassion in learning by creating a modification to existing glassware is in alignment with Morehouse's motto of developing disciplined minds who delve into the action of social change. This work is also important to providing students with the opportunity to create a pipeline into STEAAM (science, technology, engineering, arts, agriculture, and mathematics) for those with autism, which aligns with the new Divisional Mission Statement of Life Sciences highlighting community engagement.

Secondly, it gives students an opportunity to see the importance that precision and accuracy in measurement have in the discipline. This project helps students understand why proper technique and attention to uncertainties are important for the quality control/quality assurance process when developing a final product. This project was implemented as a part of the course to help students understand the extent to which precision and accuracy are crucial during product development and in limiting errors. This project allows students to see how accuracy and precision in analytical chemistry relate to interdisciplinary skills in computer science, engineering design, and process development.

Third, students gain soft/essential skills such as collaboration, creativity, communication and critical thinking (*19*), and practice presenting their own innovation in multiple forms, written and orally. Students keep their technical specifications and process documents continuously updated as a live document. Teaching how to maintain the integrity of an electronic notebook is also a competency skill that students who want to work in industry, government, and academia in research need to learn and master. My future plans include a component of the project where students explore aspects of intellectual property and patenting their devices. In this project, students are given the tools to engage in "making" giving them the freedom to cultivate their own creativity to solve a real-world problem. Regardless of the level of skill a student has, they can easily learn the software for designing these containers or other types of specialized lab equipment. The software used to do this project is free, open-source, or free to educators and students. This flexible, design-driven project engages students in social change, demonstrates the importance of accuracy and precision in measurement science, and develops students' transferable skills.

Student-Built Spectrophotometers

There is a long history of home-built spectroscopic instrumentation for teaching with early examples published in the 1950s and 60s (*20–22*). Since then, over 100 papers have been published on this topic (*23*), providing example designs for students to build their own instruments. In most cases, students have been provided with detailed instructions or limited choices of components. While these projects give students the valuable opportunity to build an instrument, they offer little opportunity for students to design the instrument themselves or explore the function of different instrument components and therefore lack the advantages of design- and model-based learning. However, there are some examples of projects in which students design their own instruments, making choices about components, geometry, etc. (*24–27*) This type of open-ended instrument building project provides the elements of active learning described in Chapter 1: students work in teams to apply prior knowledge and do iterative problem-solving with instructor feedback. In this section, I (MLK) describe an instructor-assembled kit for students to build their own spectroscopic instruments while making and justifying their decisions about the instrument's components, complexity, and applications.

I teach at Trinity College, a small liberal arts college in Hartford, Connecticut, and my instrumental analysis course is typically just 5-10 students. Instrumental analysis is the second course in a two-semester analytical sequence and follows the foundational course on statistics, figures of merit, chemical equilibria, and separations science. A key course goal is that students learn to "evaluate potential instrumental methods in the context of a specific analytical problem, identify the best method for the problem at hand, and justify [their] choice." As part of the learning activities for this goal, students design and execute a final lab project in groups of 2-4 with larger group sizes in years when enrollment is higher. Building a spectroscopic instrument has always been a popular option with 1-2 groups tackling this project each year for the past six years. In spring of 2021, students worked individually due to social distancing requirements, and two students completed the lab remotely. The build-your-own instrument option was again a popular project choice, selected by seven out of ten students, including the two remote students. The two remote students then conducted additional experiments on their home-built instruments since they did not have access to Trinity's commercial instrumentation. Students received instrument-building kits at the beginning of the semester and began their work by reading a recent review article (*23*), written by two of my former students and me, about the many possible designs for student-built photometry instruments.

In order to encourage my students to make and justify design choices for their instruments, I provide them with an open-ended kit that offers at least two choices for each component required for an instrument (Table 2). Many options are available for construction materials for photometers, and past examples have been made from cardboard, repurposed plastics, 3D prints, and other materials (*23*). However, Lego bricks are one of the most versatile and popular choices. In this kit, Lego blocks are supplemented with tape and cardstock to provide flexibility for components that are not well-fit to the Lego grid. Low cost LEDs are included as light sources and are readily available in individual colors or for "white" light. LEDs are easily powered by a coin battery or a pair of AA alkaline batteries, although a resistor may need to be included in the circuit to drop excess voltage, and students should be reminded to properly bias the LEDs. (The kit contains two LEDs of each color in case of LED damage during testing.) Students may compare the advantages and disadvantages of separate light sources for each color versus construction of a rudimentary monochromator using a grating. If desired, multiple gratings with different blazing could be included so that students can compare spectral dispersion and resolution. Color cellophane sheets are also included for use as absorption filters. The kit in Table 2 has two detector options, a photodiode or a cell phone camera. The photodiode provides a sensitive point detector and is easy to use in photovoltaic mode when connected to the multimeter. A light dependent resistor, a phototransistor, and/or a forward-biased LED could also be included as point detectors to encourage students to make comparisons (*23*, *28*). A cell phone camera is a second convenient detector option, particularly for spectrophotometers, since the camera acts as an array detector and minimizes the need for moving parts to collect a spectrum. After image acquisition, the quantitative data can be extracted from the image using an app or ImageJ, a freely available open source image processing program. Since most students have access to a cell phone camera, the cost of the kit could be reduced to $26.50/kit by omitting the photodiode and multimeter. Alternatively, prior to 2020, my students worked in groups to write a project proposal in which they described their design and generated a budget and budget justification. This method has advantages and disadvantages compared to the kit. It exposes students to proposal writing and can be more cost efficient since students are only provided with the components they actually use in their design. However, there is a lag time while parts are on order, and students may be less likely to compare the performance of multiple components unless that comparison is planned out as part of their proposal.

Table 2. Components of an open-ended DIY spectrophotometer kit and their per-kit cost[a]

Item	*Approximate Cost ($/kit)*
Construction Materials	
Toy building bricks (e.g., Lego Classics Creative Bricks Medium Kit, 221 pieces)	$13.30
Tape	$1.80
Extra heavy duty cardstock	$0.60
Light Sources	
LEDs, two each of red, yellow, green, blue, and white	$0.30
Wavelength Selectors	
Diffraction grating, 1000 lines/mm	$1.30
Cellophane sheets, one each of red, yellow, green, and blue	$0.20
Samples and Sample Holders	
Box of food coloring (red, yellow, green, and blue)	$4.00
Fluorescent yellow highlighter	$0.90
Disposable polystyrene cuvettes (6)	$1.00
Detectors	
Photodiode (e.g., Excelitas Tech VTB8441BH)	$5.10
Cell phone camera	$0.00[b]
Electronic Components	
Lithium coin watch battery, 3V, CR2032	$1.30
Resistors, 50 Ω (2)	$0.10
Digital multimeter	$10.20
Test leads with alligator clips (5)	$1.70
Total	$41.80

[a] A sample shopping list for all components except the photodiode is available at https://www.amazon.com/hz/wishlist/ls/3JPSCZ6YDFLHQ?ref_=wl_share. [b] Provided by students.

With proposals or open-ended kits, students also choose what type of instrument to construct, e.g., a colorimeter, a spectrophotometer, or a filter fluorimeter (Figure 6), and what samples to measure. To characterize the performance of their instruments, students can use traditional lab samples; however, if they will work on their projects outside the laboratory, non-hazardous samples such as food dyes (for absorbance photometers) or highlighter ink (for fluorimeters) are preferable (Table 3). For instrument type, some students choose to tackle a relatively complex instrument, such as an absorbance spectrophotometer with a monochromator. These designs require more time to perfect the alignment of components and to calibrate the wavelength axis for spectra. Other students prefer to build simple instruments, such as a single wavelength colorimeter. While these instruments can be built and characterized quickly, students must do additional reading and thinking to justify the design, for example, by identifying an application for which a small, simple instrument would prove useful. In my experience, individual students and groups will use very different components and pursue designs of widely ranging complexity, so the assessment rubric (Table 4) must be clear to students so that they make an informed decision about how to spend their time and effort.

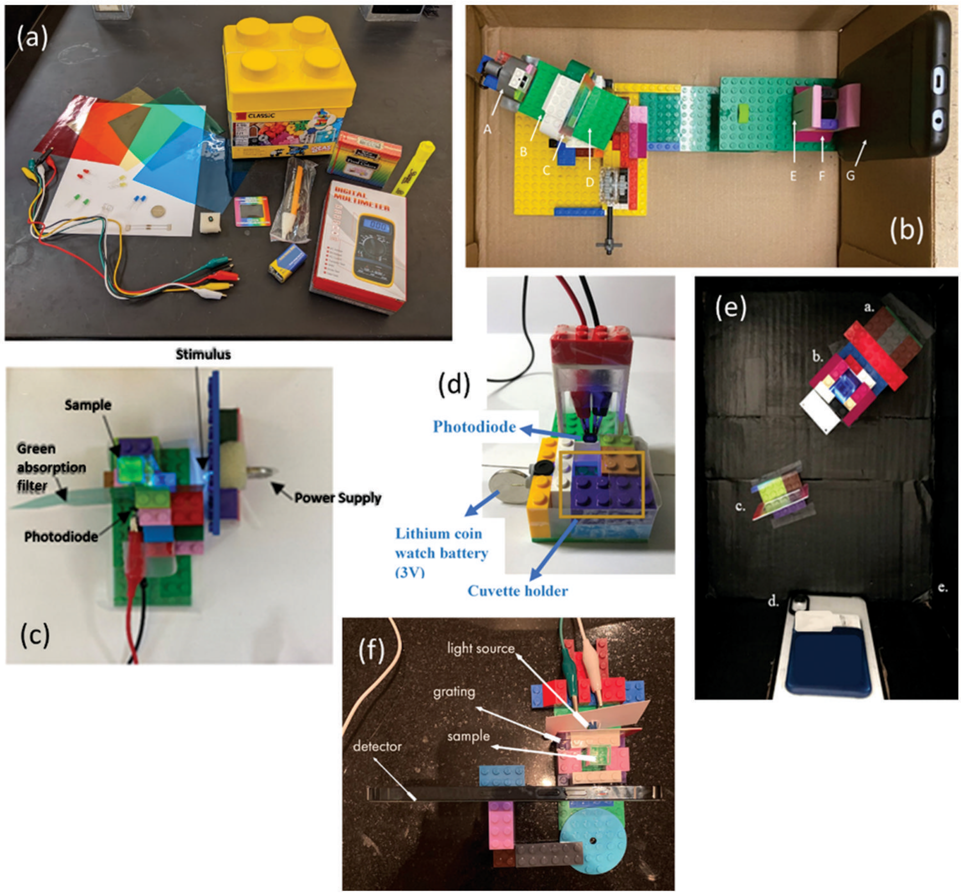

Figure 6. Photographs of (a) the kit materials and (b-f) example student-built instruments. (b) Visible spectrophotometer, photo courtesy of Philip Jaeggi-Wong. A-G are the LED light source, entrance slit, diffraction grating, rotating platform, exit slit, cuvette holder, and smartphone detector, respectively. (c) Filter fluorimeter, photo courtesy of Eve Larkin. (d) Colorimeter, photo courtesy of Huayue Ai. (e) Visible spectrophotometer, photo courtesy of K. Anika Harkins. Labels a-e are the sample holder, cuvette, grating, cell phone camera detector, and instrument housing, respectively. (f) Visible spectrophotometer. photo courtesy of Amanda Modica.

While spectrometer building projects are flexible in that they can often be expanded or contracted to fill the available time, an open-ended project should be given at least a full lab period for instrument construction, longer for more complex instruments. Additional lab periods are needed for students to do follow-up experiments to characterize and/or apply their instrument. Depending on course goals, students may use their instruments to explore the fundamentals of Beer's law (e.g., an investigation of path length) (*30–32*), pursue a specific application (e.g., photometric titration)

(*26*, *33*, *34*), or investigate the relative performance of various components or designs, including through comparison to commercial instruments (*28*, *35*–*37*). In my course, the focus was on the design and performance of the instrument. At a minimum, students were required to determine the figures of merit for the instrument (Table 4), and several made comparisons to commercial instruments. Students were given the full ten-week semester to complete their projects, but they also worked on other lab experiments during the same time period. In 2020, most students chose to spend about one-third of their total lab effort for this project, which is similar to past years when groups were given four lab periods out of 12 total to complete their projects. In all iterations of this projects, students supplemented regularly scheduled lab hours with work outside of class.

Table 3. Analytes and their wavelength maxima for non-hazardous, commonly available samples[a]

Sample	*Analyte*	*Wavelength (nm)*
red food dye	Red 40 (Allura Red AC)	502
yellow food dye	Yellow 5 (tartrazine)	428
blue food dye	Blue 1 (Brilliant Blue FCF)	630
yellow highlighter	pyranine	460 (ex) / 508 (em)

[a] Data from references (*23*) and (*29*).

Table 4. Sample assessment questions and instructions for student lab reports

<table>
<tr><td colspan="2">Overall Question: How does your instrument work?</td></tr>
<tr><td rowspan="3">Required Components of Response</td><td>Include a figure showing a block diagram of your instrument and a labeled photo. Do not forget to include a caption.</td></tr>
<tr><td>Describe and justify your design choices. What components did you use, and why? What sample(s) did you study, and why?</td></tr>
<tr><td>How did you acquire quantitative data? What data processing steps were necessary to obtain data comparable to the output of a commercial instrument?</td></tr>
<tr><td colspan="2">Overall Question: How does your instrument perform in acquiring quantitative data?</td></tr>
<tr><td rowspan="3">Required Components of Response</td><td>Plot a calibration curve (absorbance or fluorescence vs. concentration) for the analyte of your choice. Make sure that you blank-subtract all readings and include the blank on your calibration curve. Properly label all axes and include a figure caption with your graph.</td></tr>
<tr><td>Perform least squares analysis to determine the equation of the linear portion of the calibration curve. This may require removing points in the non-linear region from the fit; however, the points omitted from the fit should still be shown on the graph as a separate data set.</td></tr>
<tr><td>Calculate and tabulate the calibration sensitivity, analytical sensitivity (at a specified concentration), linearity, detection limit, and dynamic range of your instrument. Do not forget to include correct units. Compare these figures of merit to typical ones for a commercial instrument, and offer explanations for any differences.</td></tr>
</table>

Assessment of spectrophotometer building projects can take many forms, and the Analytical Sciences Digital Library resources on project-based labs include exemplars for rubrics for reports, oral presentations, and teamwork evaluations (*38*). Because students choose the instrument type, components, and samples to analyze, a major component of assessment is based on their justification of these choices. Past research has shown that students must be explicitly prompted to offer explanations and justifications, so the assignment guidelines that I provide to my students (Table 4) make a point of requesting these as part of the response (*39*). Before starting my marking, I assign point values to each required component of the response and to the overall question. For instructors who teach higher enrollment courses the ELIPSS rubrics may be a useful resource (*40*); there are examples in the literature on training teaching assistants both to aid students in developing the skills needed to answer these questions and to evaluate student work using these rubrics (*41*, *42*). Students consistently produce high quality instruments and reports as an outcome of this project, obtaining data that is sometimes comparable to low cost commercial instrumentation and deepening their understanding of how individual components contribute to spectrophotometer performance.

Model-Based Learning (MbL) to Promote the Understanding of Instrumental Techniques

Instruction in instrumental analysis should promote the acquisition of chemical knowledge at three levels: the macroscopic and tangible (what can be seen, touched, or smelled); the sub-microscopic (atoms, molecules, ions, and structures); and the symbolic (symbols, formulae, equations, mathematical manipulation, graphs etc.) (*43*). Traditionally, models are used in Instrumental Chemical Analysis courses to illustrate or communicate understanding with little emphasis placed on the predictive function of models and their limitations. We describe a model-building project that facilitates the visualization and understanding of chemical phenomena behind the instruments at the atomic/molecular scale, which is often a considerable challenge for students (*44*). We take advantage of the fact that students are highly engaged in the use of technology (e.g., smartphones, social media, apps) to promote the understanding of instrumental techniques. In this project, pairs of students build physical models and create 3-10 min videos, including a 10-60 sec animation, about their assigned instrumental analysis technique. After completing the project, students are able to:

- design and create scientific models of analytical instrumentation.
- refine their (epistemic) conceptions of how scientific instrumentation is constructed, operated and developed over time.
- select appropriate instruments for a given chemical analysis.
- identify advantages and disadvantages of a given instrumental technique.
- integrate fundamental concepts of the underlying physical-chemical principles as they relate to specific instrumentation used for atomic and molecular spectrophotometry, mass spectrometry, and chromatography.
- explain the physical and chemical processes that affect sample particles (molecules or atoms) in each part of the instruments.
- illustrate the dynamics of an instrument system over time.
- explore the use of instruments in research and other applications.
- collaborate effectively with team members.
- communicate orally and in writing.

- provide a constructive critique of other models via peer review.
- use animation and video production and editing software.
- use precise language and domain-specific vocabulary to explain a topic.

We (LMDV, BMOA) teach the Instrumental Chemical Analysis course at the University of Puerto Rico, Rio Piedras. Chemistry undergraduate students typically take Instrumental Chemical Analysis in their third or fourth year. The class is typically 60% female and 78% Hispanic, with 25% of the students over 24 years old. The classroom component has 28-42 students per semester, while enrollment for the laboratory is limited to 14 students per session. The course has two 1 hr 20 min sessions a week, while the laboratory has two 3 hr sessions a week. In addition to the MbL project, students complete six laboratory exercises, in which they prepare samples and use instrumentation to analyze them including FTIR, AA, differential scanning calorimetry, cyclic voltammetry, gas chromatography mass spectrometry, and fluorescence. The MbL project occurs over several weeks of the laboratory portion of the course and involves 13 hours of lab time. We choose instruments for the project that are not available in the academic laboratory or that have not been used by the student, but are available in the research facilities of our department, to increase students' exposure to new instrumentation. Each pair of students is assigned a different instrument, and the implementation of the activity in the laboratory component of the course also provides time for productive peer discussion between groups. Students also spend an additional 10 or more hours on their project outside of scheduled lab time. Figure 7 shows the timeline and stages of the MbL project.

Development of the video involves several steps that are shown in Figure 8 (*45*). Students start the process by developing a storyboard and progress to the construction of 2D and 3D artifacts. Pictures of the artifacts are incorporated into the video animation. Each step of the project provides an opportunity for students to articulate and express chemical concepts and receive feedback and assessment of their work. Based on the feedback, students often redesign their models and modify components of the final animation. Students are encouraged to make videos that quickly capture the attention of the target audience and are visually appealing. Groups are allowed to select their target audience. Students are also provided with evaluation rubrics for the different stages of the project to ensure that they structure their storyboard and video to include required components.

Implementation of the MbL Project

Stage 1. Motivation and Introduction (4 hours)

The first hour of a laboratory period during the first week of the semester is used to discuss the rationale for and provide background on the MbL project. We present the learning objectives of the project and explain how MbL has been shown in prior research to improve student learning outcomes (*45*, *46*). Concepts and training on model creation tools, examples of models from previous courses, and the stages of the project are presented. During this session, students are allowed to select their partners for the project. Groups also decide on a role (e.g., scriptwriter, animator/illustrator, fact-checker) for each member. Each group is assigned a specific instrumental technique by lottery and provided a kit with arts and crafts materials and molecular models. Students are made aware of video tutorials to help them use the free software required for the project.

We purposefully choose instruments available in our institution' research facilities. Students are provided with the contact information of a researcher to schedule a visit or a virtual meeting with them. Researchers are previously contacted by the course coordinator, are oriented about the requirements of the MbL project, and have indicated their willingness to help the students. This component of the project exposes students to actual applications of their instrumental technique and helps them learn about research interests of faculty members in the department. In some cases researchers allowed the students to analyze some samples in the instruments.

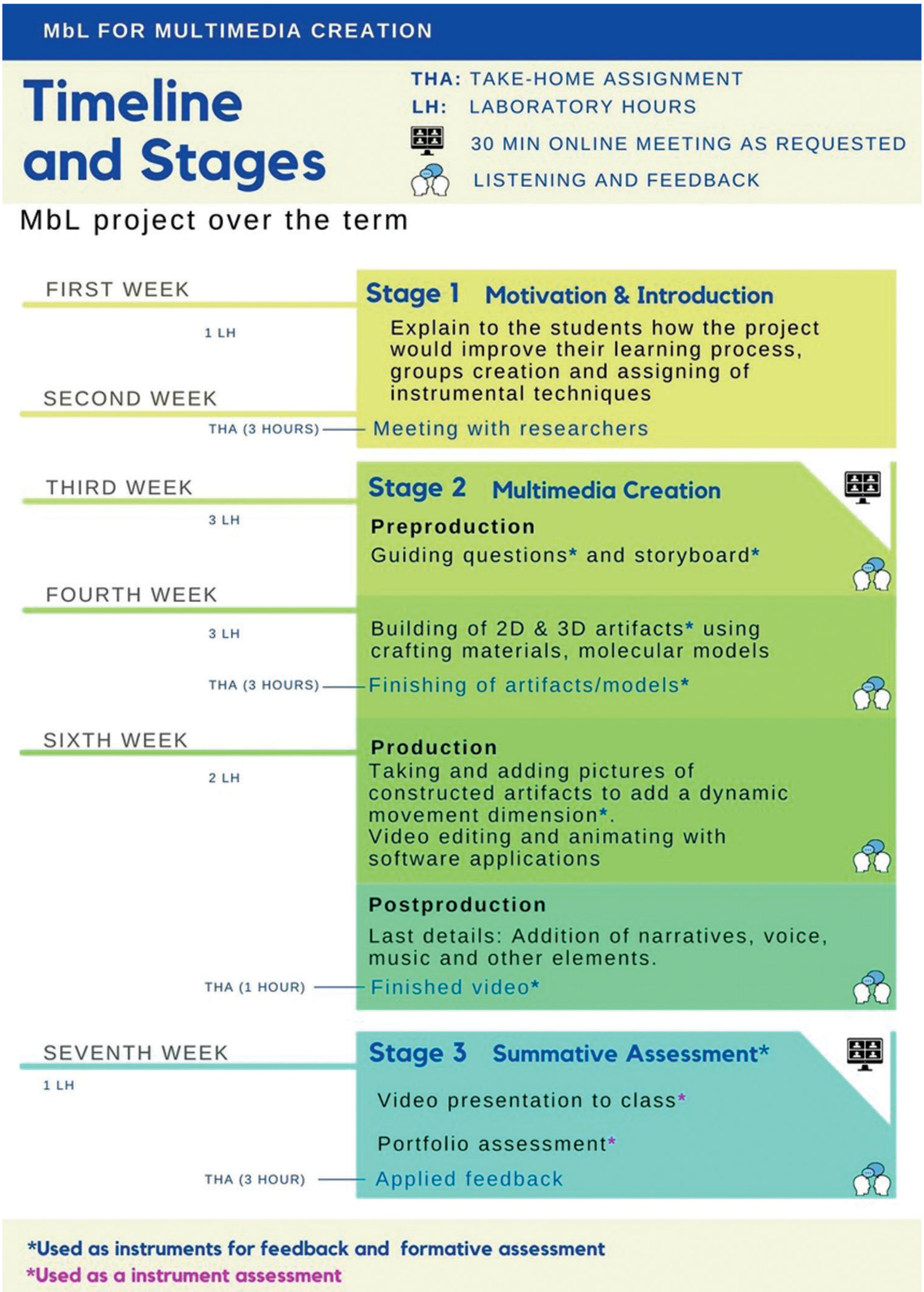

Figure 7. Model Based Learning Project Stages and Timeline.

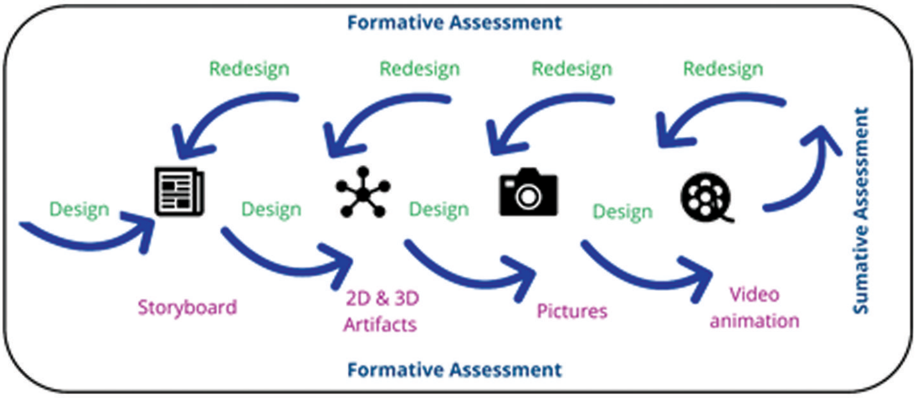

Figure 8. Cycles of conceptualization in the student learning process during the MbL project. Adapted with permission from reference (15). Copyright 2018 Bonny Ortiz-Andrade. Published by ProQuest LLC.

In the first out-of-class assignment, which is due a week later, students find information in the literature on their assigned instrument. They are required to evaluate at least three items and initiate contact with the researcher who will assist them. Students hand in a literature review report in which they identify how the instrument works: the fundamental physical-chemical principles responsible for signal generation and the information that the method provides.

Stage 2. Multimedia Creation to Build Models and Create the Animation (13 hours)

Stage 2 involves the use of three laboratory periods distributed between weeks 3-6 of the semester (9 hr) and completion of two take-home assignments (~ 4 hr). The assignment includes work related to completing their portfolio reflection and their project (model construction). At this stage, students are expected to use their chemistry knowledge, creativity, and inventiveness to design and build models, take photographs, and explore software such as PicPac, PowerPoint, or doodle videos to create an animation. The animation is then incorporated into a final project video.

The final video must cover what types of samples can be analyzed, protocols for sample preparation that are needed before being able to analyze a sample, methods of quantification, operating limits (LOD, LOQ, linearity), analysis and interpretation of the data obtained with the technique, advantages and limitations of the technique, instrument costs, and companies that sell the instrument. To obtain this information students either use the literature or get data from the department researchers. They must describe at least three applications of the technique supported with references from primary sources, preferably articles from peer-reviewed scientific journals. Students can substitute this part of the video with a short interview of a researcher with experience with their instrument.

The first lab period involves a pre-production activity where students develop a storyboard. The storyboard is an effective method to carry out a formative assessment, identify misconceptions and provide feedback. Students complete the storyboard based on their literature search and guiding questions such as: What is the primary use of the instrument? What are the essential components of the instrument? What type of transition and interactions of molecules or atoms with various forms of energy like electro-magnetic radiation, thermal energy, or matter occur? What kinds of substances can and cannot be analyzed with the instrument? While the students work on their storyboard, the instructor and TA circulate among the groups to ask questions, observe students' interaction, and intervene as needed. Students are probed to make sure they understand how their instrument works and understand which transitions, chemical and/or physical processes the analyte undergoes to produce signal. The goal is for the students to be able to communicate scientific information in a clear, coherent, and accurate manner to explain their instrumental method. A regular occurrence is that students need to rethink their design and storyboard based on feedback from the instructor and TA. During the last half hour of the laboratory, each group has 3 minutes to present their storyboard to the rest of the class, and peers and instructors complete a feedback form for the presenters. The feedback form asks evaluators to identify two strengths and offer two suggestions for improvement. It also allows students to identify whether they have questions that need to be clarified in the presentation. Groups then need to complete a form describing how they intend to respond to the feedback they received.

Figure 9 shows an example of one group's storyboard on attenuated total reflection accessory-Fourier-transform infrared spectroscopy (ATR-FTIR). The storyboard starts by representing the optical components of the instrument, then shows the molecule interacting with IR radiation, followed by the molecular vibration responsible for the generation of the spectrum, which is shown in the final slide. As part of the review that the students received when submitting this storyboard, they were required to include more details related to the instrument and the ATR component of the device and how it works with the FTIR. As a result, they included more information on the functioning of the ATR accessory in their animation, and other information (such as how the interferometer works) was presented in different sections of the video (Figure 10).

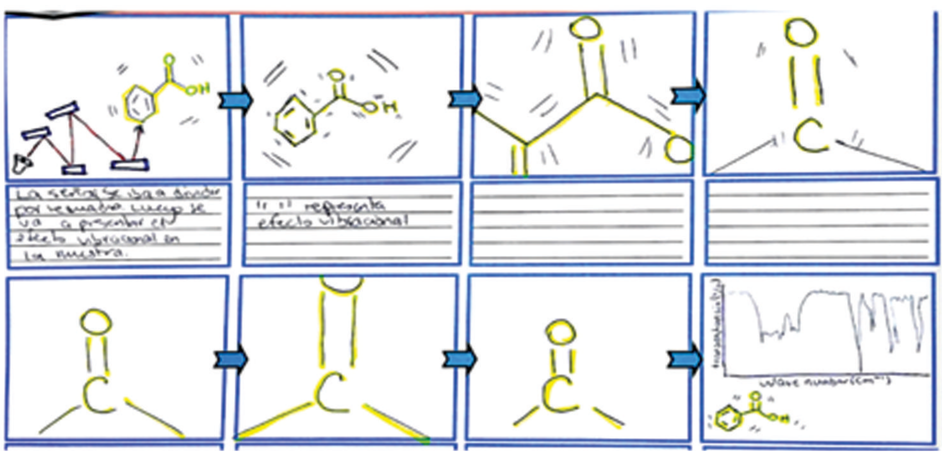

Figure 9. Example of student storyboard illustrations to explain ATR-FTIR.

Students often leave the lab with additional feedback on how to improve the presentation outlined on their storyboard. For example, the storyboard in Figure 9 was revised based on instructor feedback to focus their animation on explaining the functioning of the ATR accessory and other concepts, including the interferogram. Follow-up meetings are scheduled with each group before the next lab period. Before holding these individual sessions, groups must complete and submit a form to the instructor specifying what they are trying to achieve, the specific task(s) they need feedback on, and the progress they have made so far. After the meeting, they must write and submit a plan for how they will use the feedback from the session to improve their presentation.

In the second lab period (3 hours), students build physical models using arts and crafts supplies and digital tools to represent the different aspects of their storyboard. Figure 10 shows physical models students built to represent molecular vibrations responsible for the ATR-FTIR signal. The instructor and TA circulate among the groups and ask for explanations for their use of specific materials and the illustrations, including mathematical models and equations explaining their method. Groups are specifically asked to describe the strengths and limitations of their model and are encouraged to consider ways to overcome any of those limitations. Each presentation is expected to incorporate macroscopic (what can be seen, touched), the sub-microscopic (atoms, molecules, ions, and structures) and symbolic (symbols, formulae, equations, mathematical manipulation, graphs, etc.) representations appropriate for the method. Students can meet outside of the lab to finalize their models and schedule additional meetings with the instructor or peer leaders to receive feedback.

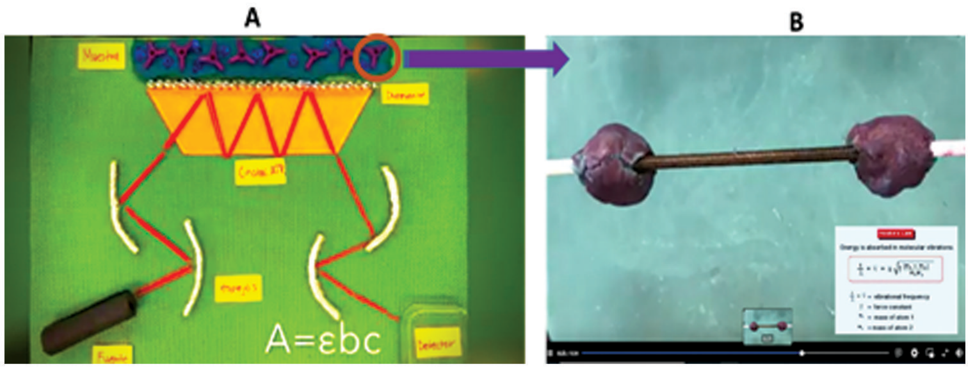

Figure 10. Example of student models for ATR-FTIR. A) ATR-FTIR instrument optical components B) Molecular representation explaining the molecular vibrational transitions.

Models, animations, and videos that students completed in prior semesters and provided consent are used as complementary materials. Students examine these materials and consider their effectiveness and how they could be improved. This helps them identify ways to improve their own presentation.

In the third lab period (2 hours), students finalize models, take pictures of their models using their cell phones, and then begin the process of video editing and animating with the help of software applications that can be used to accelerate the digital images and create the illusion of movement (*46*). The animation is a portion of the overall video on their method.

Figure 11 shows excerpts of how a group presented high-performance liquid chromatography (HPLC) including how the molecules behave as they travel through each component of the instrument. Guided by their storyboard, they built a model of an HPLC using boxes, bottles, and construction paper and incorporated that into their animation. This group had to consider the behavior of the molecules as they travel through the injector, column, and detector. They had to determine how to illustrate resolution, selectivity, and how molecules interact with the stationary and mobile phase. The instructor and TA give feedback to the groups on aspects of their animation. Students often spend time outside of lab finalizing aspects of their animation.

One hour of the next lab period is time for students to continue preparing their animation and video presentation. They also narrate the video using either voice-over or addition of text, music, and sound effects. Students also participate in a peer review and get feedback from classmates and suggestions for improvement of the video. Some of the animated models created by our students can be found on a Facebook page for the course (*47*).

Figure 11. Visuals of a student animations model for the HPLC instrument.

Stage 3. Summative Assessment

Table 5 provides the distribution of credit for the components of the MbL project, which is 25% of the overall lab grade. The project provides an excellent opportunity to assess student abilities to integrate knowledge and skills related to design principles, art, science, effective communication, and fundamental chemistry. The final video presentation represents the largest component of the grade.

Table 5. Distribution of credit within the MbL project

Task	***Elements***	***Credit (pts)***
Multimedia creation	Storyboard	25
	Physical model	25
	Narrative	25
	Animation	25
	Participation in discussion sections	20
Final video presentation	Final animated model	
	Discussion of applications or interview with a researcher	
	Other required elements (sample type and preparation, methods of quantification, operating limits (LOD, LOQ, linearity), data analysis, advantages and limitations, costs, and instrument vendors, etc.)	100
Portfolio	Evidence of completion of each of the project steps and discussion, as well as short reflection	20
Team work	Each student evaluates their partners' contributions to the project and does a self-evaluation of their performance	20
Total points		260

All students participate in a 3-hour group activity during week seven of the laboratory. Each group presents their video to the class and invited professors. Each video is evaluated by the professors and students using a rubric that rates the clarity of the concepts, the organization of content, the coverage of theory of the technique, the overall quality of the presentation, the creativity demonstrated in the animation and video, and the length. Also, students have the choice to authorize the publication of their videos on the Facebook page of the project (*47*). Each student completes a rubric to evaluate each video, and this task is part of their participation grade for the course. These completed rubrics are given back to the groups so that they may incorporate the suggestions. Also, these are used for the summative evaluation of the project.

Groups document their progress throughout the project by preparing a portfolio. The portfolio includes early drafts, subsequent revisions and final versions of the storyboard and models. Each member of the group also writes a short reflection about their experience completing the project. Finally, students complete a peer- and self-evaluation of each member's contribution to the team effort required to complete the project.

Concluding Comments

We have observed that students in lab sections that complete the project obtain higher grades on the final exam than students in lab sections that do not. We observe that the inclusion of animations in model design overcomes the limitations of traditional static models and is effective in demonstrating the complexity of what occurs during an instrumental measurement. Course evaluations indicate that students who have participated in the MbL project enjoy the project and have encouraged us to keep that activity in the course. They indicate that the project, with its emphasis on peer collaboration and feedback, promotes an enjoyable, relaxing, and safe environment in which to learn and express their ideas. They appreciate the opportunity to show off their creativity in the models, animation, and final video.

Conclusions

Modeling is one of the most memorable practices to teach science; science has been built through the creation of models. Even theories are sets of well-represented models, such as the double-helix model of DNA and the fullerene molecule representation. Scientists make models to visualize and organize their thoughts to forge complex ideas, to communicate, to test hypotheses, and to identify gaps in their understanding. In the same way, students benefit from creating models as artifacts to represent concepts (modeling), developing and connecting their knowledge. This chapter has described three active learning projects that involve building, modeling, and design. These projects, like other examples of MbL, engage students in using, constructing, evaluating, and revising their ideas while facilitating content understanding and skill development.

These activities may be implemented in-person, hybrid, or in remote sections using different levels of inquiry according to the time and resources available. All the activities allow students to apply fundamental theories to explain experimental phenomena and evaluate laboratory procedures using knowledge of chemical analysis. Although the student-built instruments' resolution and accuracy may not compete with commercial devices, the construction of spectrophotometers, models, and 3D printed glassware allows the students to understand each component's function and calibration protocols. Moreover, students learn a plethora of new technical skills, which are cross-disciplinary and soft skills like communication, teamwork, innovation, time management, and critical thinking, which increase motivation and appreciation for the chemical sciences and learning. As a result, the activities make them better prepared to become part of the future workforce.

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