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Bridging the Gap: At-Home Experiments Connecting Theory and Practice in Chemical Engineering Education

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ABSTRACT

The 2022 report by the National Academies of Sciences, Engineering, and Medicine urged a greater focus on experimental learning to bridge core course silos. ABET also requires students to design and conduct experiments, analyze data, and draw conclusions by graduation. However, the packed engineering curriculum challenges additional hands-on lab courses. To address this, we explored an idea to extend learning beyond traditional settings. Inspired by the American Chemical Society's guidelines, we aimed to study at-home experiments for connecting experiments to theories and investigated if students could independently design experiments at home, aligning with the senior chemical engineering laboratory course's objectives. Students spent four weeks conducting at-home experiments and self-evaluated their learning outcomes. Results indicated positive attitudes and their enthusiastic time investment. The at-home projects enhanced learning, fostered critical thinking, and aligned with evolving engineering education priorities. In future iterations, we plan to allocate more time and extend project timelines for greater learning experience.

Keywords: Unit operations laboratory, at-home experiments, critical thinking, bridging core course silos.

1. INTRODUCTION

In the 2022 report, the National Academies of Sciences, Engineering, and Medicine recommended an increased emphasis on experimental learning to facilitate effective connections among core courses, often referred to as 'the silos' [1]. ABET also mandates that students acquire the skills to design and conduct experiments, analyze data, and draw conclusions by their graduation [2]. Yet, the densely packed core curriculum in engineering poses challenges in accommodating additional hands-on laboratory courses. Therefore, we feel the need for creative instructional strategies to ensure that these requirements extend beyond the boundaries of traditional course objectives.

According to the American Chemical Society's guidelines on laboratory curriculum and skills, the primary imperative in laboratory instruction is to enable students to understand how to "connect experiment to theory" [3]. Numerous prior studies have indicated that traditional cookbook-style experiments generally offer a lower level of inquiry for students compared to their open-ended counterparts [4-7]. When assessing the effectiveness of traditional cookbook-style, low-inquiry-level activities in comparison to open-ended activities, it was observed that the latter type is characterized by high inquiry levels and exhibits a significant advantage over the former [4-5]. Convergent problems or experiments with well-defined parameters are often not sufficiently thought-provoking in the development of critical judgment and creativity, especially when contrasted with open-ended problems [6]. Conversely, open-ended problems should stimulate creativity, independence, and confidence, fostering a deeper connection with the subject matter [8-10].

Taking these into consideration, our aim was to investigate whether students could independently design simple experiments with limited resources, such as those available at home. This exploration commenced with the foundational task of validating (and acknowledging limitations of) a theory of their choice through experiments they designed themselves. The study was conducted within the framework of a senior chemical engineering laboratory course, specifically the Unit Operations lab taught by the author. Traditionally, this course at University of Maryland Baltimore County (UMBC) included four to six standard experiments covering various core concepts in chemical engineering, including transport (e.g., mass transfer), kinetics, controls, and separations. In addition to the conventional experiments adhering to standard procedures, students were challenged to undertake an at-home experiment, encouraging them to explore within the familiar confines of their own homes. As per the previously reported literature, the at-home experiments were anticipated to stimulate creativity and challenge students due to the constraints of limited resources [9-11].

Students dedicated four weeks for developing experiments, formulating hypotheses of their choice, collecting and analyzing data, and conducting evaluations. Subsequently, they were tasked to prepare a concise report and oral presentation at the end of their project. As an instructor, the primary objectives of this study were to assess students' capacity to establish a meaningful connection with core concepts through the lens of experimental learning, and to evaluate their critical thinking in this process. The inclusion of at-home experiments not only enhances the learning experience but also acts as a catalyst for the development of essential skills [12], aligning with the evolving priorities in engineering education.

2. METHODS

2.1 Data collection

A senior chemical engineering laboratory course, a regular offering during the fall semester at UMBC was selected for this study. The dataset considered was for fall 2023 ($n = 18$) and fall 2022 ($n = 36$) semesters. Typically, the course comprises four to six traditional experiments covering fundamental concepts such as mass transfer, heat transfer, process control, fluid flow, reaction kinetics, and water treatment.

In addition to the conventional laboratory experiments, each student group, consisting of 2-3 members, embarked on an at-home project of their choosing as part of this study. Groups were assigned the collaborative task of designing an experiment based on their preferences, collecting relevant data, and subsequently analyzing the data to validate a specific theory of their choosing, such as Fourier's law, Fick's law.

Expectations for the projects were communicated to the students through written instructions. **Figure 1** provides a snapshot of their weekly activities. In the first week, students were instructed to gather information on what they wanted to do, with an emphasis on setting realistic and measurable goals rather than undertaking ambitious projects. In the second week, they

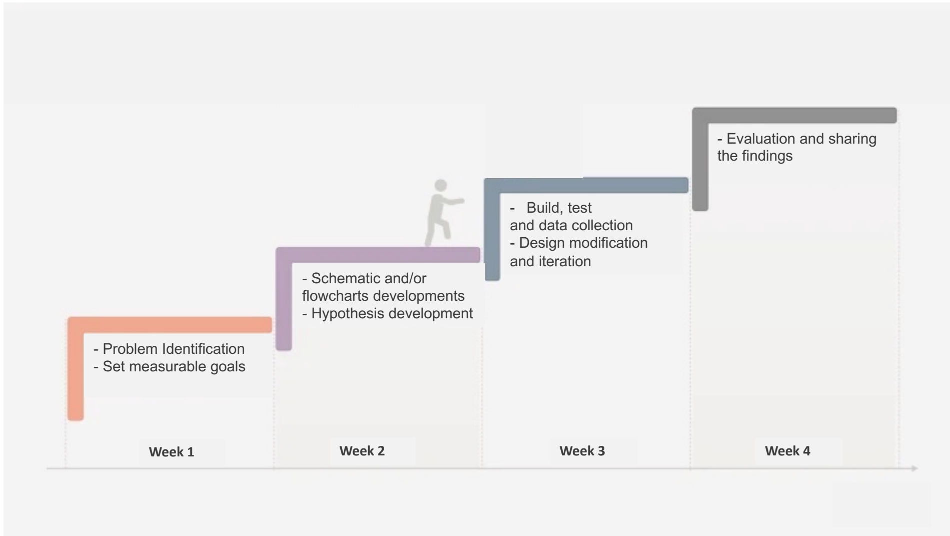


Figure 1. Snapshot of weekly activities of the four weeks long at-home projects.

developed a schematic of the setup and/or a flowchart, followed by formulating a hypothesis with rationales. We guided them to devise more than one way to test their hypothesis and identify materials that were not expensive, along with determining the order of usage. In the third and fourth weeks, they implemented their plan to build the setup and conducted tests. Throughout this process, they were prompted to ask themselves questions during any iteration: Does your design meet the needs of the problem? Can your design be improved while still meeting the needs of the problem? How would you change your design? If their design satisfied these criteria, data were collected for analysis, followed by the actual analysis, comparison with the chosen theory, and presentation of their findings. According to the results of a student survey, participants self-reported spending approximately 10 hours on the projects.

The critical factor influencing learning and the creation of effective experiments was the existing knowledge of the students. Through weekly discussions, instructors gently guided them, offering assistance to maintain simplicity yet achievability. A total of 9 projects were presented in the fall 2023, and 15 in fall 2022 semester. For the purpose of this article, we categorized these projects into core concept areas (e.g., heat transfer, mass transfer) and highlighted representative experiments in **Table 1.** In general, projects focusing on various transport theories were popular. However, students also reported working on projects related to kinetics, thermodynamics, and general chemistry (e.g., titration). A few representative problems will be further discussed in the Results and Discussion section.

2.2 Students' self-evaluation questionnaire

At the end of the semester, students completed a questionnaire related to the experiment, addressing three key aspects: i) Time allocated for preparation and execution of the experiment; ii) Students' perspectives on the experiment, including feedback and proposed enhancements; and iii) A self-assessment of their learning outcomes from the experiment.

In the third category, the question was framed as follows: "Which description best characterizes the kind of knowledge you have acquired through this experiment?" Students were provided with the Bloom categories within the cognitive domain—knowledge, comprehension, application, analysis/synthesis, and evaluation—to articulate their learning outcomes. To aid students in understanding the significance of each category, keywords were provided. While these keywords may sometimes pose challenges in translation due to nuances, two examples are as follows: knowledge (to learn, remember, understand, recognize facts, terms, and phenomena); comprehension (to interpret, to explain acquired knowledge to other students in one's own words to ensure understanding), etc. Students assessed their own learning outcomes using the scale: very much, a lot, some, a little, or nothing for each of the categories.

Table 1. A few representative at-home project titles and brief descriptions as presented by students.

Concept area	Title and brief description of an example project
Heat Transfer	*Study of unsteady-state heat transfer in a baked potato.* Students used potatoes to validate unsteady heat transfer equation with experimental data and find the minimum time required to fully cook a potato for consumption.
Mass Transfer	*What balloon and inflater combination should Jimmy choose* Students used two types of balloons (latex and mylar) which were inflated with helium, carbon dioxide and air. They used 1-dimension mass transfer model, estimated effective diffusivity to recommend the combination that would have the least mass flux through the balloon.
Fluid	*Determination of hydraulic conductivity of three types of soils* Students estimated hydraulic conductivity of soils exposed to flowing water using sands, rocks, fine soils, and soda bottles.
Kinetics	*Creating Bioethanol from Agricultural Waste* Students used corn husks and wheat straw to experimentally determine which would yield most percentage of ethanol and found optimum time for fermentation.
Chemistry	*Titration of vinegar and baking soda using black tea as indicator* Students created titration curve for vinegar and sodium carbonate using freely available software, imageJ, and black tea as indicator. Change in RGB value was used to determine the end point of the titration.
Statics	*Young modulus of commonly used materials* Students calculated Young’s modulus of commonly used polymers.

2.3 Instructor's assessment

Students presented their findings through both a concise written report and an oral presentation. Additionally, students were required to submit their measurement files, along with their analysis files or codes (such as MATLAB, MS Excel). The report and presentation served as a mean to assess four critical skills—Synthesis, Analysis, Evaluation, and Creation—articulated in terms of action words within the Bloom's Taxonomy.

Throughout weekly brief discussions, the instructor utilized check sheets [i.e. *Practical* (detailed or contextual) and/or *Theoretical* (detailed or contextual)], documenting questions posed by students or their peers. These questions were categorized into one of four types: practical detailed, practical contextual, theoretical detailed, and theoretical contextual. The classification considered whether the queries pertained to practical aspects or theory and further distinguished between those focusing on details versus those with a more contextual nature.

Qualitatively, the rigor of the experiments was assessed by evaluating the experiment's goals and supporting rationale [13]. This assessment considered whether the approach and methods were aligned to address the research question, the significance of the results, and the effectiveness of communication in presenting their work.

3. RESULTS AND DISCUSSIONS

3.1 Illustrative Student Projects

In order to maintain a focus on the key insights learned from this activity, we present select example projects in this section. These exemplar projects are categorized as a very satisfactory project (Section 3.1.1 a heat transfer project), a satisfactory project (Section 3.1.2 mass transfer project), and somewhat satisfactory project (Section 3.1.3 kinetic project). Students were responsible for choosing and obtaining the appropriate materials needed for their experiments by themselves. Our intention is not only to provide readers with a glimpse into the diversity of projects undertaken but also to get insights as educators. By examining these examples, we aim to demonstrate the pedagogical potential inherent in at-home projects.

3.1.1 Heat Transfer Project: Study of unsteady-state heat transfer in a baked potato

This project aimed to explore the **transient temperature profile** within a potato during the baking process, comparing experimental data with theoretical models; and leverage the findings to predict the cooking time. While numerous subjects could have been chosen for a heat transfer study, our student groups specifically opted to investigate the baking of potatoes for ease of availability, cheap and relatability with everyday life.

In the experiment three potatoes of varying sizes (Potato 1 had a radius of 1.5 inches; Potato 2 1.4 inches, and Potato 3 1.1 inches) were placed in an oven set at 300 °F which was approximately 50 °F above the baking temperature of potato as reported in the literature (**Figure**

2). Temperature measurements were conducted at three distinct locations within each potato: the center, halfway between the center and the surface, and the surface itself. To ensure consistency,

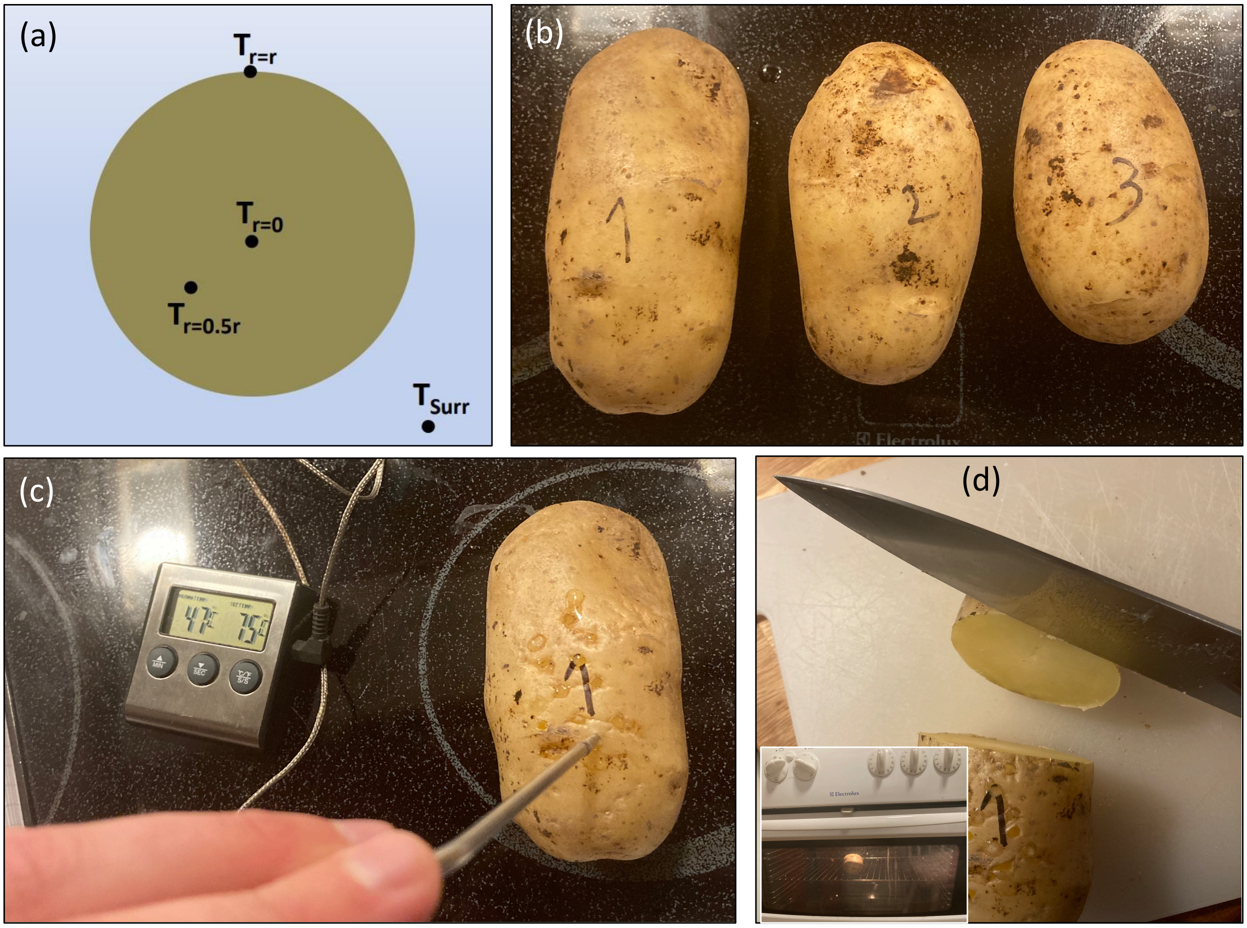


Figure 2. Experiment: (a) schematic of a potato illustrating the location where students probed the temperature; (b) Three potatoes of varying sizes were selected for the experiment; (c) Illustration of how kitchen thermometer was used to measure temperature at a single location; (d) Cross-section of a baked potato after the experiment, demonstrating a homogeneous texture throughout. The inset displays a potato in the oven.

points were marked on the thermometer, ensuring the same depth was measured for each reading. Additionally, a new hole was pierced in the potato for every measurement iteration.

Temperature measurements were captured at 4-minute intervals and persisted until the internal potato temperature exhibited no measurable increase. This study design allowed for a comprehensive exploration of the dynamic temperature changes occurring during the baking process.

3.1.1.1 Experimental Results

The subsequent section presents findings excerpted from the student report. According to their observations during the baking process, the two larger potatoes exhibited a steady-state internal temperature after approximately 45 minutes, while the smaller potato achieved the same state in about 30 minutes. This observed increase in cooking time with potato size aligns with expectations as they learnt in the textbook [14-15]. However, the literature temperature of 210°F (~99°C) [16] was not attained during the experiment. Notably, the surface temperature of the potatoes increased rapidly, reaching steady-state conditions first. In contrast, the internal temperatures required a longer due to the conductive heat transfer process through the potato. The experimental temperature profiles for the three potatoes are graphically represented in Figure 3, showcasing the reported shapes in alignment with the theoretical prediction.

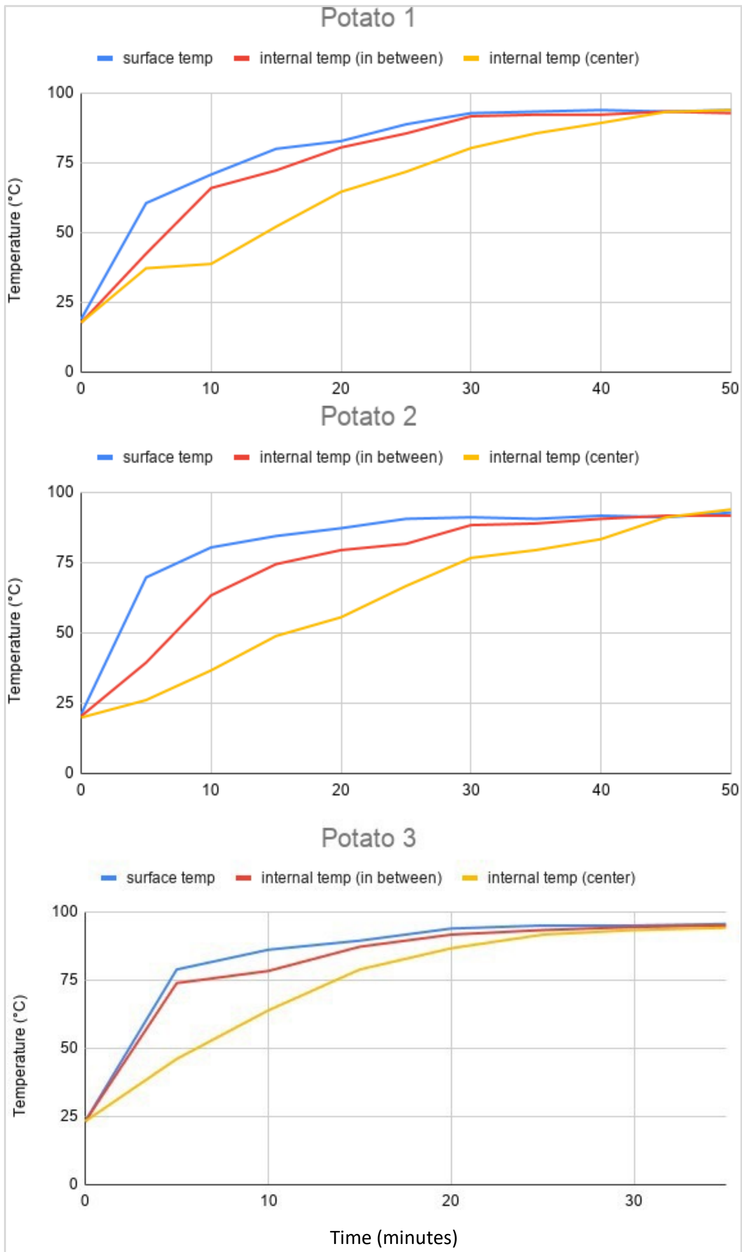


Figure 3. **Temperature Profiles of Baked Potatoes.** Temperature profiles for the three potatoes baked in the experiment. Potato 1 (radius: 1.5 inches), Potato 2 (radius: 1.4 inches), and Potato 3 (radius: 1.1 inches) illustrate the relationship between potato radius and time required to achieve steady-state temperature. The figure also visualizes the heat transfer from the surface to the center as time

progresses.

3.1.1.2 Connection to Theory

The general equation governing conduction through a medium is expressed as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla^2 kT + \dot{q} \quad (1)$$

Here, ρ is the density of the object, Cp, is the heat capacity of the object, k, is the thermal conductivity, $q^{\cdot}$ is a generation.

The assumed no heat generation and a constant thermal conductivity (independent of temperature), and considering the cylindrical geometry of potatoes, students simplified the equation to Equation (3) which relates temperature as a function of time (t) and radial position (r).

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T \quad (2)$$

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \quad (3)$$

To establish boundary conditions, students set convective and conductive heat transfer equal at the surface (Eq 4) and stipulated the maximum temperature at the center of the cylinder (Eq 5). This assumption involved no heat loss (i.e., heat flux) through the other two ends of the potato. Analyzing the potato surface and neglecting radiative heat transfer, they equated the heat transfer from the potato via conduction and convection. Finally, the temperature at the center of the potato was considered the initial condition. To compare experimental results and theoretical predictions, students utilized MATLAB (PDEPE model) to plot and overlay the theoretical predictions with the experimental data. Parameters for the potatoes, such as thermal conductivity and heat capacity, were sourced from the literature. [16-17]

$$BC.1 : \frac{\partial T}{dr}|_{r=0} = 0 \quad (4)$$

$$BC.2 : \frac{\partial T}{\partial r}|_{r=surface} = -\frac{h}{k}\left(T_s - T_{inf}\right) \quad (5)$$

$$IC = T|_{r=0} \quad (6)$$

The results are presented in **Figure 4**. The theoretical prediction deviates from the experimental results which is what we wanted as an instructor so students could think critically. Multiple factors contributed to this divergence, as acknowledged by the students. Firstly, the assumption of cylindrical potato shapes did not perfectly align with the actual, somewhat non-cylindrical form of potatoes. Secondly, the assumption of no heat loss from both ends of the potatoes proved inaccurate given the actual sizes of the potatoes. Additionally, the presumed properties of the potatoes were recognized as potentially variable based on potato types and the convective heat transfer coefficient (h). Furthermore, students acknowledged the previously overlooked

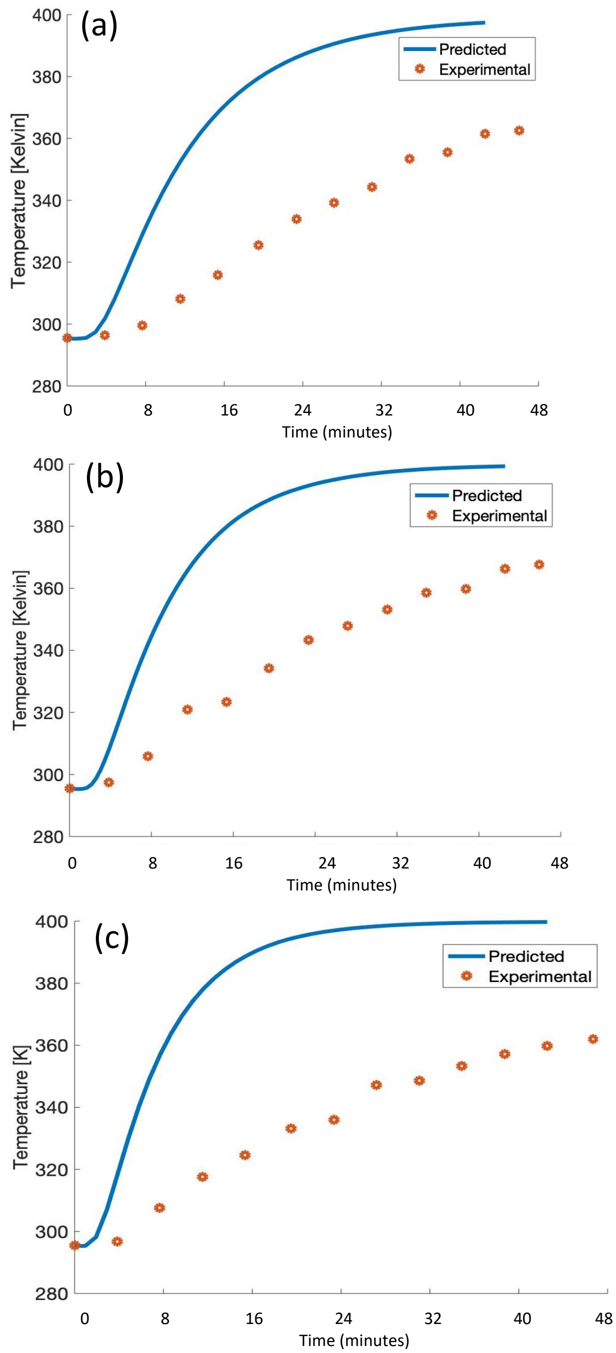


Figure 4. Comparison of experimental results with theoretical predictions as presented by one group of students.

contribution from radiative heat transfer, coupled with the potential influence of any experimental errors. This nuanced analysis adds depth to the interpretation of the results and underscores the complexity of real-world applications.

3.1.2 Mass Transfer Project: Little Jimmy's Balloon

In this project, students introduced a fictitious character, Jimmy, and presented the following conundrum:

Little Jimmy, on his birthday trip to the carnival, won a delightful balloon. Still haunted by the memory of last year's rapidly deflating balloon, Jimmy sought advice from his chemical engineer uncle on how he can have the inflated balloon for the longest period of time? Motivated by this challenge, the uncle and their team delved into a thorough analysis of the problem, employing the principles of mass transfer and presenting their insights to the class.

For their experiment, the team opted for balloons made from two materials—latex and mylar—and inflated each with three gases: helium, carbon dioxide, and air. Assuming spherical geometry, 1-D mass transfer, and referencing pertinent properties from their textbook [15], they calculated the mass flux through each balloon and offered recommendations on which combination would be the best. **Figure 5** shows the schematic of the problem that they presented.

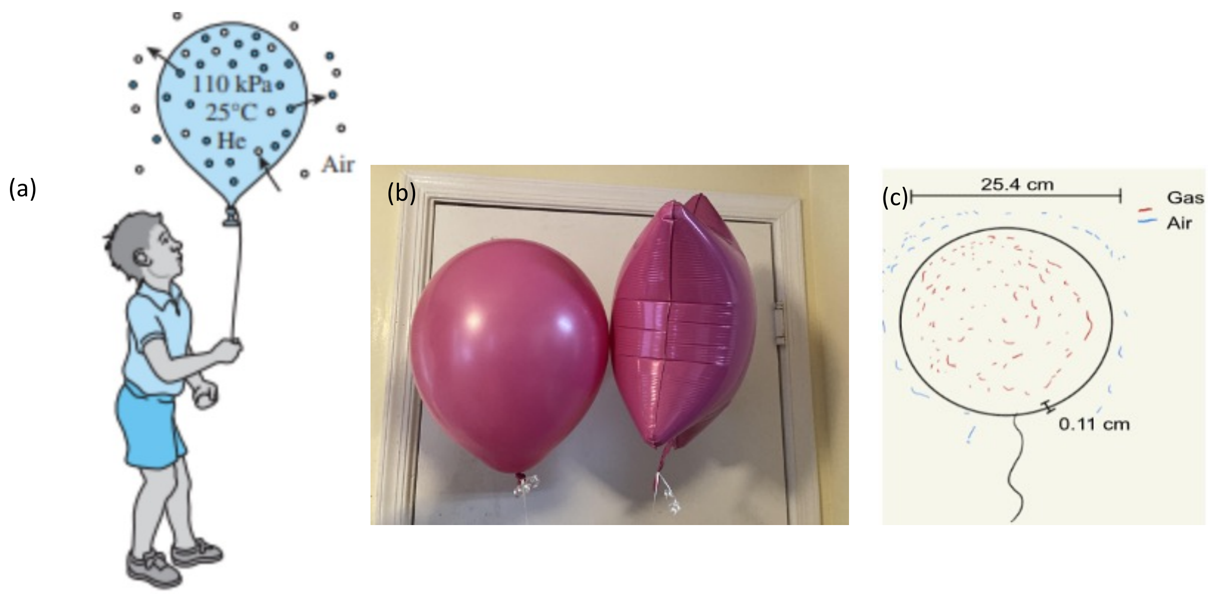


Figure 5. As students presented: (a) Schematic of little Jimmy with his balloon [Figure adapted from ref 13]; (b) two shapes and balloons made with two type of materials (latex and mylar) were used in the experiment; (c) a schematic with dimensions in one experiment.

3.2.2 Connection to Theory

The students derived the mass transfer rate of three gases through a balloon using the following equation (see Appendix for details):

$$W_A = \frac{4\pi D_{AB}\left(C_{Ai} - C_{Ao}\right)}{\frac{1}{r_i} - \frac{1}{r_o}}$$

where, W_A is the mass transfer rate of the gas molecules, D_{AB} is the diffusion coefficient of the molecules, C_{A0} and C_{Ai} is the concentration of gas molecules outside and inside respectively; and r_o and r_i is the outside and inside radius of the balloons respectively.

To estimate the mass transfer rate, they calculated the diffusivity (D_{AB}) for each gas molecule using Hirschfelder et al.'s equation [15], subsequently Knudsen diffusion coefficient (D_{KA}), and effective diffusion coefficient (D_{Ae}) were estimated considering the tortuous pores of the balloon wall. The details of their calculation are shown in **Appendix A** (as presented by the group).

Their theoretical results showed (**Table 2**) Jimmy should inflate the balloons with carbon dioxide, and he should pick Latex over Mylar. They run the experiment for 54 hours and brought all the balloons for live demonstration in the class; that is why no photographs of the balloons after end of 54 hours are included in their report. However, per qualitative evaluation their theoretical calculation were well supported by the experimental observation.

Table 2. The mass transfer rate of each gas through two types of balloons. Higher molar flow rate indicates quicker deflation.

Type of Balloon	Name of the gas	Mass Transfer Rate (mol/s)
Latex	Helium	0.353
	Carbon Dioxide	0.0839
	Air	0.112
Mylar	Helium	0.527
	Carbon Dioxide	0.113
	Air	0.115

3.1.3 Kinetics Project: Alternative use for farm waste: Bioethanol production

The objective of the experiment was to produce ethanol from two farm wastes with the following specific aims:

(i) To determine which type of farm waste will yield the most ethanol.
(ii) To find the optimal fermentation period for farm waste.

In the top panel of **Figure 6**, students presented the general process flow diagram of their experiment which involved four steps: (1) Pretreatment, (2) Enzyme Hydrolysis, (3) Fermentation and (4) Purification.

In the bottom panel they showed their own work of each step. Note, they fermented the corn and wheat husk for a total of 5 days and measured the alcohol by volume (ABV) by a hand-held refractometer in their kitchen and analyzed the results.

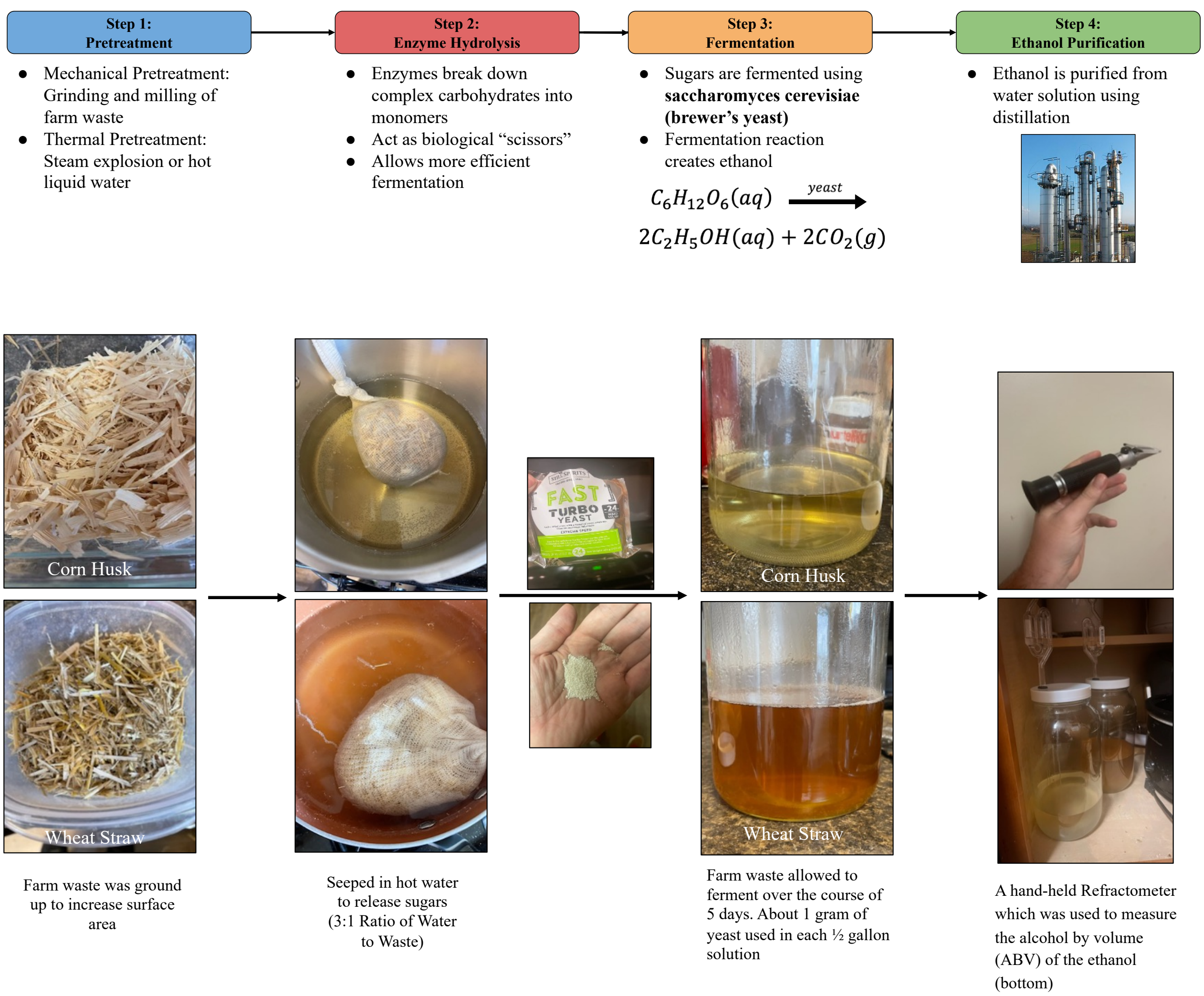


Figure 6. (**Top panel**) process flow diagram of the bioethanol production as presented by the students. (**Bottom panel**) students own work at each phase at home.

The result of the work is summarized in **Figure 7**. Their experiment suggested corn husk produced more ethanol than wheat and it also suggested about 3.5 days should be the optimum fermentation time. They attribute their findings to higher cellulose (42.6% in corn vs 35% in wheat) and hemicellulose (21.3% vs 20%) content in corn than wheat [18].

Alcohol by Volume (ABV%)

Day	Corn Husk	Wheat Straw
1	0	0
2	0.15	0.5
3	1.15	1.0
4	1.25	1.1
5	1.35	1.15

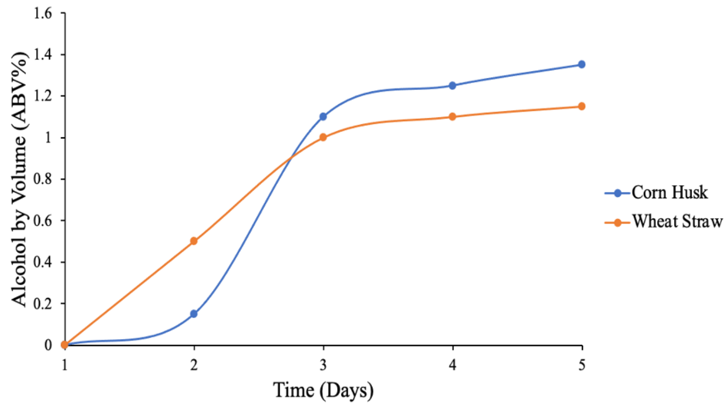


Figure 7. Data of alcohol by volume (ABV) percentage of corn husk and wheat straw over 5 days as presented by the students group.

In summary, the experiments were systematically conducted. In the heat transfer experiments, students conducted a thorough analysis and demonstrated a strong connection with the theoretical aspects. In the mass transfer experiment, students performed decently on both fronts. However, in the bioethanol project, although students presented a good experiment, there was a lack of theoretical connections. Nevertheless, witnessing the students actively engaged in a clever experimental design and analysis, and effective use of tools was truly satisfying. It showcased their praiseworthy dedication to connecting theoretical concepts with hands-on practical experimentation.

3.2 Students' self-evaluation

As indicated before, students undertook a survey pertaining to the experiment at the end. The survey included questions in three key dimensions: i) the time spent; ii) students' perspectives regarding the experiment; and iii) a self-assessment of their learning outcomes. In the following, the results from the survey are presented for the fall 2023 class.

Question 1: What is the estimated total time you dedicated to preparing and conducting the experiment (e.g., in hours)?

> Participants indicated a range of time investments, reporting anywhere from 1-1.5 hours to 4-5 hours per week. Notably, a majority of the groups reported spending approximately 2-2.5 hours per week, as illustrated in Figure 8. Based on the collected responses, the average time spent by this class on the at-home experiment project was 9.8 ± 4.7 hours.

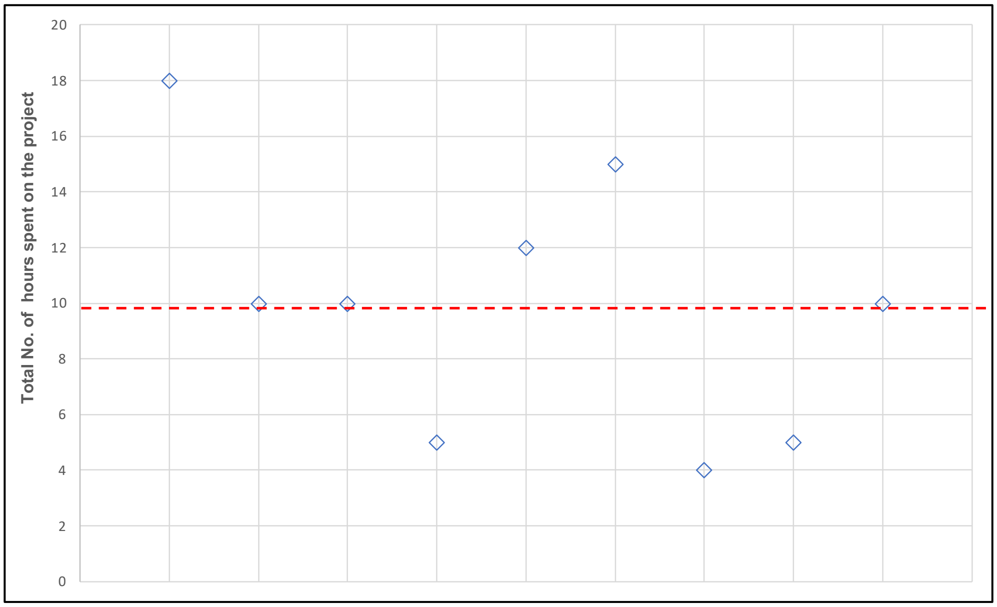
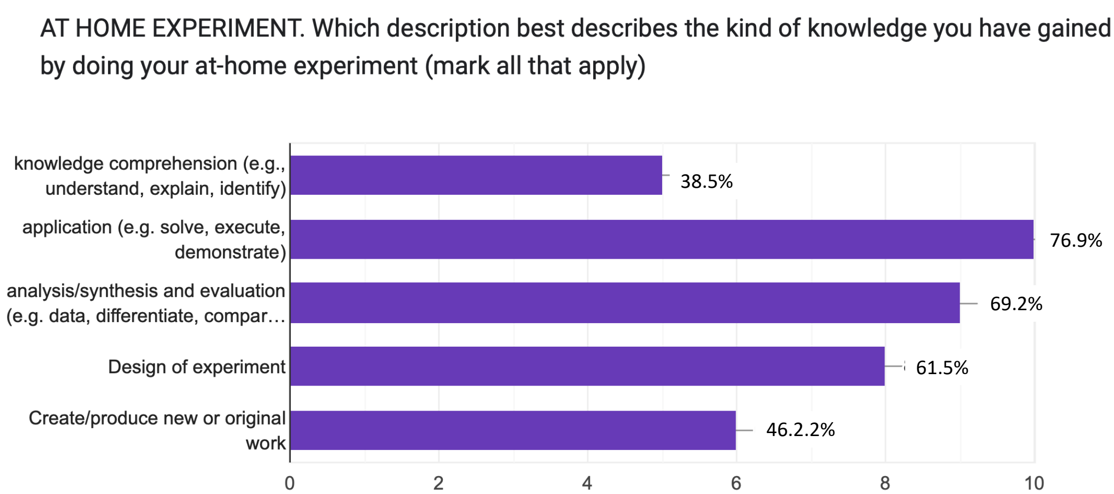


Figure 8: Each data point represents the total number of hours spent by each group over four weeks. The red dotted line signifies the average time from the data.

Question 2. Which description best describes the kind of knowledge you have gained by doing your at-home experiment (mark all that apply).

The students' responses are outlined below. According to their feedback, a majority indicated the application of knowledge as a significant outcome of their at-home experiments. Additionally, they highlighted the acquisition of skills in analysis and the design of experiments as prominent aspects of their at-home projects, with the other two options following in recognition.



Question 3. The third was an opened-ended response question. It says "I learnt _____"

Open-ended responses appeared to be both candid and insightful. The following are the responses from all groups.

I learnt ____________

- *Heat theories and how to design a heat transfer experiment without a prompt.*
- *I learnt how to prepare an experiment and try to mitigate error.*
- *How to re-design an experiment when a previous procedure wasn't working.*
- *I learnt that the things we learn about in our classes do actually hold true in real life. It was cool to see the theory come to life and get a glimpse of how chemical engineering can be used in the real world.*
- *The hands-on application of heat transfer effects in real life.*
- *Experimentation provides an excellent opportunity to witness the shortcomings of theory in application, and a true understanding of the impact of the assumptions made during theory development can be understood by comparing actual data with theoretical data. Through this experiment, I learned ways in which theory fails and I also learned how to develop an experiment based off of the scientific method.*
- *Through the at home experiment, I learned more about real life applications to the material that we learned during fluid transport course. We were able to solve a question/problem that we didn't know all the parts of.*
- *How to apply the theories to real life and also leant about tensile strength and other material properties.*
- *I learned more about experimental set up. I also learned a fair amount about propane and butane and their applications when it comes to everyday life.*
- *How to manage my time better.*

3.3 Instructor's Evaluation

Based on the students' responses, the overall attitude appeared to be very positive. Throughout the discussion sessions, instructors utilized check sheets to document students' questions, categorizing them as either *Practical* (detailed or contextual) and/or *Theoretical* (detailed or contextual). Qualitatively, it was observed that the majority of student queries fell within the *practical details* and *theoretical contextual* dimensions.

The open-ended responses were particularly encouraging and very gratifying, exemplified by comments such as the following, which aligns well with the major teaching objective of this project:

> *"Experimentation provides an excellent opportunity to witness the shortcomings of theory in application, and a true understanding of the impact of the assumptions made during theory development can be understood by comparing actual data with theoretical data. Through this experiment, I learned ways in which theory fails and I also learned how to develop an experiment based off of the scientific method."*

According to the students' reports and presentations, it is evident that they successfully met the learning objectives especially Application, Analysis, Design of Experiment. The establishment of reasonable experiments, coupled with the reporting of average experimental data and trends, generally met acceptable standards, albeit with some variabilities. These variabilities, in fact, underscored the practicality of the at-home experiment and the students' ability to independently design their experiments. While students often sought assistance in explaining results or refining experiment designs, the overall outcomes were satisfactory to the instructor.

As an instructor, it was particularly gratifying to witness the students engage in a systematic investigation. Their adept design of the experiment, coupled with their utilization of appropriate tools, demonstrated a commendable commitment to bridging theoretical concepts with practical experimentation. The satisfaction stemmed not only from the execution of a structured experiment but also from the students' ability to ask important questions and draw reasonable conclusions from their findings. This process also showcased their capacity for critical thinking and their adept use of analytical tools, reflecting an integration of theoretical knowledge with hands-on experimentation.

4. CONCLUSION

As researchers we learned something new, and the at-home projects also gave us an incentive for discussions about teaching and learning. The projects were successful in engaging the students in hands-on studies to connect to theories and augment their theoretical learning. We hope that their experience will lead to a positive development in their interest in solving open ended problems and ability to manage practical work. For future iterations, we plan to allocate more time and extended discussion hours, potentially extending project timelines to semester long projects. Research in engineering education should naturally aim to gain new knowledge and enhance development. We feel confident that not only have we as researchers learned new things from these at-home projects, but also that the findings will be beneficial to our future students and teachers.

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APPENDIX A

3.1.2.S. Mass Transfer Project: Little Jimmy's Balloon

Total molar flux of gas through the balloon can be solved through the following equation:

$$N_{A,r} = -(D_{AB} * \frac{dC_A}{dr}) - y_A(N_{A,r} + N_{B,r})$$

Now, assuming dilute concentration of gas the equation reduces to:

$$N_{A,r} = -(D_{AB} * \frac{dC_A}{dr})$$

Considering, spherical geometry, no reaction takes places within the balloon, at steady-state the general equation for mass transfer reduces to the followings:

$$\nabla N_{A,r} + \frac{dC_A}{dt} - R_A = 0$$

$$\frac{1}{r^2}(\frac{d(r^2 N_{A,r})}{dr}) = 0$$

Now, the most important parameter is to find the rate of mass transfer through the balloon is as follows:

$$W_A = N_{A,r} * 4\pi r^2$$

$$W_A = -(D_{AB} * \frac{dC_A}{dr}) * 4\pi r^2$$

Considering the thickness of the balloon and inside, outside concentration, we get:

$$W_A \int_{r_i}^{r_o} \frac{1}{r^2} dr = -4\pi D_{AB} \int_{C_{Ai}}^{C_{Ao}} dC_A$$

$$\boxed{W_A = \frac{4\pi D_{AB}(C_{Ai} - C_{Ao})}{\frac{1}{r_i} - \frac{1}{r_o}}}$$

We, estimated the diffusivity using the following Hirschfelder et al.'s equation [14]

$$D_{AB} = \frac{0.001858 T^{1.5}(\frac{1}{M_A} + \frac{1}{M_B})^{0.5}}{P\sigma_{AB}^2 \Omega_D}$$

Gas (in Air)	Diffusivity D_{AB} **(cm²/s)**
Helium	0.709
Air	0.203
Carbon Dioxide	0.1516

Knudsen Diffusion

$$D_{KA} = 4850 d_{pore} \sqrt{\frac{T}{M}}$$

From the literature,

Latex pore diameter: 3.4×10^{-5} cm
Mylar pore diameter: 0.0025 cm

Balloon Type	**Gas**	Knudsen Diffusion Coeff. D_{KA} **(cm²/s)**
Latex	Helium	1.42
Latex	Carbon Dioxide	0.429
Latex	Air	0.529
Mylar	Helium	104.65
Mylar	Carbon Dioxide	31.55
Mylar	Air	38.89

Now, estimated the effective diffusion coefficients by combining diffusivity and Knudson diffusion

$$D_{Ae} = \frac{1}{\frac{1}{D_{KA}} + \frac{1}{D_{AB}}}$$

Balloon Type	Gas	D_{Ae} (cm^2/s)
Latex	Helium	0.473
Latex	Carbon Dioxide	0.112
Latex	Air	0.147
Mylar	Helium	0.704
Mylar	Carbon Dioxide	0.1509
Mylar	Air	0.202

Results:

- Dimensions were measured for each balloon and they were kept constants as much as possible.
- Concentration outside of balloon was assumed to zero (C_{Ao} = 0)
- Concentration inside was based on the following assumptions

$$C = \frac{P}{RT} = \frac{1\ atm}{298\ K} * \frac{mol\ K}{.08206\ L\ atm} * \frac{1\ L}{1000\ cm^3} = 4.1x10^{-5}\ mol/cm^3$$

- Concentration inside of balloon was estimated assuming ideal gas law (C_{Ai})/
- 54 hours later they brought the balloons in classroom for live demonstration

Balloon Type	Gas	W_a (mol/s)
Latex	Helium	0.353
Latex	Carbon Dioxide	0.0839
Latex	Air	0.112
Mylar	Helium	0.527
Mylar	Carbon Dioxide	0.113

Mylar	Air	0.154

Conclusion: What Balloon Should Little Jimmy Get?

- **Air or Carbon Dioxide Inflated Balloon in Latex.** Larger molecule in a material with smaller pore size, harder to diffuse out.