# Designing an Educational Tool to Improve Understanding and Planning in Chemistry Laboratory Courses

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## Abstract

Chemistry laboratory courses are essential for developing experimental skills, yet students face challenges with pre-laboratory activities and materials due to the lack of details and changing environments. This study identifies these challenges and suggests design implications for future systems to help students understand and plan chemistry laboratory experiments: addressing missing details, reflecting real lab environments, and facilitating active planning and execution. Based on these findings, this study developed ChemLab Planner, a web-based tool that converts text-based lab manuals into an interactive, timeline interface. The system breaks down procedures into substeps to provide detailed descriptions that meet student needs, adapts procedures to actual lab conditions, and supports team-based planning and execution. These features directly address the identified challenges, enabling students to prepare for experiments effectively. Building upon traditional pre-laboratory materials, ChemLab Planner offers a scalable approach to help laboratory understanding and planning, exemplifying the role of computer-aided tools in chemistry laboratory education.

## CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; • **Applied computing → Education**; **Interactive learning environments**.

## Keywords

Chemistry Laboratory Education; Education Support;

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## 1 Introduction

Chemistry laboratory courses are fundamental to undergraduate chemistry education, equipping students with experimental skills and reinforcing theoretical knowledge. However, insufficient pre-laboratory activities and materials often leave students struggling, resulting in incomplete experiences that fail to meet the course objectives. With advances in educational technology, web and XR-based tools have emerged to enhance comprehension by recreating experimental experiences. While these technologies improve understanding, they often overlook challenges in actual laboratory work, such as planning experiment sequences and adapting to changes in procedures. This gap highlights the need for solutions that help students navigate actual experiment tasks.

This research is motivated by the need for an effective solution to support students in understanding and planning chemistry laboratory experiments. By identifying student challenges and perceptions of pre-laboratory activities, this study suggests design implications for systems that enhance experiment preparation. Through this process, this research aims to design and implement an educational tool that addresses the students' challenges in chemistry laboratory courses. Specifically, this research aims to answer the following research questions:

(1) What challenges do students face in pre-laboratory activities for chemistry laboratory courses?
(2) What design implications can inform the development of a tool to assist students in understanding and planning chemistry laboratory experiments?
(3) How can a system be designed to address these challenges while incorporating the identified design implications?

## 2 Related Works

### 2.1 Chemistry Laboratory Education

Laboratory courses are an important part of undergraduate STEM education. Chemistry laboratory courses play a crucial role in developing students' experiment design abilities, understanding of laboratory equipment, and adherence to safety measures essential in the field [6, 7, 11, 24]. Schlesinger identified the primary goals of laboratory education as illustrating classroom principles through material engagement, fostering an appreciation of science's reality, making scientific facts memorable, and providing hands-on training in laboratory methods [17].

Preparation before conducting experiments is critical for ensuring safety and improving experimental accuracy and academic performance. Pickering [15] highlights that students who familiarize themselves with experimental processes in advance are better equipped to approach laboratory work with confidence and precision. Consequently, pre-laboratory activities, such as writing pre-reports or completing quizzes on experimental methods, have thus become standard practice in chemistry laboratory courses to enhance student engagement and understanding [2]. Among the various materials used in laboratory courses, lab manuals serve as the primary resource for experiment instruction and preparation. A


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| Section | Example Questions and Agreement Statements |
|---|---|
| General Information | What chemistry-related lab courses have you completed? |
| Pre-laboratory Material Provision | How often were [experiment videos] provided in your chemistry lab courses? |
| Pre-laboratory Material Helpfulness | How helpful was the [lab manual] for understanding the experiment beforehand? |
| Experiment Understanding | After [completing the required preparation], I understand the experiment well. |
| Lab Manual Sufficiency | The lab manual provides a sufficient explanation of [the purpose of the experiment]. |
| Lab Manual Challenges | [Omitted steps in the manual] make the experiment hard to understand and plan. |
| Lab Environment | I often participate in experiments as part of a group of two or more members. |

**Table 1: Survey Structure. Example questions and statements are in the right column, where brackets indicate variables.**

survey of American Chemical Society-accredited programs found that 91% of institutions rely on step-by-step laboratory guides, reflecting the traditional lab format [1].

Despite these efforts, challenges remain in preparation for laboratory work. Traditional lab manuals often lack sufficient detail or fail to adapt to the dynamic nature of laboratory environments. Moreover, while student perceptions and understanding of chemistry experiments have been studied for assessment purposes [22] or to evaluate overall course satisfaction [16, 20], limited attention has been given to identifying specific challenges students face with experiment preparation. This work aims to identify these challenges and improve pre-laboratory resources to better support learning.

### 2.2 Computer-aided Chemistry Laboratory Education

Research has explored computer-aided tools to enhance students' understanding of chemistry laboratory procedures. Shelby and Fralish [18] showed that integrating experiment videos with interactive quizzes on platforms like Edpuzzle enhances student experiences and performance in biochemistry labs. Similarly, studies [14, 21] highlight the positive effects of videos and interactive materials on student motivation and performance. Additionally, several works [12, 13, 19, 25] have utilized simulations and virtual or mixed reality to replicate lab experiences. Flesch et al. [9] demonstrated how virtual pre-laboratories in hypothetical conditions improve understanding of analytical chemistry.

While videos and simulations are valuable supplements, their adoption is often constrained by cost [3], as producing and maintaining these media for each experiment [4] can be resource-intensive. Moreover, many existing tools primarily focus on replicating experimental experiences, which may not fully address the students' challenges in planning actual experiments. Recognizing this gap, this work aims to design a tool that supports students in planning experiments without requiring experiment-specific content generation, thereby providing greater scalability and adaptability.

## 3 Methods

### 3.1 Survey

A survey was conducted to identify the challenges faced by undergraduate students in chemistry-related laboratory courses. A total of 62 undergraduate students with experience in these courses participated in an online survey, exceeding the required sample size of 43 calculated using a priori power analysis in G*Power [8, 10] (effect size = 0.25, $\alpha$ = 0.05, power = 0.95). Of the participants, 27 identified as female and 35 as male, with ages ranging from 18 to 28 (M = 22.44). The majority of participants were enrolled in chemistry-related majors, including Materials Science and Engineering (n = 19), Chemical and Biological Engineering (n = 16), Chemistry (n = 7), and Chemical Engineering and Materials Science (n = 2). Others included Nuclear Engineering, Medicine, Pharmacy, Chemistry Education, General Studies, and Economics. Participants completed 1 to 7 chemistry-related lab courses (M = 2.58), including General Chemistry, Materials Science, Biochemistry, and Chemical Process Labs.

Participants completed a survey comprising four open-ended questions and 39 Likert-scale questions, each rated on a 7-point scale, to assess their experiences in chemistry-related laboratory courses as in Table 1. Friedman tests were used to analyze differences in responses across grouped questions, and post-hoc Wilcoxon signed-rank tests [23] with Bonferroni correction [5] were applied to determine the significance of pairwise comparisons. The survey required approximately 10 minutes, and each participant received a compensation of 5,000 KRW. As all the participants were Korean, questions were presented in Korean to ensure clarity and accessibility for participants.

### 3.2 Interview

Follow-up interviews were conducted with five survey participants to gain deeper insights into the rationale for their survey responses. The interviewer and each participant reviewed the survey responses together, and the participant was asked to elaborate on their answers, provide clarifications and examples, and suggest improvements. Each online interview lasted approximately 30 minutes, and each participant received a compensation of 10,000 KRW. All human studies included in this work were approved by the Institutional Review Board of Seoul National University.

## 4 Results

### 4.1 Pre-laboratory Activities and Materials

*4.1.1 Provision of Pre-laboratory Activities and Materials.* Based on related works [2, 15], key experiment preparation activities and materials were identified as reading lab manuals, watching experiment videos, attending lectures, taking quizzes, and writing obligatory pre-reports. Participants rated how often these activities or materials were provided in their courses on a 7-point Likert scale (1 = Never, 7 = Always). Lab manuals were the most frequently used, with 79% selecting "Always" and 98% providing positive ratings (5-7). Pre-reports ranked second (47% "Always," 77% positive), while

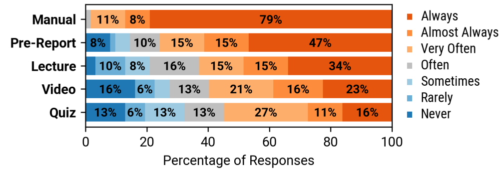


Figure 1: Provision of Pre-laboratory Activities and Materials

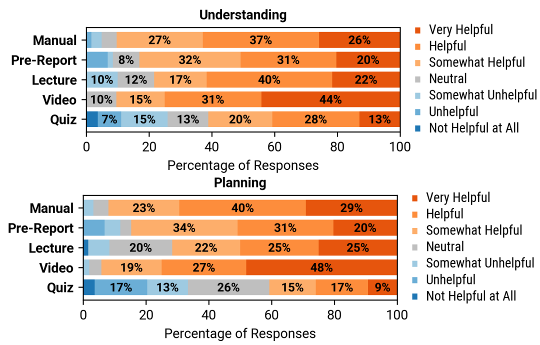


Figure 2: Perceived Helpfulness of Pre-laboratory Activities and Materials

lectures, videos, and quizzes were less frequent (refer to Figure 1). Additional materials mentioned in short-answer responses either matched predefined categories or reflected personal strategies beyond course resources.

*4.1.2 Perceived Helpfulness of Pre-laboratory Activities and Materials.* Participants rated the helpfulness of experiment preparation activities and materials for understanding and planning experiments on a 7-point Likert scale (1 = Not Helpful at All, 7 = Very Helpful, N/A = No Experience). While helpfulness ratings generally aligned with usage frequency, experiment videos were perceived as highly helpful despite lower usage rates, receiving the most 'Very Helpful' responses (44% for understanding, 48% for planning, refer to Figure 2). Friedman tests revealed significant differences in the perceived helpfulness of materials for both understanding ($\chi^2$ = 26.76, p = 2.222e-5) and planning ($\chi^2$ = 41.14, p = 2.519e-8). Experiment videos were significantly more helpful than quizzes and pre-reports for understanding and more helpful than all other materials for planning. Quizzes were significantly less helpful compared to lab manuals, experiment videos, and pre-reports for understanding and less helpful than all other materials for planning.

During interviews, participants elaborated on their preferences for specific materials. Two participants (I1, I2) favored experiment videos over lab manuals, citing detailed explanations absent in manuals. Three participants (I2, I4, and I5) emphasized pre-reports' value in active planning. They explained that writing pre-reports allowed them to identify gaps in their knowledge and engage deeper with the materials.

## 4.2 Student Perspectives on Lab Manuals

*4.2.1 Perceived Sufficiency of Lab Manuals.* Participants evaluated the sufficiency of lab manuals, the primary preparation material, on a 7-point Likert scale (1 = Very Insufficient, 7 = Very Sufficient) in aspects such as procedures, purposes, principles, safety, equipment,

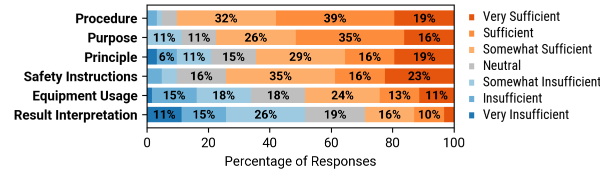


Figure 3: Perceived Sufficiency of Lab Manuals

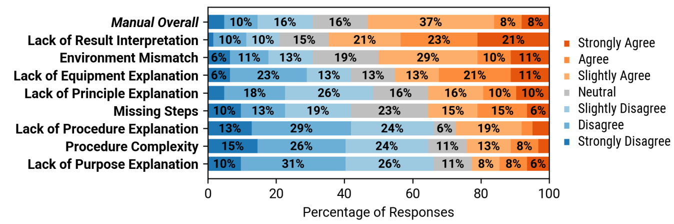


Figure 4: Challenges with Lab Manuals

and result interpretation. A Friedman test revealed a significant difference in the perceived sufficiency of lab manuals across these aspects ($\chi^2$ = 90.96, p = 4.226e-18). Explanations on result interpretation and equipment usage were perceived as significantly less sufficient than all other aspects (refer to Figure 3).

*4.2.2 Challenges with Lab Manuals.* To identify challenges associated with lab manuals, participants rated their agreement with various challenges on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree). Overall, 53% agreed that planning an experiment solely with lab manuals is difficult (8% strongly, 8% moderately, 37% slightly, refer to Figure 4). In addition to challenges identified in 4.2.1, new issues such as environment mismatch and missing steps were identified.

A Friedman test revealed a significant difference in the perceived challenges associated with lab manuals across different aspects ($\chi^2$ = 97.47, p = 3.567e-18). *Lack of explanation on result interpretation* was the most significant challenge. During the interviews, many (I2, I3, I4, I5) reported relying on external resources, such as prior examples shared by peers or seniors, internet searches, textbooks, or academic papers, to understand how to interpret results. *Environment mismatch* and *lack of equipment explanation* were the second most significant group of challenges. Participants (I1, I3, I4) noted that outdated lab manuals often conflicted with actual laboratory setups. Specific examples included different equipments (P48, I1, I3), the use of different solvents (I4), and instances of broken equipment (P3, P20, P48, I2). I5 reported time mismatches, with manuals assuming longer durations than allocated class time, leading to rushed procedures. Participants also emphasized the lack of explanations on using equipment, such as statistical programs (I1) or the buttons on complex chemical engineering process equipment (I2). *Missing steps* and *lack of principle explanation* formed the third group of challenges. I2 explained that manuals often oversimplify procedures, stating, "The manual will simply say 'create a vacuum to separate the solution'—it's hard to imagine what I would have to do with only this explanation." Participants (I2, I3) also noted that the principles behind experiments are disconnected from the procedural steps, making it difficult to understand their relevance. While short-answer survey responses mostly aligned with the predefined challenges from the Likert scale questions, additional challenges

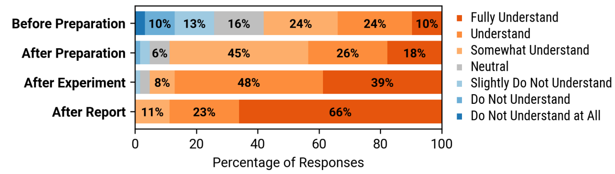


**Figure 5: Change in Understanding Across Different Stages**

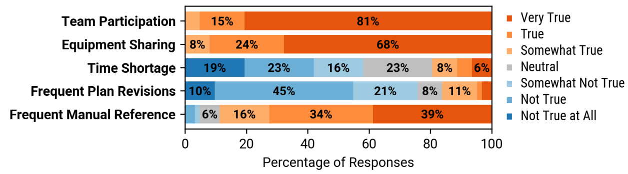


**Figure 6: Laboratory Course Environment**

were also identified, including poor readability and inconsistencies between lab manuals and other resources.

## 4.3 Insights into Laboratory Environments

To explore how students progress through laboratory courses, participants evaluated their understanding of the experiment at four stages: before preparation, after preparation (pre-laboratory activities), after experimenting, and after writing the report, on a 7-point Likert scale (1 = Do Not Understand at All, 7 = Fully Understand). While understanding improved after preparation, most responses remained in the 'somewhat understand' category, highlighting the need to enhance comprehension during the preparation phase (refer to Figure 5).

Participants were also asked about their laboratory environments on a 7-point Likert scale (1 = Not True at All, 7 = Very True). Most reported conducting experiments in teams with shared equipment and minimal plan modifications during experiments. Notably, 89% referred to the lab manual during experiments (refer to Figure 6). Although most participants did not report time shortages, interviews revealed that students adjust plans to finish early (I2) or employ systematic planning by dividing tasks among team members to improve efficiency (I3).

## 4.4 Design Implications

Despite being the primary resource for preparing chemistry laboratory experiments (4.1.1), 53% of participants found lab manuals insufficient for planning (4.2.2), highlighting the need to bridge this gap. Educational tools should offer generalizable and scalable support to enhance preparation using lab manuals. Drawing from survey and interview insights, this study suggests design implications for developing an educational tool to enhance lab preparation.

**Addressing Missing Experimental Details in Lab Manuals.** Lab manuals often lack detail in result interpretation, equipment usage, experimental principles, and procedural details. Surveys and interviews revealed that participants frequently consult online resources for clarification. To address this, the system should integrate external academic resources (as proposed by I1, I4) and explain underlying principles to bridge theory and practice (I2, I3, I4). Additionally, it should supplement missing procedural steps with detailed descriptions.

**Reflecting Actual Laboratory Environments.** Participants explained that mismatches between lab manuals and actual setups caused by outdated materials or last-minute changes are a significant challenge. The system should be able to provide updated procedures reflecting current equipment and conditions. Additionally, it should account for group dynamics and shared resources, helping students plan experiments more effectively.

**Supporting Effective Planning and Execution.** The system should help students actively plan experiments by allowing them to customize and annotate steps, similar to writing pre-reports. Since students frequently consult lab manuals during experiments, the system should be intuitive and easy to navigate during experiments.

# 5 ChemLab Planner

## 5.1 System Design

Informed by the design implications, this study developed a web-based educational tool, ChemLab Planner (Figure 7), to assist students in understanding and planning chemistry laboratory experiments. ChemLab Planner operates in three main steps: **(1) Step Breakdown and Customization:** Lab manuals, including experiment procedures, are processed using few-shot prompting with GPT-4o-mini to break each step into substeps and detail omitted steps. Information about the laboratory environment—such as changes in equipment, procedural adjustments, or specific requirements (e.g., finding MSDS for chemicals)—is also used to adapt the procedure to the actual environment. The substeps are displayed (Figures 7B and 8B), allowing users to reorder, edit, add, or remove them to align with their goals and preferences. **(2) Experiment Timeline:** A multi-person timeline (Figures 7C and 8C) is generated based on the time and participant information provided. Users can assign substeps to individuals, share tasks across team members, and adjust durations for each substep. Descriptions for substeps, generated by few-shot prompting with GPT-4o-mini, address gaps identified in the survey—such as result interpretation tips, equipment usage, or step principles—while also reflecting user-specified laboratory environments. **(3) Experiment Execution:** During the experiment, the system facilitates task management by allowing users to mark substeps as completed, make real-time edits to address unforeseen issues, and access descriptions for guidance (Figures 7D and 8D).

## 5.2 User Feedback

To assess the helpfulness of ChemLab Planner and identify areas for improvement, informal user tests were conducted with three survey participants. Participants first received a walk-through of the system using an example experiment, then independently used the system to plan another experiment with self-defined scenarios. All three participants found the system helpful for understanding and planning chemistry laboratory experiments, especially for novice undergraduates with limited experimental experience. The breakdown of tasks into substeps was highlighted as a key feature, as it directly improved understanding and served as a useful checkpoint during the planning process. Participants noted that students would be motivated to use this system because it resolves conflicts in team management and facilitates planning to finish experiments earlier.

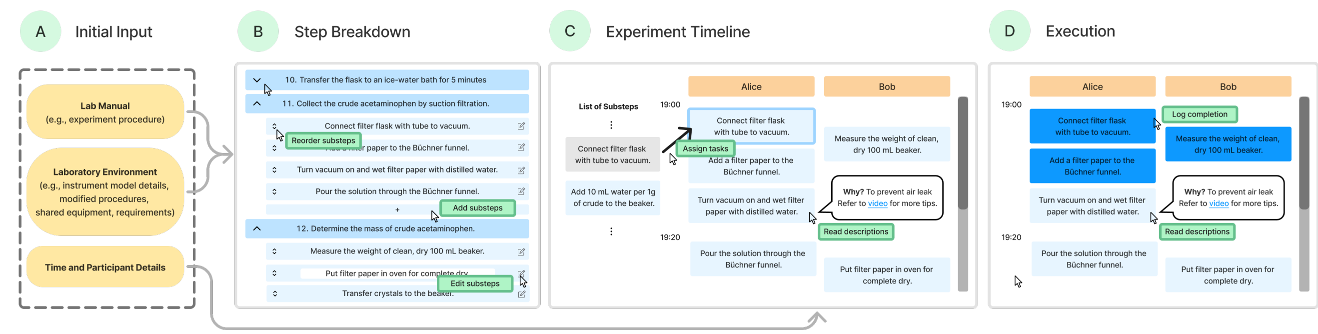


Figure 7: ChemLab Planner: System Design Overview

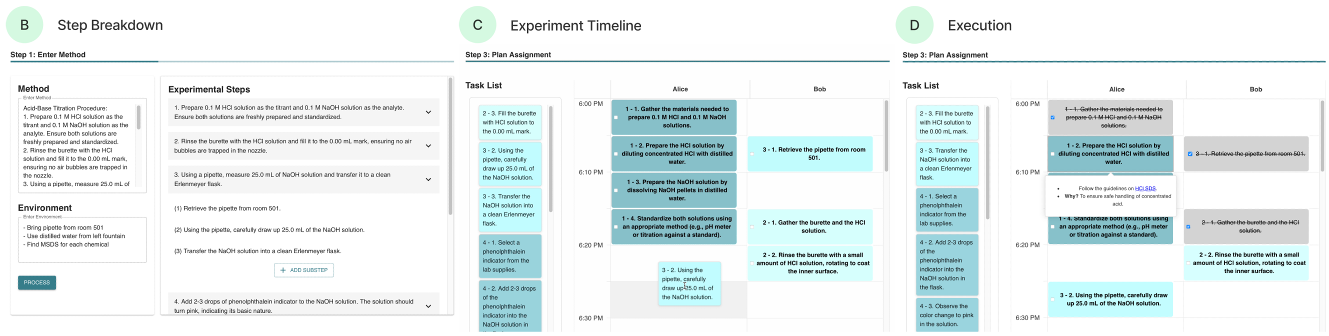


Figure 8: ChemLab Planner: Implemented using React and Node.js.

Participants suggested adding features to detect sequencing issues, such as conflicts in step order and whether tasks can be performed simultaneously or must be sequential. They also suggested including predicted time durations for substeps. Additionally, one participant suggested enhancing result interpretation by providing tools to log data, perform basic calculations, and create plots, enabling real-time understanding of results during experiments.

# 6 Discussion

## 6.1 Future Work

Three key improvements were identified to enhance ChemLab Planner further. First, the system could detect impossible sequences and inefficiencies in substep assignments to help optimize workflows. Second, implementing real-time data logging and analysis would enable students to better understand results during experiments. Lastly, integrating supplementary materials—such as equipment images, videos, lecture slides, or textbook excerpts—into each step can enhance comprehension by facilitating cross-referencing across multiple resources. Following these enhancements, formal user studies can be conducted to evaluate ChemLab Planner's effectiveness. One approach is comparing students' experiment planning and understanding using traditional lab manuals versus ChemLab Planner. Additionally, deploying it in actual lab courses and collecting student feedback can assess its impact on experiment execution.

## 6.2 Expansion to Other Fields

While ChemLab Planner addresses student challenges in chemistry laboratory courses, its approach can extend to other STEM fields like biology and physics, where experimental settings pose similar issues. The system can also help reproduce experiments from research papers by breaking down text-based protocols into substeps, offering structured guidance and identifying knowledge gaps. More broadly, ChemLab Planner can support non-academic tasks requiring sequence planning, such as cooking or knitting. ChemLab Planner can be generalized into a planning tool applicable to learning a wide range of sequential, protocol-driven activities beyond science experiments.

## 6.3 Proficiency-awareness

ChemLab Planner provides substep descriptions to address gaps in traditional lab manuals, enhancing understanding of principles, result interpretation, and equipment usage. However, the descriptions are general and not tailored to user proficiency or curriculum needs. Some participants found them too simplistic or broad, highlighting the need for adaptive content. For example, the system could prioritize detailed guidance on unfamiliar equipment while offering minimal verification cues for experienced users. Further research can explore how information and its presentation should vary for different proficiency levels. Customizing descriptions based on expertise could significantly enhance the system's support for diverse learners.

# 7 Conclusion

This research proposed design implications and introduced ChemLab Planner, a web-based tool to address student challenges in understanding and planning chemistry laboratory experiments.

Grounded in surveys and interviews, the implications focused on supplementing lab manuals, reflecting real lab environments, and supporting active planning. ChemLab Planner applies these by breaking down methods into modular substeps, adapting to lab conditions, and offering a timeline-based interface for planning and execution. The flexibility of the design suggests applicability beyond chemistry to other disciplines. This work contributes to improving laboratory course experiences by examining the challenges students face in real-world educational settings.

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## References

[1] Michael R Abraham, Mark S Craolice, A Palmer Graves, Abdulwali H Aldhamash, Joann G Kihega, Julieta G Palma Gal, and Valsamma Varghese. 1997. The nature and state of general chemistry laboratory courses offered by colleges and universities in the United States. *Journal of Chemical Education* 74, 5 (1997), 591. doi:10.1021/ed074p591

[2] Hendra Y Agustian and Michael K Seery. 2017. Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design. *Chemistry Education Research and Practice* 18, 4 (2017), 518–532. doi:10.1039/C7RP00140A

[3] A.W. Bates and A. Sangra. 2011. *Managing Technology in Higher Education: Strategies for Transforming Teaching and Learning.* Wiley.

[4] A. W. Bates. 2015. *Teaching in a Digital Age: Guidelines for Designing Teaching and Learning.* Tony Bates Associates Ltd., Vancouver, BC.

[5] Carlo Bonferroni. 1936. Teoria statistica delle classi e calcolo delle probabilita. *Pubblicazioni del R istituto superiore di scienze economiche e commericiali di firenze* 8 (1936), 3–62.

[6] W. G. Bowers. 1924. The advantages of laboratory work in the study of elementary chemistry. *Journal of Chemical Education* 1, 11 (1924), 205. doi:10.1021/ed001p205

[7] Hasok Chang. 2011. How historical experiments can improve scientific knowledge and science education: The cases of boiling water and electrochemistry. *Science & Education* 20 (2011), 317–341. doi:10.1007/s11191-010-9301-8

[8] Franz Faul, Edgar Erdfelder, Axel Buchner, and Albert-Georg Lang. 2009. Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior research methods* 41, 4 (2009), 1149–1160. doi:10.3758/BRM.41.4.1149

[9] Madison M Flesch, Nicholas J Humphrey, and Stephen A Mang. 2024. Virtual Choose-Your-Own-Adventure Prelabs Improve Student Understanding of Analytical Chemistry Concepts and Instrumentation. *Journal of Chemical Education* 101, 3 (2024), 941–948. doi:10.1021/acs.jchemed.3c00803

[10] Milton Friedman. 1937. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the american statistical association* 32, 200 (1937), 675–701. doi:10.1080/01621459.1937.10503522

[11] Avi Hofstein and Rachel Mamlok-Naaman. 2007. The laboratory in science education: the state of the art. *Chemistry education research and practice* 8, 2 (2007), 105–107. doi:10.1039/B7RP90003A

[12] Guanxuan Jiang, Xuansheng Xia, Yue Li, Hai-Ning Liang, and Pan Hui. 2024. ChemistryVR: Enhancing Educational Experiences through Virtual Chemistry Lab Simulations. In *SIGGRAPH Asia 2024 Educator's Forum (SA '24)*. Association for Computing Machinery, New York, NY, USA, Article 1, 5 pages. doi:10.1145/3680533.3697068

[13] Shan Jin, Yuyang Wang, Lik-Hang Lee, Xinyi Luo, and Pan Hui. 2023. Development of an immersive simulator for improving student chemistry learning efficiency. In *Proceedings of the 16th International Symposium on Visual Information Communication and Interaction* (Guangzhou, China) *(VINCI '23)*. Association for Computing Machinery, New York, NY, USA, Article 13, 8 pages. doi:10.1145/3615522.3615535

[14] Yujuan Liu. 2021. The effects of online organic chemistry laboratory videos on students' perceptions and intrinsic motivation. *Journal of Research in Science, Mathematics and Technology Education* 4, 3 (2021), 239–255. doi:10.31756/jrmste.435

[15] Miles Pickering. 1987. What goes on in students' heads in lab? *Journal of Chemical Education* 64, 6 (1987), 521. doi:10.1021/ed064p521

[16] Chanyapat Sangsuwon and Netdao Yooyong. 2020. Measuring Undergraduate Science Students Satisfaction for the services provided by Chemistry Laboratories in SSRU University. In *Proceedings of the 11th International Conference on Education Technology and Computers* (Amsterdam, Netherlands) *(ICETC '19)*. Association for Computing Machinery, New York, NY, USA, 250–253. doi:10.1145/3369255.3369294

[17] H. I. Schlesinger. 1935. The contribution of laboratory work to general education. *Journal of Chemical Education* 12, 11 (1935), 524. doi:10.1021/ed012p524

[18] Shameka J Shelby and Zachary D Fralish. 2021. Using Edpuzzle to improve student experience and performance in the biochemistry laboratory. *Biochemistry and Molecular Biology Education* 49, 4 (2021), 529–534. doi:10.1002/bmb.21494

[19] Kyohyun Song, Gunhee Kim, Inkyu Han, Jeongyoung Lee, Ji-Hyung Park, and Sungdo Ha. 2011. CheMO: mixed object instruments and interactions for tangible chemistry experiments. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI EA '11)*. Association for Computing Machinery, New York, NY, USA, 2305–2310. doi:10.1145/1979742.1979907

[20] Chin-Chung Tsai. 2003. Taiwanese science students' and teachers' perceptions of the laboratory learning environments: Exploring epistemological gaps. *International Journal of Science Education* 25, 7 (2003), 847–860. doi:10.1080/09500690305031

[21] Nicolás Veiga, Florencia Luzardo, Kenneth Irving, María N Rodríguez-Ayán, and Julia Torres. 2019. Online pre-laboratory tools for first-year undergraduate chemistry course in Uruguay: student preferences and implications on student performance. *Chemistry education research and practice* 20, 1 (2019), 229–245. doi:10.1039/C8RP00204E

[22] Jianye Wei, David F Treagust, Mauro Mocerino, Venkat Rao Vishnumolakala, Marjan G Zadnik, Anthony D Lucey, and Euan D Lindsay. 2021. Design and validation of an instrument to measure students' interactions and satisfaction in undergraduate chemistry laboratory classes. *Research in Science Education* 51, 4 (2021), 1039–1053. doi:10.1007/s11165-020-09933-x

[23] Frank Wilcoxon. 1992. Individual comparisons by ranking methods. In *Breakthroughs in statistics: Methodology and distribution*. Springer, 196–202.

[24] Kurt Winkelmann, Monica Baloga, Tom Marcinkowski, Christos Giannoulis, George Anquandah, and Peter Cohen. 2015. Improving students' inquiry skills and self-efficacy through research-inspired modules in the general chemistry laboratory. *Journal of Chemical Education* 92, 2 (2015), 247–255. doi:10.1021/ed500218d

[25] Mikołaj P. Woźniak, Adam Lewczuk, Krzysztof Adamkiewicz, Jakub Józiewicz, Maya Malaya, and Piotr Ladonski. 2020. ARchemist: Aiding Experimental Chemistry Education Using Augmented Reality Technology. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–6. doi:10.1145/3334480.3381441