# Effectiveness of Incorporating Inquiry-Based Learning into Pre-Laboratory Exercises

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## Abstract

To incorporate a greater level of inquiry-based learning into our Introduction to Biomaterials course, we have designed several pre-laboratory exercises that not only serve the purpose of familiarizing students with the concepts, equipment, and methods that will be introduced in the laboratory, but also actively engages students in the learning process. Students are presented with a biomaterials problem related to the laboratory activity and are asked to generate knowledge through a scientific literature review, synthesize and interpret their findings, and propose a potential solution to the problem. After receiving instructor's feedback on their proposed ideas, the students implement these ideas in the laboratory exercise. It is hypothesized that this approach allows students to take greater ownership of the laboratory exercises, increases motivation, and allows them to develop a deeper understanding of the concepts taught in the laboratory. Through a student survey, we study the effectiveness of this inquiry-based approach on the learning outcomes and learning experiences of the students. The results of the survey suggest that incorporation of the pre-laboratory activities enhances student learning; however, its effect on student motivation and interest in research is less conclusive.


## Introduction

There has been a focused effort to incorporate inquiry-based learning (IBL) strategies into science and engineering education. These approaches are based on the constructivist theory of learning and involve active, self-directed learning to facilitate the formulation of a solution to a question or problem[1]. By incorporating IBL into the classroom, the course instruction shifts from a traditional lecture-based format where students are passive learners to one where students are actively involved in the pursuit of knowledge. This active engagement has been shown to improve critical thinking, confidence, problem solving, motivation, and student interest in the sciences and engineering[2, 3].

Given the benefits of inquiry-based learning, it has become an integral part of many undergraduate education programs. Courses have been developed that focus on IBL such as the Course-Based Undergraduate Research Experience (CURE) and Process-Oriented Guided Inquiry Learning (POGIL)[2, 4]. IBL has also been incorporated at the programmatic level, where curricula are built around inquiry-based learning techniques[5, 6]. IBL can take on many different forms, ranging from structured approaches, where instructors provide guidance to students as they explore a question or problem, to open inquiry, where students formulate and explore questions on their own with little guidance from instructors[3]. Aditomo et al. further classified IBL by the type of activity: scholarly research, simplified research, literature-based inquiry, discussion-based inquiry, applied research, simulated applied research, enactment of practice, and role playing[1]. Given these various forms of inquiry-based learning, it is reasonable to assume that the outcomes of the IBL approach is highly dependent on how it is implemented in the classroom.

Striking the right balance between providing guidance and allowing students to fully explore an open-ended problem can be challenging given the diverse range of student backgrounds and the available resources. Studies have shown that not all students are equally receptive to the IBL approach, and the transition from passive learning to inquiry learning can be uncomfortable and frustrating for some students since a particular level of guidance from instructors is often expected[3, 7-9]. Furthermore, IBL is often resource intensive[3]. It can require extensive preparation time from instructors to ensure that the necessary structure and guidance is in place to promote self-directed learning[4]. A large number of resources (e.g. equipment, materials, supplies) may also be necessary to allow students to fully explore an open-ended problem. Despite these challenges, there is widespread agreement that learning through inquiry leads to valuable educational gains, such as a deeper understanding and greater retention of knowledge and development of research and professional skills[1].

In an effort to integrate more inquiry-based learning into our Introduction to Biomaterials course, we have designed several pre-laboratory exercises that encourage students to explore a biomaterials problem before tackling that problem in the laboratory. These exercises incorporate both literature-based inquiry and simplified/applied research methods and offer the advantage of not requiring major modifications to the course structure. We evaluated the effectiveness of these IBL activities on the learning outcomes of the students through a student survey that was administered at the end of the course. Although our results are preliminary given the small class size and survey response rate, the survey results suggest that the pre-laboratory exercises were a worthwhile learning experience for the students and deepened their understanding of the course material. The following sections describe these IBL activities and the survey results in more detail.

## Methods

### Course Background

Introduction to Biomaterials is an upper level undergraduate elective course offered at Robert Morris University as part of the requirement for a bachelor of science in general engineering. The course covers the synthesis, characterization, properties, and applications of synthetic and natural biomaterials. It is taught primarily through an on-ground lecture format. The course enrollment is generally less than 15 students, and it is taught in the fall semester of each academic year. Two years ago, several laboratory sessions were added to the course instruction to provide hands-on learning experiences for the students, and along with these labs, two pre-laboratory exercises were added to incorporate inquiry-based learning.

### Implementation of Pre-Laboratory Exercises

The pre-laboratory exercises were designed to give students greater ownership of the experiments conducted in the laboratory session and to further engage the students in the research and design process. Instead of providing the students with step-by-step instructions on how to perform the experiments, the students were required to formulate their own experimental procedure after acquiring knowledge from a literature review. The pre-laboratory exercises were completed as a collaborative team effort in the week preceding the laboratory session. Both of the pre-laboratory exercises followed a similar structure. They incorporated an exploratory phase where students were provided with a biomaterial problem to explore. The students engaged in the research process by performing a scientific literature review, gathering information, synthesizing that information, and finally formulating a solution to the problem. This solution was in the form of a proposed experimental procedure. The pre-laboratory exercise also included a discussion of the expected results from the literature review. Before implementing their proposed methodology in a guided laboratory experiment, students received instructor feedback on their proposal. Using this feedback, they made modifications to their experimental design, and then implemented their ideas in the lab.

One of the pre-laboratory exercises that was incorporated into the course instruction involved the development of an experimental protocol to characterize the critical surface tension of two biomaterials. This surface property plays an important role in material biocompatibility and the adsorption of proteins on the material surface. The students were provided with some background knowledge on surface energy characterization techniques through the lecture material, such as contact angle measurements using the sessile drop, captive bubble, capillary rise, and Wilhelmy plate methods. The students then participated in a guided inquiry activity. The students were asked to design a sessile drop experiment to characterize the critical surface tension of the two biomaterials. They were provided with a list of equipment and materials that had to be incorporated into their experimental design, such as a light source, camera mount, CCD camera, image analysis software, and various liquids with known surface tensions. This requirement was necessary to ensure that their proposed experimental procedure could be performed in the lab. Although a basic background of the sessile drop method was provided in class, the details of the methodology were left for the students to explore. The pre-laboratory exercise was submitted by each lab group in the form of a written report that included a description of the proposed test set-up, the experimental procedure, the analysis method, and expected results based on their scientific literature review. Following the submission of their experimental protocol, the students received feedback on their proposed methodology and re-designed their experiment based on instructor feedback before implementing their protocol in the laboratory.

The second pre-laboratory exercise that was implemented in the course focused on the characterization of the mechanical properties of polyvinyl alcohol (PVA) hydrogels. The students were tasked to develop a PVA hydrogel replacement for degenerated cartilage with a similar compressive stiffness to native cartilage. They were required to research the compressive properties of native cartilage and to study the freeze-thaw method of preparing PVA hydrogels. In this process, PVA is subjected to sequential freezing and thawing periods, which introduces physical cross-links into the molecular structure and alters the mechanical stiffness of the material. The students acquired information about the effect of PVA concentration and the duration/number of freeze-thaw cycles on the mechanical properties of PVA through a scientific literature review, and based on this knowledge, they proposed a freeze-thaw preparation protocol that would produce a hydrogel with similar compressive properties to native cartilage. They submitted a written report of their proposed methodology along with supporting evidence from published studies. Similar to the first pre-laboratory exercise, they received feedback on their proposed methodology before implementing their protocol in the laboratory where they synthesized the PVA samples and measured the compressive stiffness of the samples.

**Assessment Method**

To evaluate the effect of the pre-laboratory exercises on the learning outcomes of the students, a questionnaire was administered to all of the students who were enrolled in the course in the Fall of 2016. The survey was administered online through Google forms after the conclusion of the course. Students were informed about the purpose of the survey, and the survey indicated that their participation was voluntary and their responses would be kept anonymous. Since this course had not been taught in the past with the same labs without the pre-laboratory exercise component, we were unable to compare the class performance to a control group.

The survey consisted of ten statements related to the laboratory exercises and the course learning outcomes. The students were asked to rate each statement on a five point Likert scale (strongly disagree, disagree, neutral, agree, and strongly agree). For each statement, the percentage of students within each rating category was computed. The statements evaluated student perception of the learning process, the learning outcomes, sense of independence and personal ownership, and level of interest in research as a result of the IBL activities. The statements included in the survey are listed below.

- Perception of the learning experience:
    - The pre-laboratory exercises were a worthwhile learning experience.
    - The pre-laboratory exercises challenged me to think more deeply about the subject matter.
    - I found the pre-laboratory exercises to be frustrating.
- Perception of the learning outcomes:
    - The pre-laboratory exercises improved my ability to conduct a scientific literature review.
    - The pre-laboratory exercises improved my understanding of the laboratory material.
    - My learning would have been the same had I not performed the pre-laboratory exercises and step-by-step experimental protocols were directly provided to me.
    - The instructor's feedback on the ideas that I proposed in the pre-laboratory exercises was helpful in improving my understanding of the laboratory material.
- Perception of independence and personal ownership:
    - The pre-laboratory exercises encouraged me to think like an independent researcher.
    - Applying the methods that I proposed in the pre-laboratory exercises gave me a sense of personal achievement.
- Level of interest in research:
    - The pre-laboratory exercises increased my enthusiasm for research.

In addition to rating these ten statements, the survey also included a few open-ended questions that allowed students to provide additional feedback on how the pre-laboratory exercises affected their understanding of the laboratory material and on how the activities could be changed in the future to enhance their learning experience. These open-ended questions provided further insight into the effectiveness of the pre-laboratory exercises.

## Results and Discussion

A total of eight students were enrolled in the course in the Fall of 2016, and five students completed the survey. Preliminary results from the survey are shown in Figure 1. Given the small sample size, more data will need to be collected in future offerings of the course to draw definite conclusions about the impact of the pre-laboratory exercises on student learning. However, these preliminary results provide some initial insight into the effectiveness of these exercises.

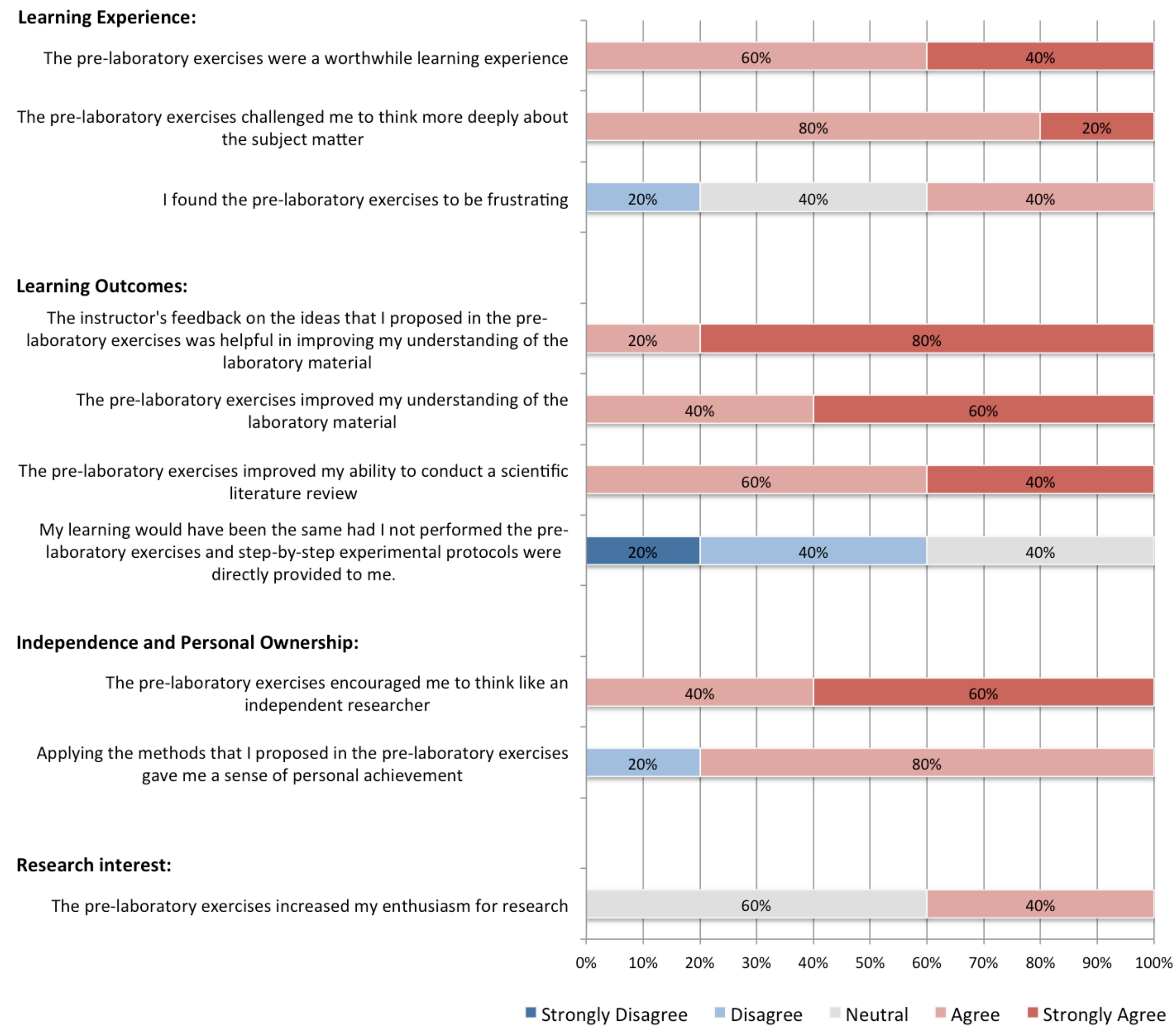


Figure 1. Survey results on student perception of the pre-laboratory exercises. The percentages of students responding in each category are shown for each statement.

In terms of perceived learning outcomes, all of the students who completed the survey indicated that the pre-laboratory exercises improved their understanding of the laboratory material and their ability to conduct a scientific literature review. The survey results also highlight the importance of instructor feedback. The majority of students were in strong agreement that the feedback was helpful in improving their understanding of the material. Student answers to the open-ended question provided further insight into the value of the pre-laboratory exercises:

- "It made it easier to understand the importance of the lab. Plus it helped to have a basis for our own experiments."
- "Challenged me to look up some of the information on my own and understand the scientific literature versus being just handed the information."
- "It helped me understand why certain things were happening and why certain steps had to be done in order for the lab to go correctly."
- "I felt that I got more out of the labs from doing the pre-lab because I was able to relate background knowledge to results obtained in the lab."
- "I think pre-labs are really useful because being able to learn something and then have the lab reinforce that is a pretty cool feeling for students to experience!"

Adding this explorative phase of the cognitive learning cycle and forming a connection between their own research and results of the lab seemed to strengthen student understanding of the course material. Sixty percent of the respondents agreed that their learning would not have been the same if step-by-step experimental protocols were directly provided to them. Forty percent did not have a strong opinion one way or the other. It is unclear whether the same level of learning could have been achieved if the pre-laboratory exercises had not been incorporated into the course instruction; further studies would have to be conducted to assess the role of the pre-laboratory exercises versus the laboratory activity alone on student learning.

In terms of the perceived learning experience of the students and the effect of performing the pre-laboratory exercises on their views of research, the results are more mixed. All of the respondents felt that it was a worthwhile learning experience. They agreed that it challenged them to think more deeply about the subject matter and to think like an independent researcher. However, forty percent of the students also found the pre-laboratory exercises to be frustrating. This frustration has also been seen in other studies of inquiry-based learning[3, 7-9]. One of the students attributed their frustration to having to search for a specific value (i.e. compressive modulus of cartilage) in the literature given the wide range of values available in the scientific literature. The student suggested providing more guidelines on what to search for or providing a range for the expected value. Previous studies have indicated that IBL requires careful scaffolding and guidance to support students through the learning process[10], and in this case, more guidance may have been helpful. Incorporating a class discussion about the expectations of a literature review may have improved the learning experience for the students. It is not uncommon to feel frustration when engaging in the research process. To prevent this frustration from influencing student motivation and confidence, it is important for students to fully understand the goals of a literature review. They must understand that the goal is not to find the "right answer" to a problem, which they are accustomed to in engineering, but to survey the literature to develop an understanding of the knowledge that has been established from previous scientific studies. Based on this knowledge, they can develop their own ideas about the topic and identify areas that need further study.

Overall, 40% of the students who completed the survey indicated that the pre-laboratory exercises increased their enthusiasm for research whereas 60% of the students indicated that it did not have an effect on their enthusiasm for research. It would have also been interesting to assess whether the IBL activities led to a greater appreciation of the research process. While the survey seems to show that the integration of the pre-laboratory activities enhance learning and personal ownership of the lab experiments, the effect on student motivation is not as conclusive due to the increase in frustration and lack of a sense of personal achievement for some students.

## Conclusion

Our preliminary results on the effectiveness of incorporating pre-laboratory exercises on the learning outcomes and learning experiences of students supports our hypothesis that these activities allow students to take greater ownership of the laboratory exercises and to develop a deeper understanding of the concepts taught in the laboratory. These exercises were designed to engage students in inquiry-based learning, and the effect on student learning is in agreement with the published IBL literature[1, 3]. Although the results of this study are promising, further research is necessary to fully understand the benefits of these activities and to enhance the learning experience of students. A major challenge with inquiry-based learning methods is providing an opportunity for students to openly explore a problem and take increasing responsibility for their learning without increasing levels of anxiety and frustration. Although the pre-laboratory exercises were intended to be a low stakes assignment in the course, the open nature of the assignment still led to frustration for some of the students. In the future, strategies should be implemented to reduce these levels of frustration, such as providing more guidance on how to perform a literature review and explaining the expectations for the literature survey. Despite these needs for improvement, the implementation of these pre-laboratory exercises in the Introduction to Biomaterials course proved to be an effective way to incorporate inquiry-based learning into a course with a laboratory component without having to make major modifications to the course structure.

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## Appendix A:

### ENGR4510 – Survey on Effectiveness of Pre-Laboratory Exercises

By completing the following survey, you are granting consent for this information to be used as part of a research study on the effectiveness of pre-laboratory exercises, which has been approved by the Robert Morris University's Institutional Review Board (irb@rmu.edu, 412-397-6227). Your participation is voluntary, and you may choose not to answer any of the questions. You may also withdraw from the study at any time. Your responses will be kept anonymous (your responses will not be identifiable in any way). If you have any questions regarding your participation in this study, please contact Rika Carlsen (carlsen@rmu.edu, 412-397-3531).

**Instructions:**
In this course, we conducted two pre-laboratory exercises prior to performing laboratory experiments. The first pre-laboratory exercise involved designing an experiment that characterized the surface energy of polystyrene (PS) and polytetrafluoroethylene (PTFE). In the second pre-laboratory exercise, a protocol was developed for preparing polyvinyl alcohol (PVA) hydrogels that matched the compressive properties of native cartilage. Based on your experiences with these pre-laboratory exercises, please indicate your degree of agreement with the following statements.

| | | Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree |
|---|---|---|---|---|---|---|
| 1 | The pre-laboratory exercises improved my ability to conduct a scientific literature review. | | | | | |
| 2 | The pre-laboratory exercises improved my understanding of the laboratory material. | | | | | |
| 3 | The instructor's feedback on the ideas that I proposed in the pre-laboratory exercises was helpful in improving my understanding of the laboratory material. | | | | | |
| 4 | My learning would have been the same had I not performed the pre-laboratory exercises and step-by-step experimental protocols were directly provided to me. | | | | | |
| 5 | The pre-laboratory exercises challenged me to think more deeply about the subject matter. | | | | | |
| 6 | The pre-laboratory exercises increased my enthusiasm for research. | | | | | |
| 7 | I found the pre-laboratory exercises to be frustrating. | | | | | |
| 8 | The pre-laboratory exercises encouraged me to think like an independent researcher. | | | | | |
| 9 | Applying the methods that I proposed in the pre-laboratory exercises gave me a sense of personal achievement. | | | | | |
| 10 | The pre-laboratory exercises were a worthwhile learning experience. | | | | | |

**Additional Questions:**

How did the pre-laboratory exercises affect your understanding of the material taught in the lab?

How could the pre-laboratory exercises or laboratory experiments be changed to enhance your learning experience?

Any other comments?

## Appendix B:

# ENGR 4510 – Introduction to Biomaterials
Lab #1: Surface Energy Characterization

**Learning Objectives:**

- Understand the fundamental principles of hydrophobic/hydrophilic surfaces and surface energy/tension
- Demonstrate an ability to integrate knowledge from a literature review and apply that knowledge to design an experiment
- Design and conduct experiments that apply the sessile drop technique to characterize the critical surface tension of materials
- Learn and apply image analysis methods for measuring contact angles

**Equipment & Materials:**

- Camera mount & sample platform – includes aluminum breadboard, optical posts with mounting bases, lens mounting clamp, sample platform, cap screws
- Olympus DP26 camera
- Intralux 5100 light source
- Tracing paper
- Pipettors (1 μL – 1000 μL)
- Glass microscope slides
- Probe liquids:
    - **White vinegar**, Surface tension: 56 dynes/cm
    - **Olive oil,** Surface tension: 33.5 dynes/cm
    - **Whole milk**, Surface tension: 48 dynes/cm
    - **99% Isopropyl alcohol**, Surface tension: 22 dynes/cm
- Materials to be tested:
    - **Polystyrene (PS)**
    - **Polytetrafluoroethylene (PTFE) film**

**Software**

- ImageJ - open source software developed by the National Institutes of Health
- Drop Analysis Plug-in – open source plugin developed by École polytechnique fédérale de Lausanne (EPFL)

**Pre-Lab Assignment:**

- **Goal:** Design an experiment that characterizes the surface energy/tension of PS and PTFE samples using the equipment and materials listed above. The experiment should utilize the sessile drop method, where the contact angle of a droplet of liquid is measured.
- **Research** the sessile drop method, contact goniometers, and surface energy analysis methods (e.g. Zisman method) to obtain the necessary background knowledge to design your experiment.
- **Submit** a write-up of the experimental methods, analysis procedure, and the expected results.
    - Describe the testing set-up (e.g. liquid drop volume, placement of the light source, sample size, etc.)
    - Describe the analysis procedure (i.e. required calculations to determine the critical surface tension of the materials). Note that ImageJ software will be used to measure the contact angle from images of the liquid drops.
    - Describe the expected results based on literature values of the critical surface tension of PS and PTFE.
    - Cite all sources in your write-up and include a list your references (any standard reference citation style may be used)
- **Re-design** your experiment based on instructor feedback.

# Appendix C:

## ENGR 4510 – Introduction to Biomaterials

Lab #2: Hydrogels for Cartilage Replacement

**Learning Objectives:**

- Develop an understanding of structure-property relationships of hydrogels
- Demonstrate an ability to integrate knowledge from a literature review and apply that knowledge to define design parameters to meet a specified need
- Demonstrate an ability to define the mechanical properties of a biomaterial by assessing mechanical characterization data
- Evaluate the ability of a biomaterial to meet a functional need

**Material:**

- Poly(vinyl alcohol), PVA (61,000 g/mol, Sigma Aldrich, Mowiol 10-98)

**Pre-Lab Assignment:**

- **Goal:** You have been tasked to develop a hydrogel replacement for degenerated cartilage (e.g. degenerative meniscus). You must develop a procedure for preparing PVA hydrogels that have a similar mechanical *compressive* stiffness to native cartilage.
- **Research** the mechanical properties of native cartilage from the literature. In addition, learn about the freeze-thaw method of preparing PVA hydrogels. Review scientific papers that have analyzed the effect of PVA concentration, duration and number of freeze-thaw cycles on the mechanical properties of PVA hydrogels. Use this information to define the appropriate PVA concentration and duration/number of freeze-thaw cycles necessary to produce hydrogels that have a similar mechanical behavior (in compression) to native cartilage.
- **Submit** a short write-up that includes the following:
    - Report the value of the unconfined compressive modulus of native cartilage (using scientific literature sources)
    - Explain how freeze/thaw cycles contribute to the strengthening of PVA
    - Propose a PVA concentration (%w/v) and duration/number of freeze-thaw cycles that will produce hydrogels with a similar compressive stiffness to native cartilage. Briefly discuss the scientific studies that you are using as the basis of your proposal.
    - Discuss the expected compressive stiffness of the PVA hydrogels prepared using your method
    - All sources must be peer-reviewed scientific publications. In-text citations and a list of references must be included in your write-up (any standard reference citation style may be used).
- **Next lab**: You will synthesize PVA hydrogels using your proposed methodology and measure the mechanical properties of the hydrogels.