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Fostering STEM competency in high-school students by bridging engineering and ophthalmology through eye research

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ABSTRACT

Recent data across the globe indicates a decline in stem competency among secondary education students. Despite persistent interest in STEM fields this decrease in preparedness could yield detrimental effects for both future scientists and engineers. To address this current trend, a collaborative partnership between a university and high school commenced. The goal was to create an advanced experiential engineering course focused primarily on ophthalmology principles, research, and hands-on solutions. Twenty-one high school students (grades 9-12) enrolled in the course. Their objective was to investigate research questions involving ocular physiology. These ranged from surveying intraocular pressure measurement methods, examining the nature of vitreous humor properties, and investigating the inherent connection between blood flow and fluid dynamics. Furthermore, students engaged in hands-on experimentation that resulted in a hydraulics-based model which attempted to link the correlation between blood pressure and intraocular pressure involved in glaucoma progression. Post-course interviews revealed three major themes: i) an increased appreciation for the utility of mathematics and its real-world use; ii) the importance of the mentor-mentee relationship and professional networking; and iii) increased access to resources beyond what is traditionally found in a high school classroom. These findings suggest that incorporating research into a high school classroom can foster positive outcomes and spark students' interest in ophthalmology research and in STEM more broadly. This course can serve as a model in future development of project-based engineering curriculum and help broaden participation in STEM.

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Introduction

Post-COVID-19, secondary education schools across the country have reported declines in reading comprehension (Kuhfeld *et al*., 2023) and mathematical proficiency (Institute of Education Sciences, National Center for Education Statistics, 2023; Sattem *et al*., 2022). The most recent Programme for International Student Assessment (PISA) illustrated significant declines in mathematics performance from 2018 to 2022 for several countries including the United States, Germany and Italy, indicating that reduced proficiency in science, technology, engineering and mathematics (STEM) education is a global concern (Institute of Education Sciences, National Center for Education Statistics, 2023).

While a general decline in STEM competencies affects the population at large, perhaps more worrisome are the detrimental effects on training of future engineers and scientists. These deficits are particularly concerning for future engineers, as the lack of high school math and science preparation leaves first-year engineering majors facing significant academic challenges (Wormley, 2003). Lack of STEM preparedness threatens to hinder essential foundational knowledge, emphasizing the need for targeted educational interventions to support the next generation of engineering professionals.

The future workforce requires STEM education to be strengthened globally to face the unprecedented societal, environmental and economic challenges of modern society (OECD, 2019). As such, the OECD has indicated innovation as a key transformative competency that should be prioritized worldwide (OECD, 2019), making it critical to support STEM education to meet this goal. This may require targeted educational efforts designed to bridge gaps between K-12 schools and universities (Wormley, 2003).

Pre-engineering coursework and experiential learning opportunities can be created AS a novel approach to foster positive student outcomes (Fantz *et al*., 2011; Long *et al*., 2020; Phelps *et al*., 2018; Zeid *et al*., 2014). Specifically, experiential learning in K-12 settings can increase interest in STEM careers (Long et *al*., 2020) and promote STEM content learning (Zeid *et al*., 2014). Advanced pre-engineering courses in high school can foster self-efficacy (Fantz *et al*., 2011), which plays a crucial role in whether a student pursues a STEM major (Sahin *et al*., 2011). Teaching practices which allow students to collaborate, think outside the box, and apply their learning to real-world scenarios have also been shown to be critical educational components (OECD, 2019).

To address these unmet needs a partnership between university and high school faculty and students was formed to develop an advanced experiential engineering course for high school students. The course engaged high school students in hands-on, discovery-driven learning on topics that are still active areas of research. Specifically, engineering and ophthalmology research were bridged to foster critical thinking through cutting-edge research applications in the discipline to provide real-world solutions to current clinical challenges and identify the next steps for the future generations.

Table 1. Course enrollment.

Grade	Number of students
9	5
10	5
11	10
12	1

Methods

Needs assessment

Our general needs assessment highlighted the decline in STEM competencies among secondary education students. This general deficiency has significant downstream effects, particularly for the future engineering and science workforce. Without an adequate STEM foundation in secondary education, students enter higher education unprepared, creating challenges for both learners and educators. This targeted need highlights the importance of bolstering STEM preparedness in order to ensure a capable workforce of scientists and engineers. Our general and targeted needs assessment directly informed the redesign of the course which is the focus of this study.

Study context, goals, and objectives

The content of Engineering I (John Bapst Memorial High School, ME, USA) was redesigned to teach engineering design process, documentation, modeling, research techniques, and iteration by addressing cutting-edge research questions in ophthalmology. The course learning objectives were designed to ignite curiosity in understanding how complex systems work (within the eye) and experience how mathematics and engineering can be used to gain such understanding. The specific learning objectives for the course are listed below:

i) Describe the anatomical structure and functions of the eye.
ii) Understand the fundamental biological principles related to fluid dynamics and pressure in a biological system.
iii) Understand how physical models can relate to biological systems.
iv) Understand how to interpret research and conceptual frameworks in an engineering exploration and exercise.
v) Develop an appreciation for the use of software and computational aids in developing models and conceptual frameworks for model development and simulation.
vi) Construct physical models that represent the blood vessel network within the eye.
vii) Develop an understanding of how engineering simulations and models can help us to better understand the potential health implications of specific circumstances in an analogous biological system.
viii) Collaborate effectively in teams and learn to break down tasks in a way that leverages resources available within that team.
ix) Communicate technical ideas and findings through written reports, diagrams, oral presentations, and visual aids.

Multi-grade classrooms are common in the United States K-12 system for classes that are considered elective. This particular course, Engineering I, allowed students of any grade level to participate and had at least one student enrolled from each grade (Table 1), though it was majority grade eleven students.

Educational strategies

To meet the learning outcomes of the course, the instructor implemented inquiry-based, experiential learning, meaning that projects were hands-on and led by students' own interests. Starting from common reading and discussion of published research articles, students were prompted to identify interesting engineering questions within the field, formulate the problem statement, design experiments and protocols to investigate the problem, iterate to fine-tune the strategy, and present the process and the results in a professional manner to the entire team.

Any students willing to continue their research after the course concluded had access to resources and mechanical engineering laboratories at the University of Maine. This allowed for students to conduct hands-on research outside of the classroom and work closely with university faculty and graduate students. Three students opted to continue with the help of their high school teacher, as well as students and faculty at the Maine College of Engineering and Computing.

Implementation

The 21 students (Table 1) were divided into 6 groups with 3-5 students per group. Examples of the themes and questions identified and explored by the individual groups are listed below.

Group 1: This group focused on the importance of intraocular pressure (IOP) with respect to ocular function in health and disease. The group explored the available methods to measure intraocular pressure, and questioned their advantages, limitations, and overall accuracy. The group studied Goldmann tonometry that is used to measure IOP (Stevens, 2007) and the associated Goldmann equation (Brubaker, 2004), but proposed to test and compare various methods using a 3D printed eye.

Group 2: This group focused on the role of the vitreous humor, the clear gel that fills the space between the lens and the retina in the human eye. Specifically, this group researched what is known about the material properties of the vitreous, how they are measured, and how they are seen to change with age and disease.

Group 3: This group utilized a published circuit (Guidoboni, 2014) depicting a correlation between the vascular network supplying the eye and its properties on a circuit diagram. Specifically, the blood flow (i.e., current) into the central retinal artery (CRA) and out through the central retinal vein (CRV) were studied as different resistors were placed throughout the layers of the eye to represent real-time blood pressure variations. Group 3 used a breadboard with resistors and studied the effects of differing resistance values and its subsequent effect on current through the circuit. This experimental apparatus enabled students to observe that the blood flow through a vessel is directly decreased if resistance is increased. This is a key pathophysiological mechanism observed in glaucoma diagnosis and progression.

Group 4: This group focused on the combined effects of IOP and blood pressure (BP) on the retinal hemodynamics. This was driven by the therapeutic approaches in glaucoma management primarily focusing on lowering of the IOP despite vascular risk including BP being well-established risk factors for the disease (Harris, 2020). Group 4 built a hydraulic circuit to explore the combined effect of IOP and BP on the blood flow in the eye, the details of which can be found in Section 3.1 below. This group consisted of three students, E. Marquis, L. Hart, and G. Aulisa, who are also co-authors of this article.

Evaluation

Upon completion of the project the students and their high school teacher presented their outcomes at the 2024 international Annual Meeting of the Association for Research in Vision and Ophthalmology (Murphy, 2024), and participated in public interviews with local news stations including Maine News Center (Delaney, 2024) and WABI (Magliozzi, 2024) where they discussed their project and how they benefited from conducting research. The three students who opted to continue with the research project after the conclusion of the course voluntarily participated in interviews. The public interviews were qualitatively analyzed to better understand how students' STEM competencies evolved and to capture the academic benefits they reported. We utilized thematic analysis (Braun and Clark, 2006) which involved an iterative process of repeatedly reviewing the interview transcripts to gain familiarity, generating notes regarding any responses relevant to STEM competencies or academic benefits, and coding line-by-line. Related codes were assembled into provisional themes, which were next reviewed, refined, and clearly labeled. The themes that emerged from these interviews are discussed in the results section.

Results

Hydraulic circuit project results

Driven to understand the interplay between IOP and BP, and their combined effects on the retinal vasculature, students in Group 4 formulated ideas to replicate different blood vessels in the eye. The circuit was built and tested in the Mechanical Engineering labs of the Maine College of Engineering and Computing (University of Maine, Orono, ME).

The close-looped circuit consisted of a pump, a flowmeter and a valve, with a pressure sensor on either side of the valve, as schematized in Figure 1. The pump was controlled by an Arduino connected to a computer, with a 12V battery serving as its power source. A second Arduino, also connected to the computer, interfaced with the pressure sensor to record pressure data as the valve was adjusted to different levels of closure. Adjusting the valve created varying resistances, simulating the effect that different IOP levels exert on ocular blood vessels.

Pressure sensor readings collected for fully open (Figure 2a) and partially closed (Figure 2b) valve under a sinusoidal input were recorded and plotted. When the valve is partially closed, the pressure upstream of the valve increases (Pa, red curve), while the pressure downstream of the valve decreases (Pb, black curve). This experiment showed that pressure may rise upstream of an obstruction, possibly leading to bursting of blood vessels and hemorrhages.

The students also proposed future improvements to enhance their projects. For the hydraulic circuit, this involved redesigning the system to include a shunt (Figure 3a), allowing fluid a new path as resistance increases. Additionally, they aimed to improve the simulation of IOP by integrating a pressure chamber into the setup (Figure 3b).

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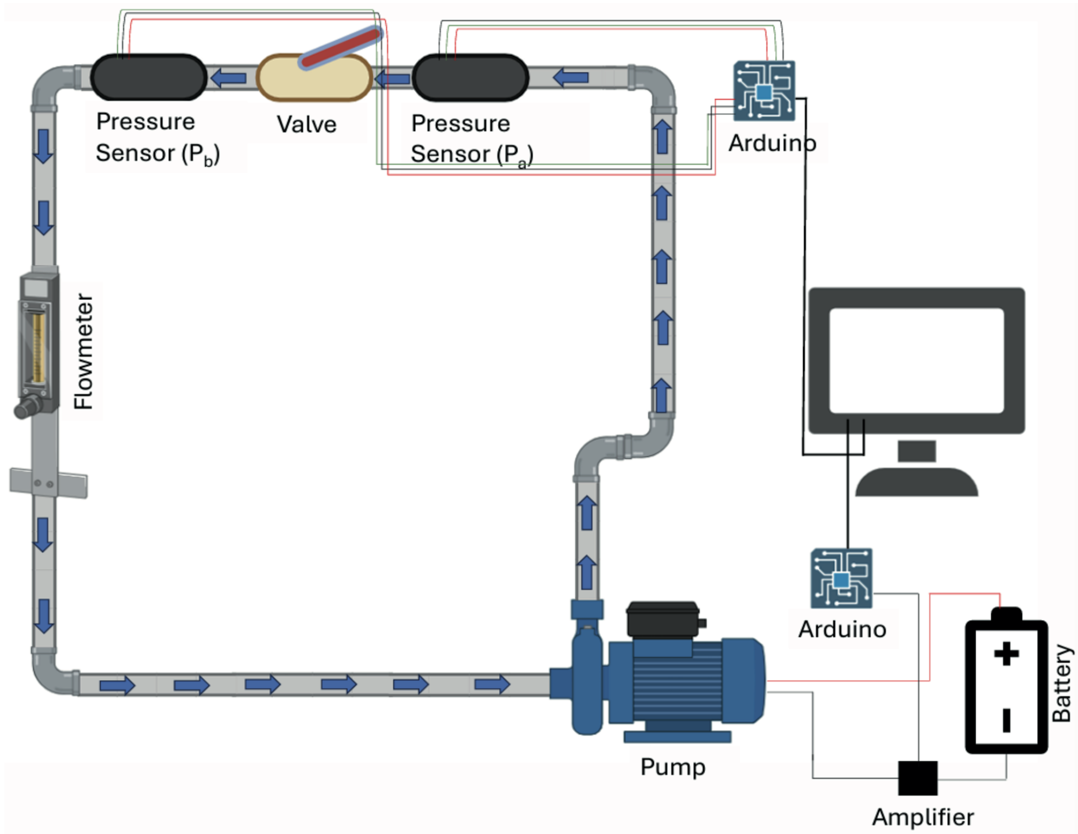

Figure 1. Schematic of the hydraulic circuit representing blood flow in the retinal vasculature.

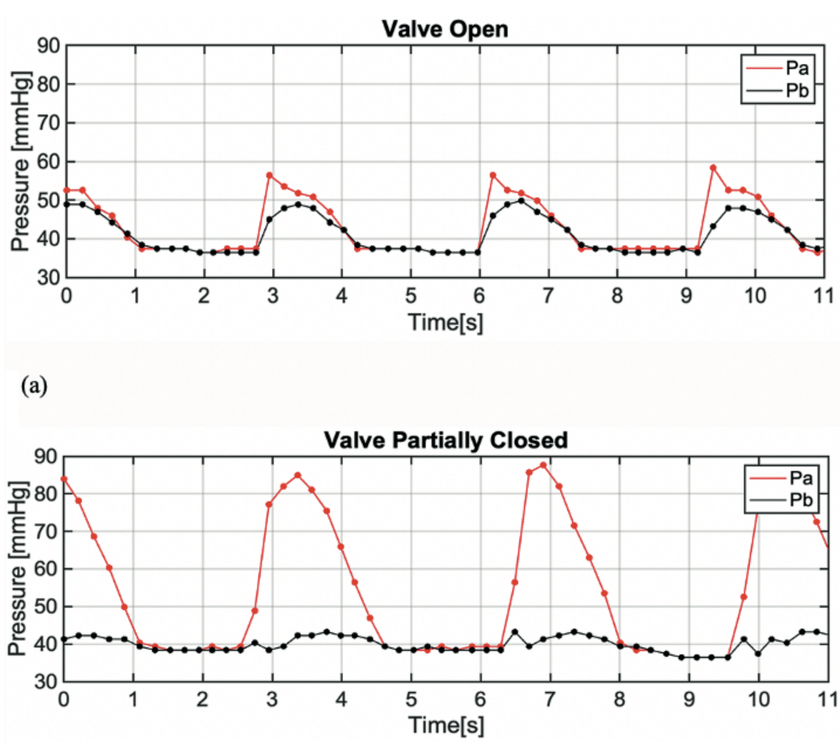

Figure 2. Pressure sensor readings obtained from the hydraulic circuit with valve (a) fully open (no resistance) and (b) partially closed (some resistance applied).

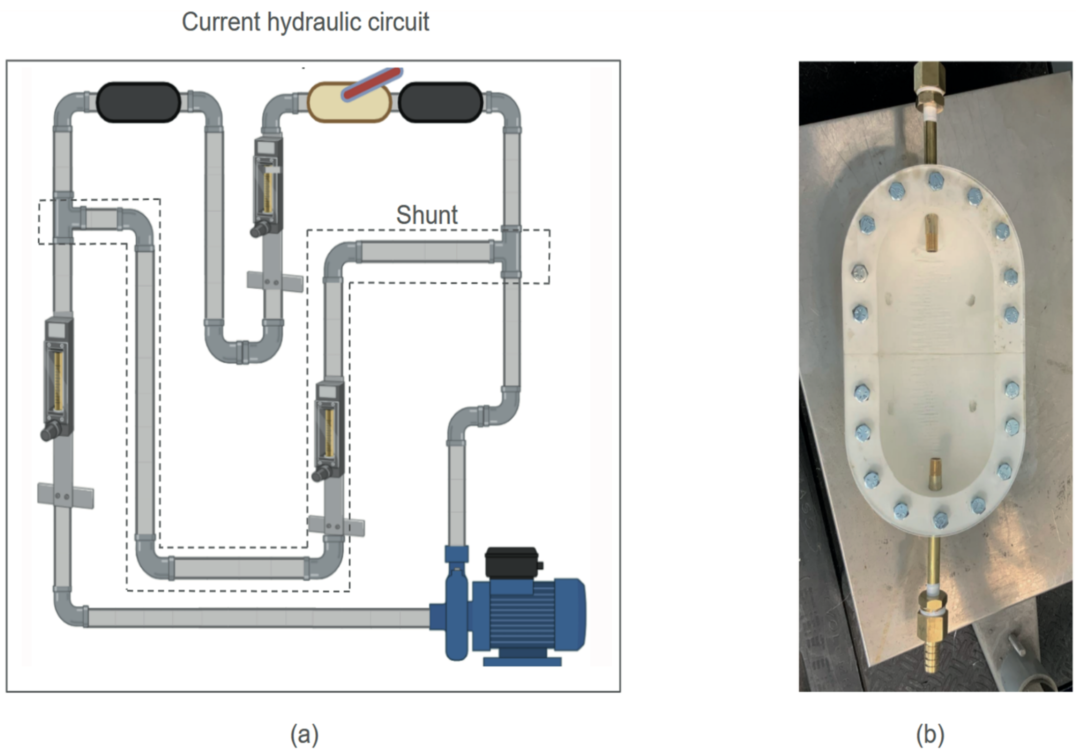

Figure 3. Plans for modifications to the hydraulic circuit by (a) addition of a shunt and (b) incorporating a pressure chamber for tubes representing blood vessels to pass through.

Student outcomes

High school students reported several key benefits stemming from the research project. Specifically, we highlight three major themes that were revealed during the public interviews (Delaney; Magliozzi, 2024): i) utility of math, ii) mentorship and networking opportunities, and iii) increased access to resources.

Utility of math

The students gained real-world engineering experience which prompted them to reflect on the usefulness of math for problem solving and their future careers. One student conveyed excitement about math as a real-world problem solving tool:

> *"It's [math] for solving real world problems, which is the best thing in the world."* (Giuseppe)

Another student expressed interest in continuing the research project, particularly because it would benefit his future:

> *"Once we did more research and we found topics that interested us, we decided we want to pursue it further because we thought that this could benefit us in the future."* (Ethan)

This student intends to pursue a degree in biomedical engineering, and benefited from the opportunity to "*be an engineer*" through the research*:*

> *"Getting to really be an engineer and do high-level engineering in high school gives me a greater look at what I'll hopefully be doing in the future."* (Logan)

Mentorship and networking

Students also benefited from the mentorship they received from faculty and graduate students at the university. One student noted his appreciation for their expertise:

> *"... we can learn something from ... professors who know quite a bit more than us. So, that was also super cool to do."* (Ethan)

The students emphasized how the mentors assisted in their personal and professional development:

> *"[The professor and graduate student mentors] are both great mathematicians, and I know some of the equations I do are way outside of my expertise, but I think working with them, not only will I learn on a personal level about how to do this math in my future but also learn how to apply it to real world situations."* (Giuseppe)

Furthermore, networking with other professionals while presenting at a conference was a particularly impactful experience for one student:

> *"The experience was amazing; there were so many intelligent people. Speaking with those people just took our knowledge to the next level and also gave us more ideas to do with our project."* (Logan)

Access to resources

Finally, students gained access to resources that helped them advance their project. The students were given increased access to materials, equipment, and lab space that would have otherwise

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not been available to them. For example, one student highlighted that they were able to access materials that were not available or limited at their high school:

> "*It's been amazing, the people that we've been given access to are so intelligent, so kind, and so smart. And we've been given access to more materials here at [university name] greater than at our high school, and it's just been really great working with them."* (Logan)

Students were also exposed to academic journals and papers that high school students don't typically engage with. Their instructor observed:

> "*The kids were able to read academic papers that are probably about eight years beyond their current education level*." (Mike)

Discussion

Bridging the span of science from academic discovery to medical intervention are our students, the next engineers and modern-day problem solvers. Through study of the eye and development of models consistent with the properties of the ocular system, students here developed significant appreciation for and knowledge of the anatomy and physiology of the human eye and its impact on human lives. Student learning was driven by their curiosity for real world problems, and this yielded a higher level of engagement and ownership than previous years. In addition, students have been exposed to peer reviewed research, learning how to read and decipher work that is years ahead of their educational level. Intentionally integrating engineering and ophthalmology may help excite the next generation of scientists and clinicians who will be able to work collaboratively to advance disease diagnostics and ultimately cures. This is particularly relevant in the field of ophthalmology, as projections based on data from the Department of Health Resources and Services Administration (HRSA) forecasts it is one of the medical specialties with the lowest rate of projected workforce adequacy by 2035 including major geographic disparities (Berkowitz, 2023). Thus, it's essential to develop intentional approaches to broaden and diversify access to STEM and ophthalmology education and research, as well as inspiring young minds to join the field.

This project helped bridge a critical gap between a local high school and the University of Maine, which is an important step in promoting student success during the transition to college. Many universities aim to improve first-year student success and retention by engaging with students early on, often through high impact teaching practices such as undergraduate research (Kuh, 2008). One such effort at the University of Maine is the Research Learning Experience (RLE) program which engages first-year students in authentic, hands-on research in small cohorts to foster research self-efficacy and belonging (White *et al*., 2025). For example, first-year engineering students have the opportunity to join *Charismathic,* an RLE that invites students to explore how mathematics can be applied to real-world problems ranging from climate change to healthcare. Since its pilot in 2021, UMaine's RLE initiative has expanded significantly, growing from approximately 200 first-year students to currently serving over 1,000 first-year students (Internal Dashboard, University of Maine, *unpublished internal data* 2025), highlighting the interest and need for increasing access to early research experiences.

This course was particularly unique in that all grade levels enrolled and participated. For other K-12 systems outside of the United States it may not be possible to create multi-grade classrooms. However, similar activities and programs can be conducted as after-school programs, particularly if paired with motivated university faculty and researchers who seek to shape the future of STEM.

It is important to emphasize that identifying interesting areas of study and formulating specific research questions was done independently by each student group. Deciding what to study and what to focus on are crucial and non-trivial endeavors, even for established researchers. These high school students explored the anatomy and physiology of the eye driven by their curiosity, constantly asking questions and looking for answers, while stumbling on major open research areas along the way. This, per se, is a major accomplishment as the eye represents the one of the greatest challenges to model in medicine as the organ has the highest metabolism and perhaps most complex fluid dynamics of any major body organ.

These findings are based on a small sample (n=3) which limits generalizability. These students were not randomly selected but instead were members of one of the groups that opted to continue their research after the class concluded. Data were descriptive in nature rather than, for example, based on standardized pre-post assessments. Future research should utilize standardized, validated measures of student learning in order to better understand outcomes.

Conclusions

In summary, hands-on research experience with university mentors helped the students link classroom mathematics to real-world engineering challenges, build early professional networks, and work with laboratory equipment and literature beyond what is typically available to high school students. These results suggest that similar school-university partnerships may be a practical way to broaden participation in STEM, especially in areas with high projected demand. Future iterations should also include formal assessment of learning outcomes to strengthen the evidence.

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