

Inquire and engage: getting college students to learn about electromagnetic waves and quantum physics with photonics-based Nobel prizes

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Abstract. To engage college students with electromagnetic waves and quantum physics, connecting course content to their everyday lives and to promote “photonics awareness,” a 12-week group research project on a photonics-based Nobel prize was developed. The project uses an inquiry-based approach and is designed as a five-part activity, each with a specific scaffold helping guide students regulate their inquiry. © *The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: [10.1117/1.OE.61.8.081805](https://doi.org/10.1117/1.OE.61.8.081805)]

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1 Introduction

Learning about electromagnetic waves and quantum physics is a challenging endeavor for many college science students. Connecting the class content to their everyday lives and to their future careers is not completely obvious. Furthermore, when surveyed and asked, “Do you know what photonics is? If yes, describe it,” 92% of 113 Vanier College students do not know what photonics is or cannot describe it correctly on the first day of their Waves and Modern Physics class. This situation needs to be addressed—not only is photonics a central concept that encompasses much of the course content but it is also ubiquitous in everyday life. Therefore, to engage the college students with course content, connecting it to their everyday lives and to promote “photonics awareness,” a group research project on a photonics-based Nobel prize was developed.

The project is set in a Québec (Canada) college-level Waves and Modern Physics course taken by all students pursuing studies in the natural sciences (including health science and pure and applied science).¹ This course is equivalent to a freshman-year physics course elsewhere in North America. A semester is 15 weeks, with 5 h of class time per week—3 h for lecturing and active learning activities, and 2 h for laboratory experiments, demonstrations, and tutorials. Typical class sizes range in between 30 and 40 students. All colleges in Québec share the same general framework for the Waves and Modern Physics course, which dictates the specific course content. It includes kinematics and dynamics of vibrations; longitudinal and transverse waves; progressive and stationary waves, resonance; sound waves; geometric and physical optics (which includes interference and diffraction of light); and elements of modern physics (which can include special relativity, quantum physics, and/or nuclear physics). Geometric and physical optics and quantum physics are the content that link to photonics, and hence, are relevant to a chosen Nobel prize.

Since there is no specific reference to which elements (or topics) of modern physics must be presented in class, the different college physics departments and their teachers can choose what elements to present and assess in class. In the context of the project to be described, teachers can even allow for groups of students to engage with different elements of modern physics,

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thus, for this project, allowing students to choose what elements of quantum physics they wish to engage with.

The project uses an inquiry-based (IB) approach. That is, students choose the Nobel prize of interest, the questions to investigate (i.e., the research questions), the elements of the Nobel prize to present to classmates, and their final presentation style. The project is designed as a five-part activity, each with a specific scaffold, including individual and group worksheets, and a final presentation assessment rubric. These scaffolds guide students to regulate their inquiry, stay organized and on-task, and manage the time constraints (i.e., timeline). The final presentation assessment rubric supports the students' capacity to evaluate the quality of their work before submitting the final product. Teacher feedback, which is also a scaffold for students, is provided at the end of each step and students are encouraged to seek help and advice when necessary. This allows the students to engage with, and even go deeper, with electromagnetic waves and quantum physics content that is typically more challenging to teach, and understand, than in a regular freshman college classroom setting.

IB instruction in the field of optics and/or photonics education have been reported for high school² and community college³ laboratory contexts. In each example, a series of standalone IB activities was developed. The novelty of what we present is how the scaffolding in the inquiry can foster both individual and group engagement with complex ideas related to electromagnetic waves and quantum physics in a multiweek project. A background on IB instruction and the use of scaffolds to help guide the inquiry is provided in Sec. 2. Section 3 presents the group research project, including the timeline, the student and group tasks, the scaffolds provided, and the deliverables for each part of the project. Last, in Sec. 4, we discuss the quality of the final presentations and the student learning reflections.

2 Inquiry-Based Instruction and the Use of Scaffolds

2.1 *Inquiry-Based Instruction as a Student-Centered Active Learning Technique*

Empirical studies of implementations of student-centered active learning approaches show benefits such as increases in learning and reduced dropout rates.⁴⁻⁶ Research shows that student-centered active learning approaches encourage students to take on a more meaningful approach to learning, with implications on strategies used in the process of knowledge construction.⁷ Typically, this is because such instruction focuses on deep approaches versus surface approaches.^{8,9} In addition, active learning approaches positively impact students' attitudes and motivation toward learning.^{10,11} It has been shown to have positive influences on students' self-efficacy particularly as it relates to gender differences and minoritized individuals in STEM.¹² This said, we caution that this field of study contains conflicting results primarily because of the differences in the contexts and descriptions of active learning. Our efforts here are to help start the process of clarifying and identifying what are the key elements in one of the approaches, that is, IB instruction.

IB instruction is situated within the context of investigating authentic problems.¹³⁻¹⁸ It promotes the use of high-level cognitive skills—analysis, decision-making, and evaluation—and scientific thinking, including the importance of rigor, reliability, and use of evidence to justify claims. IB is distinct from discovery learning in that guidance, also known as scaffolding, is a critical and essential component of the instructional approach.¹⁹ Supporting learners' management of the inquiry and decision-making, scaffolds are strategically built into the lesson activities.²⁰ Meanwhile, just-in-time scaffolds provided by teachers' feedback, *in situ*, regulate, and keep the learning on track. Like problem-based learning (PBL, e.g., Refs. 21 and 22), IB can be classified as a type of active learning that is grounded in sociocognitive and sociocultural theories of learning.²³ We elaborate briefly on what this means.

Growing out of the fields of educational psychology, cognitive sciences, and learning sciences, sociocognitive and sociocultural models describe how knowledge construction and learning are social processes, these include situated cognition,²⁴⁻²⁶ distributed cognition,^{27,28} and group cognition.²⁹ These paradigms view learning as a process mediated by social interactions

(e.g., Refs. 25, 26, and 30). Knowledge and knowing are highly dependent on content and context.^{24,31} Furthermore, the theory of situated cognition informs us about the process of learning and highlights the need for learning activities to be contextualized and embedded in authentic activity—i.e., realistic and/or typical to the domain. For instance, learning physics is more than mere concepts, it is also learning about the discipline's practices and the epistemology embedded in its inscriptions and tools.

The goal of instruction, therefore, should not only be cognitive development, but it should also be to familiarize students with the language, tools, norms, and standards of a discipline. In a way, this means students become members of a discipline's community as they engage in authentic activity—i.e., their thinking and understanding of the concepts, tools, and traditions is shaped.^{32,33}

This social paradigm relies heavily on forms of group work that fall into two categories: collaborative learning³⁴ and cooperative learning.³⁵ While there are differences between these approaches,³⁶ they both foster the students' use of disciplinary knowledge. In addition, they both provide students to work within a setting that has been referred to as a zone of proximal development,³⁰ which defines the working limits of a student's capabilities and knowledge. On one side of this zone, students are capable of working on their own, within this zone students need support of an adult or a more knowledgeable other, and beyond this zone students are lost even with help. Research shows that when students are given the opportunity to work together, with targeted scaffolding and group organization, their learning outcomes are increased, and the quality of that learning is richer.³⁵

2.2 Scaffolds

Scaffolding involves supporting the learner to complete a task or achieve a goal they are not yet capable of doing on their own without assistance. Originally identified as ways the adult or expert helps children solve complex problems,³⁷ it has come to describe the support of learning at all levels. Scaffolds reduce the cognitive load of complex tasks, thereby allowing the novices to concentrate on elements of the task that are within their reach. As such, it is closely associated with ideas of the zone of proximal development described earlier. Instructional scaffolds aim to offer types of support that fall into categories, such as focusing the learner, simplifying the task by reducing the degrees of freedom, managing task frustration, guiding competition by highlighting critical problem features, demonstrating or models ideal solutions, etc.³⁷ Originally, scaffolds referred to human tutors, however, the metaphor now extends to tools, resources, and even curricula that include strategies that make thinking visible.³⁸ Thus, scaffolds can be such things as worksheets, templates, and rubrics,³⁹ and as well as the designed technological resources (i.e., software) embedded into instruction to pace and prompt (i.e., scripts) the learning.⁴⁰ Because scaffolds are intended to be removed, known as fading, learners should be made aware explicitly of the role they play and what aspects of the learning they support. As such, the removal of scaffolds is associated with the development of the learners' self-regulation skills as their capacity to take on more responsibility for their knowledge acquisition and task completion.

3 Project Timeline, Tasks, and Deliverables

What follows is the description of the project based on IB instruction and its use of scaffolds. [Note that all materials produced by the authors (i.e., the scaffolds, including individual and group worksheets, and the final presentation assessment rubric) are available for sharing. The materials can be tailored by other teachers to fit their course content and learning objectives. Please contact the lead author. However, since students did not sign consent forms, the authors cannot share any of the student work or final presentations.] The project can be implemented in different teaching modalities. The first iteration of the project began in a prepandemic, in-person setting that transitioned into a fully online, asynchronous setting after the mid-term break (winter 2020 semester). The following two iterations of the project were done completely in an online setting (fall 2020 and winter 2021 semesters). Much of the work was done asynchronously as

homework, but some of the work was done synchronously online during class (e.g., weekly group meetings and Q&A with the teacher). Students were provided with an online group space for video conferencing and document sharing. To respect the ponderation and the general framework of the course, some of the synchronous meetings were done during lab periods (eliminating some lab experiments) and the final presentation replaced two full lab reports.

The project overview, as shown in Fig. 1, is first presented to the class. Students are informed of the multiple parts, the timeline, the individual and group tasks, and deliverables, and the final presentation assessment rubric. In their final presentation, groups must be able to describe the physics of a photonics-based Nobel prize and be able to connect it to course content and to their everyday lives. Making these connections, refining, and elaborating them are deliverables for each step of the project as students progress with course content during the semester.

Part 1 consists of an introduction and a short task. Students are introduced to the term “photonics”; it is defined, applications are presented (e.g., key components in a fiber-based communication link¹), and the teacher presents an overview of his photonics research linked to telecommunications. The students are then presented with a list of photonics-based Nobel prizes, from 1964 (Maser-Laser Principle) to the present, like Fig. 2 of Ref. 41. The teacher provides a worksheet in which each student must choose and rank three Nobel prizes and provide a short description for each. They begin listing keywords/ideas and connecting them to course content and to everyday applications. For instance, when choosing the 2014 blue light-emitting diode (LED)-based Nobel prize, students typically write something similar to, “Blue light means blue waves and/or photons, and these LEDs are used in graphical displays and for white light generation.” The teacher then forms groups of three to four students, trying to respect each student’s Nobel prize preference while minimizing project repetition.

In part 2, as an individual task, students are prompted to propose at least four “primary” questions they wish to research and answer. These questions are usually broad and more general. For example, continuing with the blue LED-based Nobel prize, students ask: What is a diode? How can it emit light? Why are blue LEDs Nobel prize-worthy and not the other LEDs? How are they used in graphical displays? and so forth. The students provide detailed answers to their questions, include references, and are to propose new “secondary” questions that are to be answered later in part 3. These “secondary” questions are usually more specific and refer to

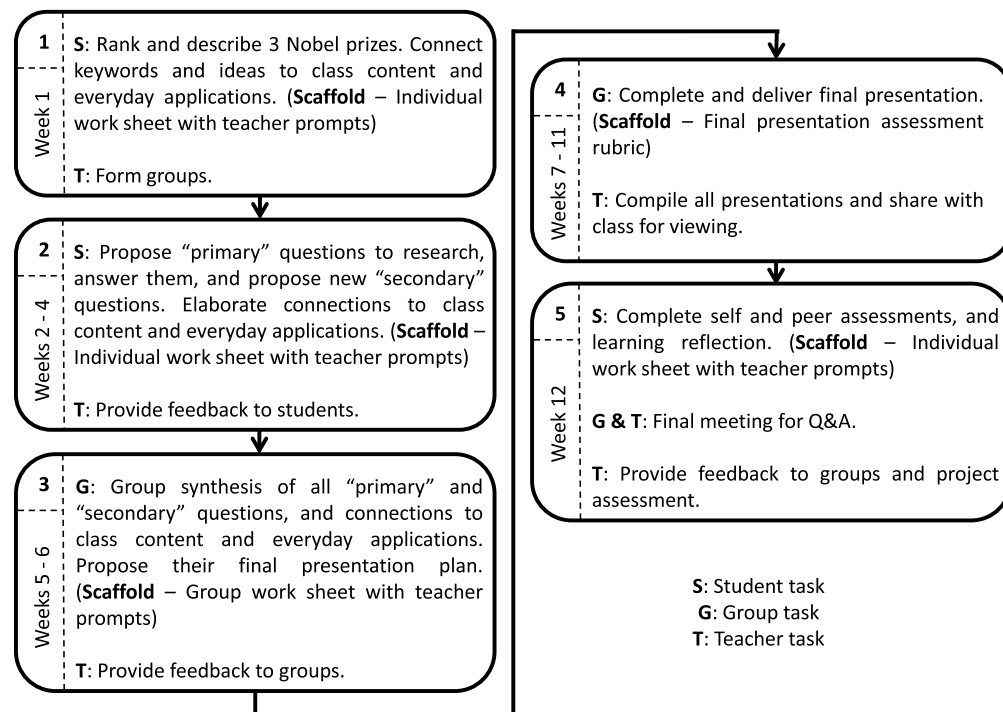


Fig. 1 Five-part, 12-week project overview containing all tasks and deliverables.

Propose a research question (RQ) based on your project that you wish to research:

RQ1:

Compile information that you found. This can include text, diagrams, pictures, etc. Include all your references. The information you find should prompt new questions. Compile these new questions (they will be researched in part 3 of the project).

Information:
New question(s):

From the information that you gathered, find connections to....

EM Waves section of course	
Modern Physics section of course	
Other physics not part of course	
Use and/or impact to our everyday life	

Fig. 2 Individual worksheet for part 2 of the project.

terms foreign to most students, for example, here: semiconductors, p-types, n-types, band gaps, etc. The students also refine and elaborate their list of connections between keywords/ideas and course content and to everyday applications. Figure 2 shows the worksheet for part 2 (this page is repeated three more times). The teacher reviews the questions, answers, and references and provides written feedback to each student.

For part 3, each group prepares a synthesis of all their individual work from part 2. They peer review each other's contributions. They then compile all their questions (primary and secondary), answers, and references and complete their list of connections between keywords/ideas and course content and to everyday applications. The worksheet provided for part 3 is similar to that for part 2. In addition, they must propose a final presentation plan. This includes the medium—most groups do a narrated slideshow video or a documentary style video. The target time is between 9 and 12 min for a group of three and 12 and 15 min for a group of four, and their audience are their classmates. The plan must also include their individual and group roles for part 4, and they are to indicate if they have more research to conduct. The teacher reviews the synthesis and final presentation plan and provides written feedback to the groups.

The groups then have several weeks to complete and deliver their final presentation in part 4. By this stage, it is common for groups to have too much material to present and/or need guidance to shorten their final presentation. The groups can revise their final presentation plan and are encouraged to seek teacher feedback if necessary. At the end of this part, the teacher compiles all presentations and shares them with the class for viewing.

The individual task for part 5, includes completing (1) self and peer assessments based on their contributions and quality of work during the project and (2) a learning reflection about the project. The goal with the self and peer assessments is to help students manage the group dynamic and the division of work. The students are presented with the assessment questions at the start of the project and hence better understand what the expectations are with regards to individual and group roles. The learning reflection document has two roles. First, it is an evidence-based technique that helps students deepen, critique, and document their learning.^{42,43} It allows students to reflect on how their project helped them to learn physics and to better understand its role in their everyday lives. Second, it provides feedback to the teacher. The questions associated to both tasks are presented in Fig. 3. Last, each group has one final meeting with the

	Always	Mostly	Sometimes	Seldom	Never
1: The individual was present for all group meetings					
2: When present, the individual participated actively					
3: The individual listened and respected the opinion of others					
4: The individual took responsibility for the assigned roles					
5: The individual completed their roles with rigor and timeliness					

(a)

Learning Reflection: With regards to this project, take a moment to reflect on your learning (the content, connections to your everyday life, working in a team, etc.). Provide 1-2 sentences for each of the following questions.

- 1) Was a project setting a good one to better learn and understand complex topics associated with EM Waves and Quantum Physics?
- 2) What part of this project did you find the easiest to understand and explain why? Were you able to help a team member better understand this part?
- 3) What part of this project did you find the most difficult to understand and explain why? Did members in your team help you to better understand?
- 4) What part of this project did you find the most interesting and explain why?
- 5) Early in the semester, I asked a series of questions to you (including: Why do we care about Waves & Modern Physics? What do you think you will learn from the class and/or how will it impact you in the future? Do you know what photonics is? What is the physics behind all the tools and devices we use to communicate?). Has your opinion changed with respect to this courses content? Would you answer these questions differently today?
- 6) Any other comments that you would like to share?

(b)

Fig. 3 (a) Self and peer assessment questions and (b) learning reflection questions.

teacher. Students must provide a rationale for their final presentation, i.e., the presentation style and medium, and how/why they chose specific elements to present, connections to elaborate, etc. They must also answer questions that relate to course content.

As stated previously, the final presentation assessment rubric (see Fig. 4) acts as a scaffold for the groups when completing their final presentation. It indicates the criteria that will be assessed and the level of proficiency expected for each. The common group grade component of the final presentation is worth 75% and includes the following criteria: (1) general description of the

TEAM GRADE		Excellent (80 - 100%)	Good (50 - 80 %)	Adequate (30 - 50 %)	Unacceptable (0-30 %)
Description of Nobel Prize - General	Nobel Prize, winner(s), year it was awarded, context for the Nobel Prize, its significance at that moment it was awarded, etc. (10 pts)	The five stated elements are presented and are accurate. The 'context' and 'significance' parts are well researched.	The five stated elements are presented and are accurate.	Most elements are presented and/or are accurate.	Few elements are presented and/or most are inaccurate.
Description of Nobel Prize - Specific	Describe the physics of the Nobel Prize (it can include complex terms and math) and assure that you can then describe it such that a younger friend with limited scientific knowhow can understand and appreciate it. (20 pts)	The main physics component(s) of the Nobel Prize are clearly stated, are accurately described and is accessible to the target audience.	The main physics component(s) of the Nobel Prize are stated and described but is not fully accessible to the target audience.	The main physics component(s) of the Nobel Prize are not all stated and/or are poorly described and is not accessible to the target audience.	The main physics component(s) of the Nobel Prize are not all stated, and what is stated is poorly described.
Ability to Connect to Physics	State and explain all the links to the EM Waves and/or Modern Physics sections of the course. You can also include links to physics in other courses. (15 pts)	There are several connections and are well elaborated.	There are some connections and/or they are not well elaborated.	Few connections are made; not really elaborated.	No - little connections; simply stated.
Ability to Connect to Everyday life	Describe its use and/or impact (etc.) to our everyday life; both current and future. (15 pts)	There are several connections and are well elaborated.	There are some connections and/or they are not well elaborated.	Few connections are made; not really elaborated.	No - little connections; simply stated.
Production Quality	Quality of the Final Product (document, power point, video, etc.) including the assessment of language proficiency. (15 pts)	The quality of the final product is excellent. It is technically/visually pleasing to read/watch/listen. It follows the recommendations (if applicable).	The quality of the final product is good. It mostly follows the recommendations (if applicable).	The quality of the final product is fair. There are production/formatting errors that compromise the final result. Few recommendations were considered (if applicable).	The quality of the final product is poor. Many production/formatting errors hinder the final result. It does not follow any of the recommendations (if applicable).
INDIVIDUAL GRADE	Rationale for the final product and answering questions. (10 pts)	The team and Rhys will meet online.			
	Peer and Self Assessments. (15 pts)	Refer to Peer and Self Assessment information.			

Fig. 4 Final presentation assessment rubric.

Nobel prize (10%), (2) physics description of the Nobel prize (20%), (3) ability to connect to course content (15%), (4) ability to connect to everyday applications (15%), and (5) production quality of final product (15%). The final 25% individual component for each student in the group is based on how well they answered their questions during the final group meeting with the teacher (10%) and on their overall self and peer assessment scores (15%).

4 Project Quality and Learning Reflection Feedback

The final presentation assessment rubric, along with the teacher feedback, allows students to better evaluate the quality of their work before they submit the final project. Including the three cohorts (winter 2020, fall 2020, and winter 2021), the overall average project grade was 87% with a standard deviation of 12%. The projects were of great quality, creative, informative, and appreciated by classmates. As stated before, narrated slideshow and documentary-style videos were the most common presentation styles. For these videos, some chose a more traditional approach, as if they were presenting a slideshow in class. However, some groups chose to give each other roles in the video—some videos flowed like a classroom setting between a teacher and students asking questions, and some were interview style, between an expert and the interviewer.

During the last meeting between the teacher and each group, students had to orally answer questions that linked their project to course content. The average of this individual grade on a 10-point scale was 7.5, with a standard deviation of 2.5. Unfortunately, no grade comparison was made between students who engaged in the project to those who did not. A quantitative study comparing the two sets of students is intended for future implementations of this project.

Regarding the student learning reflection, 93 of the 100 students who completed it agreed that this project setting was a good one to better learn and understand complex topics associated with EM Waves and Quantum Physics. Students who elaborated listed reasons that made their learning experience positive. The most popular reasons were working in a group setting (the social aspect of group video meetings during pandemic online learning and the peer instruction involved when explaining their work to groupmates), being engaged in a research setting (i.e., being able to research and learn about a topic as opposed to relying on lectures, the textbook, and rote laboratory experiments), and understanding the course content via their applications in science and everyday life. Other reasons for agreeing with the statement include being able to choose their project topic and research questions and having the ability to work at their own pace. Clearly, using IB instruction with individual and group work elements played a positive role in the student's perception of their learning.

Question 5 of the learning reflection ties in with the survey done at the start of the semester when too few students were able to correctly describe photonics. By the end of the semester, everyone was able to identify what photonics was and to make multiple connections between it and their everyday lives.

5 Conclusion

We have presented a 12-week group project centered on researching and presenting a photonics-based Nobel prize in a college classroom setting. The project uses IB instruction and is designed as a five-part activity, each with a specific scaffold helping guide students regulate their inquiry. By researching a photonics-based Nobel prize, students engage with content that is part of the Waves and Modern Physics course, especially, electromagnetic waves and quantum physics. This approach promotes the use of high-level cognitive skills as students tackle complex ideas associated with electromagnetic waves and quantum physics. As the students individually and then collectively construct and refine their knowledge about electromagnetic waves and quantum physics, they also connect the course content, and photonics in general, to their everyday lives. This approach to teaching and learning, and the materials produced, can be adapted by other teachers at different levels of education (e.g., upper K-12 and postsecondary) to fit their course content and learning objectives.

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