

The PBL Projects: Where we've been and where we are going

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ABSTRACT

Problem-based learning (PBL) is an instructional approach in which students learn course content by using a structured approach to collaboratively solving complex real-world problems. PBL addresses widespread industry concern that graduates of technician and engineering programs often have difficulty applying their technical knowledge to novel situations and working effectively in teams. Over the past 9 years, the PBL Projects of the New England Board of Higher Education (Boston, MA) have developed instructional strategies and materials that research shows address industry concerns by improving student learning, retention, critical thinking and problem-solving skills as well as the transfer of knowledge to new situations.

In this paper we present a retrospective of the PBL Projects, three National Science Foundation Advanced Technology Education (NSF-ATE) projects that developed twenty interdisciplinary multi-media PBL case studies called "Challenges" in the topic areas of optics/photonics, sustainable technology and advanced manufacturing, provided faculty professional development in the use of PBL in the classroom to teachers across the U.S. and abroad, and conducted research on the efficacy of the PBL method. We will describe the resources built into the Challenges to scaffold the development of students' problem solving and critical thinking skills and the support provided to instructors who wish to create a student-centered classroom by incorporating PBL. Finally, we will discuss plans for next steps and examine strategies for taking PBL to the next level through actual industry-based problem solving experiences.

Keywords: Problem-based learning, technician education, critical thinking, problem-solving, photonics, optics, internship, NGSS

1. INTRODUCTION: FROM OPTICS/PHOTONICS TO PBL

The origins of Problem-Based Learning (PBL) projects of the New England Board of Higher Education (NEBHE, Boston, MA, USA) can be found in the NEBHE PHOTON Projects, a series of optics/photonics educational projects dating from 1995-2006.¹ Funded by the Advanced Technological Education program of the National Science Foundation (NSF/ATE), the projects provided professional development and mentoring to over 160 secondary and postsecondary educators plus career and guidance personnel throughout the United States. PHOTON Projects curriculum development included an algebra/trig based textbook, *Light- Introduction to Optics and Photonics*,² a laboratory kit and accompanying instructions for 26 laboratory experiments, sixteen simple "Explorations in Optics" aimed at grades 5-8, and more than 40 instructional videos. All of the PHOTON Projects, indeed, all of the NEBHE NSF/ATE projects, feature collaboration among educational levels, career counselors and teachers/faculty, and industry and academia. Feedback from participants in the form of classroom field-testing is also essential for continuous improvement of materials.

One of the first NSF/ATE grants awarded in the U.S., the Fiber Optic Technology Education Project (FOTEP, 1995-1998) brought together more than 40 secondary and post secondary educators from the six New England states in a series of short term and week-long workshops. During the three-year grant, educators learned fiber optic theory and practiced fiber handling and testing. Each participating institution received \$4000 of laboratory equipment and supplies to begin to teach fiber termination and testing, and project personnel provided ongoing technical support and mentoring through email, phone conferencing and personal visits. FOTEP participants created certificates, courses, and non-credit workshops, exposing more than 4200 students to fiber optics over a 30-month period even before the grant completed. In addition, 60% of FOTEP participants contacted at that time stated they were collaborating with local fiber optic companies.

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The second NSF/ATE project, PHOTON (2000-2003), expanded content beyond fiber optic technology to include all of optics/photronics. The PHOTON project included four successful features of FOTEP that would, in fact, be the hallmark of all future NEBHE projects:

- Collaboration between secondary and postsecondary educators, leading to pathways from middle school to high school to college
- Collaboration with industry, resulting in internships for students, externships for faculty, donations of equipment and supplies and post graduation employment
- Pro-active technical support by project staff even after the end of the grant period
- High quality and flexible curriculum materials, including an equipment kit

In addition, PHOTON required participants to form regional "alliances" of secondary and postsecondary teachers and career/guidance counselors. Mentoring was provided through an email listserv, still active today, created with the assistance of volunteers from the New England Section of the Optical Society of America (NES-OSA). Even before the grant was completed, participants reported that over 3600 middle school, high school and college students had been exposed to photonics concepts and careers through the project materials. In addition, 17 high schools and colleges had new relationships with area photonics companies, and high schools and colleges were working together to create new educational pathways.

PHOTON2 (2003-2006), the nationwide online version of PHOTON, included the successful innovations of FOTEP plus those developed during PHOTON:

- Regional alliances, now extending from New England to Hawaii and including teachers from Romania in an online supportive community.
- Career counselors included in workshops and provided with up-to-date employment information

A map illustrating the locations of PHOTON projects participating institutions is shown below in figure 1.



Figure 1 – Map of NEBHE PHOTON projects participating institutions

Although the bulk of the professional development was delivered online, initial 2-day regional workshops were held at sites across the U.S. to introduce teachers to the PHOTON2 kit and to develop a personal relationship with teachers and counselors in each region. Teachers then enrolled in an innovative hands-on collaborative online course, developed with the assistance of experts at the Neag School of Education, University of Connecticut. PHOTON2 also included industry externships for both teachers and counselors. A final showcase workshop, held in conjunction with SPIE's Optics and Photonics conference in San Diego, allowed participants to showcase the curricula they developed and implemented at their own institutions during the PHOTON2 project. Additional offerings of the PHOTON2 online course were supported after NSF grant funding ended by an SPIE outreach grant, leading to several international teachers joining the online community.

At the conclusion of PHOTON2, the NEBHE team had developed the content for a complete introductory course in optics/photronics suitable for junior/senior level high school or college students. At the same time, the authors were hearing a common complaint from the industry that hired our graduates: Students know all the facts (content) but they are unable to connect the facts to workplace reality in order to effectively solve open-ended problems. Critical thinking and structured problem solving were the missing pieces. Additionally, graduates even on the 4-year university level were

lacking written and oral communication skills. In order to address these deficits, the NEBHE team applied for and was granted funding from NSF/ATE for the first of three problem-based learning projects, PHOTON PBL.

2. THE NEBHE PBL CHALLENGE MODEL

2.1 What is problem-based learning?

Problem-based learning is an instructional method that teaches content and structured problem solving simultaneously through collaborative engagement with authentic "real-world" problems. PBL was developed for use in medical education in the 1970's, and has been widely adopted in other fields including business, law, police training and even laser safety training.³ Research shows that PBL improves students' learning and retention, motivation, critical thinking and problem-solving skills, and their ability to skillfully apply knowledge in new and novel situations – skills deemed critical for lifelong learning.⁴⁻⁸ Like the similarly named *project*-based learning, problem-based learning focuses on open-ended questions or problems, is student centered, emphasizes inquiry, and provides authentic application of skills. Problem-based learning, however, does not require the creation of a product or a final performance, but once a problem is solved the addition of a project can lead to further learning. Since a project is not a necessary element of PBL the method may be used to solve problems in the classroom that are not practical to build in a school laboratory because of expense, complexity, time constraints or safety.⁹ In short, problem-based learning focuses mainly on the *process* of structured problem solving and can be independent of content. Put another way, problem-based learning teaches students "what to do when they don't know what to do."

Problem-based learning may take many forms, but all have some common elements:

- Problems are presented *before* any formal preparation has occurred - the problem itself drives the learning of content.
- Students work collaboratively in teams to frame the problem and identify learning objectives.
- New information is acquired through independent research.
- The instructor is a facilitator who provides focused instruction and guidance on an "as needed" basis.

Lecturing does not disappear entirely in PBL, but takes place on an as-needed basis as groups of students request help to understand some aspect of their independent research. The instructor's job is to guide students in learning how to ask the right questions and to focus students' efforts on finding information relevant to solving the problem.

2.2 The PBL Challenge Model

Problem-based learning is a major departure from traditional "end-of-chapter" problems with well-defined parameters and single solutions. During the first year of the PHOTON PBL project, the PBL team developed a format for the industry-based case studies, called *Challenges*, that guides students through the problem-solving process and at the same time introduces them to the types of problems common in industry and the people whose job it is to solve those problems. As with previous NEBHE NSF/ATE projects, the first step in developing PBL classroom materials was to convene a focus group of engineers, technicians, and managers from the photonics industry across New England to learn more about problem solving in an industry setting. Clearly, to become successful employees students would need to be proficient with structured problem solving, that is, a set of problem-solving techniques that can be applied to any unfamiliar and open-ended problem.

The PBL Challenges are designed to emulate the real-world context in which the problems were encountered and solved by partner organizations. Each PBL Challenge contains five main sections, each with a short video and link to section-specific resources as shown in figure 2.

The *Problem Discussion* and *Problem Solution* sections are password protected to allow instructors to control the flow of information and pace of instruction. Novice problem solvers may work together as a whole class with the instructor showing each video and allowing for discussion time after each. Students who have had some exposure to PBL may be allowed to work on the problem until they reach the point where further hints are needed, then the Problem Discussion video is shown and work continues. The most experienced students might only watch as far as the Problem Statement before engaging in long-term problem solving, perhaps followed by construction of a project. Depending on the needs of instructor and students and the time available, a PBL Challenge may be completed in as little as an hour or two (as a class discussion) or with added depth and the requirement of a tangible project it can fill an entire semester.

1. Introduction - This short video introduces the general topic area of the problem to be solved. For example, a problem about laser wire stripping is introduced with a video about laser micromachining.
2. Organization Overview - To emphasize that the problem was solved by engineers and technicians working at a real company, this video describes the company, its location and major products. A link to the organization web site is included in the resources.
3. Problem Statement - The video provides re-enactment of the situation and context in which the problem was originally encountered by the actual team of people who solved it. The *Problem Resources* link provides additional information on problem specifications.
4. Problem Discussion - To model teamwork and good problem solving skills and to provide students with additional hints, this video presents a re-enactment of a brainstorming session conducted by the team. The *Discussion Resources* help guide students in the problem-solving process.
5. Organization's Solution - Finally, we document the detailed description of the organization's solution to the problem. The title of this section emphasizes that this is the solution chosen by the organization, not the only solution to the problem.



Figure 2 – Main PBL Challenge Sections

Finding the content for optics/photronics Challenges of PHOTON PBL was not difficult because of the large network of industry and research university contacts developed during the nine years of the PHOTON Projects. Learning how to efficiently record a problem and present it as a final product on the web required quite a bit more effort. During the development of the first few Challenges the team spent 1.5 days at the organization's site; now the recording process takes only a few hours on location with much of the groundwork accomplished beforehand by email and phone conversations. Video production has improved tremendously as well, as excellent audio and video tools are now widely available for use by amateurs.

A Challenge begins by identifying a problem with an industry or research university partner. Suitable problems can be found through discussion with local industry or government agencies, in scientific literature and technical journals and in media resources, such as newspapers, web sites and blogs. To successfully engage students in genuine problem solving, a problem must be:

- Built on current student knowledge.
- Open-ended with several possible solutions.
- Ill-structured to challenge students and promote inquiry.
- Interdisciplinary in nature, and requiring collaboration and teamwork.
- Of sufficient complexity that a solution is not immediately available through a web search

We found that a problem that has been solved by “experts” allows students to compare and contrast their solutions to the expert solution and provides a benchmark to teachers evaluating student solutions; thus, all of the PBL Projects Challenges include an "organization's solution".

Once a problem is agreed upon, the company is asked to provide a (preferably) diverse team of 3-4 employees for the recording session, including engineers and technicians. Each employee is asked to bring and use notebook to the session to illustrate the importance of good record-keeping. A change of clothing is also requested to illustrate the passing of time since the scenario depicted takes place over several days or weeks. The session is video-recorded to assist with script-writing and typically hundreds of photographs are taken. The actual videos used in the online Challenges are audio over still photos allowing the script to be easily altered without requiring further visits to the site.

During the recording session, the organization's team is asked to reenact the discovery of the problem, for example, a customer makes a request for a new product or process or a production issue is discussed at a team meeting. Next, the team reenacts a brainstorming session that might have taken place a few days or weeks after the problem is discovered. Finally, the organization's solution is recorded. Any drawings, documents or other media that will help define the problem or explain the company's solution are requested at this time, as well as company marketing materials to use in developing a company overview video. Once the photographs are sorted and the script is written and audio-recorded by volunteer voice actors, creating the five 2-3 minute videos that will make up the Challenge is a relatively straightforward process using the iMovie application.

The NEBHE PBL Projects, PHOTON PBL (2006-2009), PBL for Sustainable Technologies: Increasing the STEM Pipeline (STEM PBL, 2009-2012) and Problem-based Learning in Advanced Manufacturing (AM-PBL, 2012-2015) have developed 20 Challenges with industry partners. These are listed in Table 1 and are available at no cost at <http://www.pblprojects.org>. As additional Challenges are they will be added to the PBL Projects library.

Table 1 - Topic and collaborating organization for PBL Projects multimedia PBL Challenges available at www.pblprojects.org

PHOTON PBL	STEM PBL	AM-PBL
Laser Safety International Laser Display Association.	Wind Turbines FloDesign Wind Turbine, Inc.	Photolithography IBM (now Global Foundaries), Inc.
Laser Wire Stripping PhotoMachining, Inc.	Submarine Lighting RSL Fiber Systems, Inc.	Nanotechnology/thin films FastCAP Systems, Inc.
DNA Microarray Fabrication Boston University	Solar Power SPG, Inc. and City of Tucson	Sheet Metal Manufacturing Sound Manufacturing, Inc.
High Power Laser Burn in Test IPG Photonics, Inc.	Sustainable Agriculture Cape Cod Cranberry Growers and USDA	Scale up for Medical Device Manufacturing Cirtec Medical Systems
Infant Jaundice Home Cure Photodigm, Inc. and Drexel University	Storm Water Management TTF Watershed Partnership	Advanced Quality Systems Hypertherm, Inc.
Measuring Light Output Cal Poly Pomona	Eczema Treatment Johnson & Johnson, Inc.	Laser Cleaning IPG Photonics, Inc.
Non-contact measurement UPenn McKay Orthopedic Lab		
Thermal Imaging Penn State Electro-optic Center		

3. RESOURCES FOR STUDENTS AND TEACHERS

3.1 Student resources

The first encounter with PBL can be frustrating for both students and teachers. Students whose academic life has consisted of taking notes on lectures and completing back of chapter problems perhaps supplemented by cookbook laboratory experiments with defined outcomes can react to the open ended problems of PBL with anxiety and frustration. To help scaffold student learning of both content and structured problem solving, student resources are built into each section of a PBL Challenge and are reached via a "Resources" link in each of the five sections. Technical resources include articles and web sites with information that leads students to a possible solution to the problem without making the solution explicit. The key problem-solving resource is the "Whiteboards", a set of instructions that guides students through a structured approach to problem solving by helping them systematically record their thoughts, ideas, and learning strategies during each stage of the problem solving process.

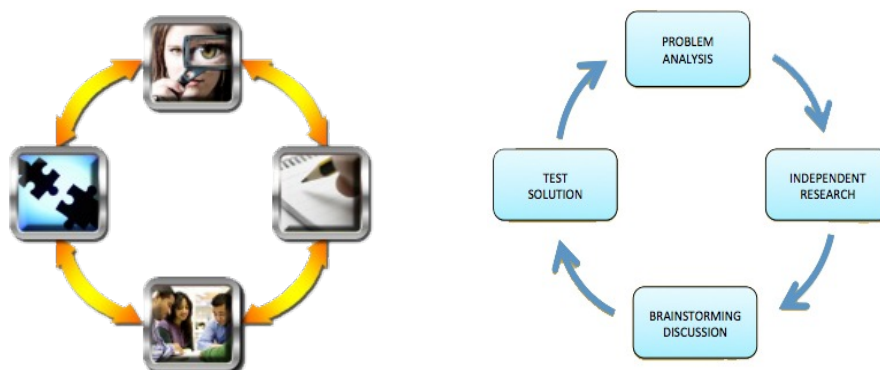


Figure 3 - The problem-solving cycle

The Whiteboards were developed with the assistance of the focus group of optics/photonics engineers and technicians convened early in the PHOTON PBL project to learn more about how industry approaches problem solving. Guided by the focus group discussion, we developed the Whiteboards to include four distinct steps:

1. Problem Analysis: Clearly define the problem. Identify and list the criteria against which the solution will be measured, what is known, what information is missing and any assumptions that must be made. List criteria that a successful solution must meet.
2. Independent Research: Develop a plan to acquire the knowledge identified during Problem Analysis as necessary to solve the problem. Divide up the learning with team members, set deadlines and develop an action plan for acquiring the required knowledge.
3. Brainstorming: Share what was learned during independent research in order to generate possible solutions. Decide collaboratively which solution best meets the criteria of a successful problem identified in the Problem Analysis phase.
4. Solution Testing Develop a detailed plan to validate the solution based on the criteria for a successful solution identified in the Problem Analysis phase.

The Whiteboards, shown in figure 4, derive their name from their ability to be projected onto a classroom whiteboard so that an entire class can work together, which is especially useful for novice problem solvers. They are also available to students within each PBL Challenge as a text document. Although students are usually reluctant at first to work through each step of the process and want to jump right to a solution, practice with the Whiteboards over time proves the usefulness of the method. Upon many occasions, the authors have had students return from other instructors' classes request a copy of the Whiteboards to help them manage a complex project.

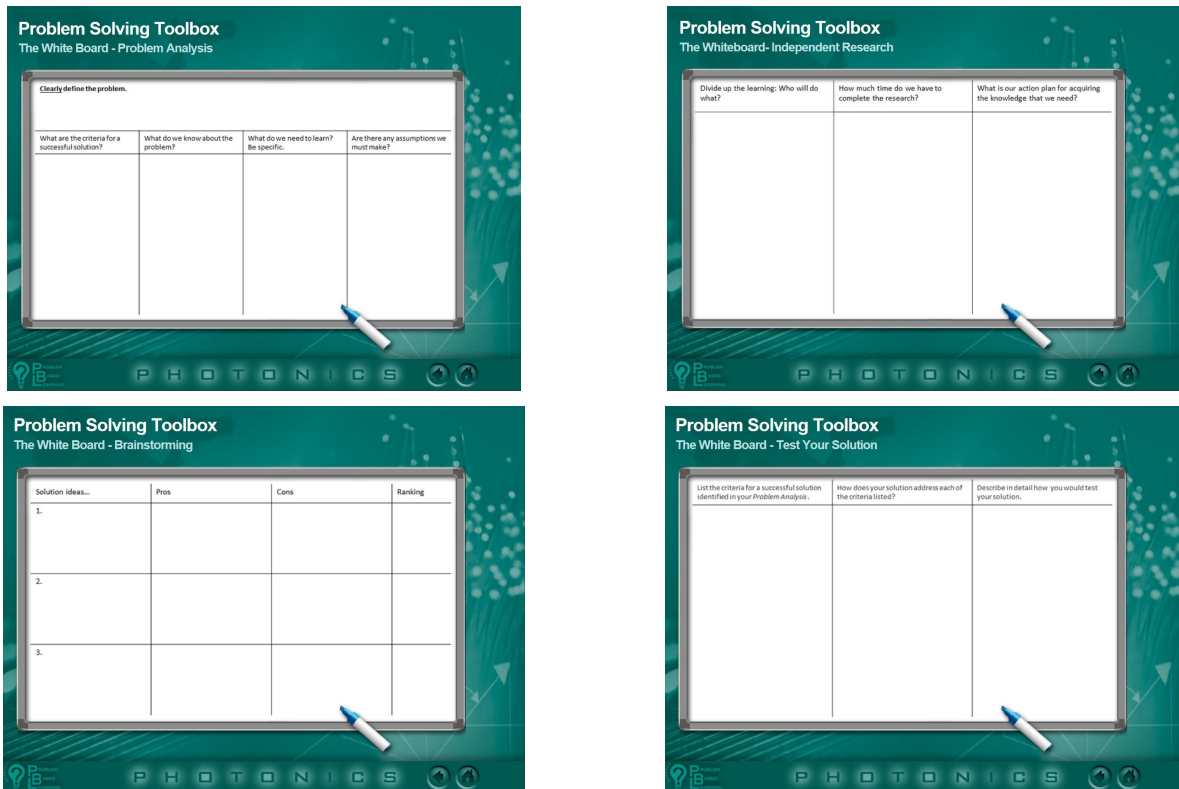


Figure 4 – The Whiteboards

3.2 Resources for teachers

A colleague once referred to Problem-based learning as "teaching without a net." Once students have been presented with a problem and the instructor assumes the role of facilitator, the conversation can go in many unpredictable directions. For instructors used to being in control of the classroom, this situation can be unnerving. To assist faculty in implementing PBL in the classroom, the NEBHE team has developed a series teacher/faculty professional development workshops and webinars on the implementation of PBL, with workshops lasting from a few hours to several days. Resources built into each Challenge also help give instructors confidence in their ability to use the method. In addition to the technical resources available to students in each of the five Challenge sections, there is a separate "*Teacher Resources*" button that links to a password protected instructors' resources site. Teacher resources include:

1. Technical Background - Recognizing that teachers may not be experts in the technical area of the Challenge, this document provides background science and technology information as well as references for further information and suggestions for supplemental activities.
2. Assessment Strategies - Assessing student learning in PBL is quite different from simply marking test questions right or wrong. Description and tools for a four-pronged approach to assessment is included. This method is described below in section 4.
3. Implementation Resources - To help teachers know what to expect in the classroom when they implement a PBL as well as to provide Challenge-specific assistance, this section includes:
 - *Implementation Guide* - A step-by-step guide for using PBL Challenges, including a Challenge site map and implementation flow chart
 - *PBL How-To Video* - A five-minute video developed during the PHOTON PBL project on classroom implementation. Although the Challenges have evolved since this video was made, it is still an excellent short introduction to PBL.

- *Engaging Students with PBL Video* - A two-part video (total approximately 30 minutes) showing how PBL works in a classroom, recorded with novice high school problem solvers and an experienced PBL instructor
 - *Khan Academy Math Alignment* - Links to the alignment with Khan Academy math modules for each Challenge for students who need extra practice on specific Challenge-related math topics
 - *Implementation Stories* - Detailed reports from instructors who used this Challenge in their classrooms, both secondary and post-secondary
4. Standards Alignment - alignment of the Challenges to the U.S. Common Core (mathematics and English) and Next Generation Science Standards, important to grade K-12 teachers.
 5. Grade Level Adaptations - Modifications to content and assessment to use Challenges with younger students or for differentiated instruction. A team of middle school consultants developed these adaptations.
 6. Update Button - Any changes to the technology or the partner companies since the Challenge was recorded.

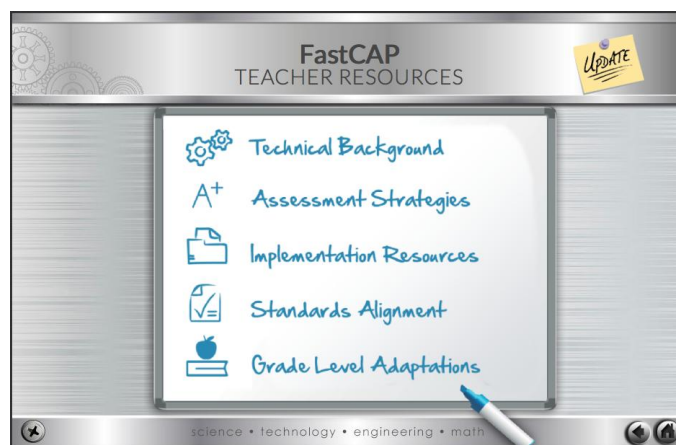


Figure 5 - The teacher resource page from an AM-PBL Challenge

All teachers participating in the PBL workshops are also invited to join an email listserv for discussing implementation of Challenges or sharing STEM topics of interest. The NEBHE team also posts to the listserv any changes to the PBL web site or Challenges, plus news about the project and participants.

4. ASSESSING STUDENT LEARNING

Educational assessment involves measuring a student's knowledge, skills, and attitudes (KSA). Assessing student learning in PBL is quite different from simply marking a problem correct or incorrect or even giving partial credit points on an exam. While problem sets and multiple-choice questions can measure a student's knowledge of facts, they are not adequate for measuring student performance in PBL, where it is necessary to assess the *process* students used to solve the problem as well as their content knowledge. The NEBHE team developed an assessment strategy for PBL that employs multiple measures of learning while at the same time is not overly burdensome to instructors used to grading "right" or "wrong" with a red pen.

The PBL Projects assessment model was informed by research conducted by the Vanderbilt-Northwestern-Texas-Harvard-MIT (VaNTH) Research Center for Bioengineering Educational Technologies.¹⁰⁻¹² The NEBHE approach uses four measures of assessment: Content Knowledge, Conceptual Knowledge, Problem-Solving Ability and Teamwork. Weights are applied to each measure depending on the type of course, and the final score is the sum of the weighted measures. Specific weighting factors depend on course outcomes, for example, in one case content and conceptual knowledge may be judged to be of primary importance, in another it may be teamwork and the problem solving process that are considered more important and thus more highly weighted.

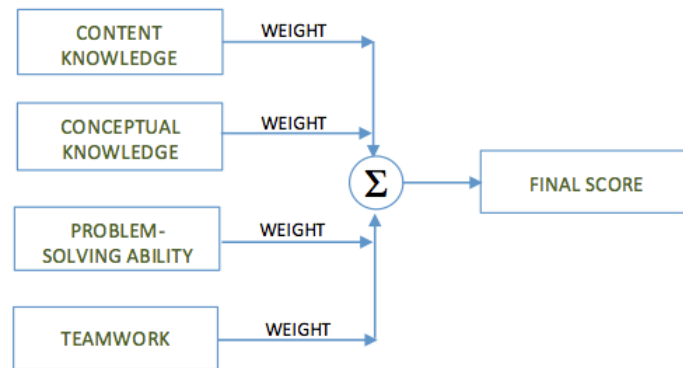


Figure 6 - PBL Challenge assessment scheme

4.1 Content knowledge

Content knowledge refers to a student's understanding and recall of facts in a specific discipline. A test bank of multiple-choice and short answer questions, single and multiple step problems, and open ended more thought provoking problems is included in the Teacher Resources of each Challenge. These relate to the science and technology addressed by the Challenge and may be used as traditional tests, quizzes and homework. Since the PBL Challenges were designed to be implemented as either a supplemental activity in a traditional course or as a stand alone instructional method, instructors have the flexibility to assess content knowledge by traditional textbook assignments, lab reports, quizzes or tests.

4.2 Conceptual knowledge

Conceptual knowledge refers to a students' understanding of the relationship between concepts within a subject area or between subject areas. Traditional courses often ignore assessment of concept knowledge as long as students "can do the problems." Research on expertise shows that compared to novices, experts have a deep foundation of factual knowledge, understand facts and ideas in the context of a conceptual framework centered on core concepts and principles, and organize knowledge in ways that facilitate retrieval and application. Experts' rich interrelated framework of concepts and principles allows them to understand and give meaning to new information by seeing patterns and relationships that are not apparent to novices, allowing them to access relevant information more efficiently. As expertise in a particular domain of knowledge increases through experience and practice, however, an individual's conceptual framework becomes more complex and interrelated, improving their ability to transfer learning to new situations and domains¹⁰⁻¹².

Concept mapping has been shown to be a useful tool for assessing students' conceptual knowledge.¹³⁻¹⁴ Developed in the 1970s by Joseph Novak (Cornell University) as a means of assessing student conceptual knowledge in science, concept mapping provides a graphical representation of students' understanding (or misunderstanding) of the connections between concepts in a particular subject area. A concept map consists of circles or ovals labeled with individual concepts and connected by arrows labeled with words that express the relationship between the concepts. Each pair of concepts and linking words forms a proposition that states the connection between concepts. (See figure 7.)

Concept maps can be created using an "open-ended" approach with students generating their own list of concepts, or a more structured approach where the instructor providing a list of concepts to be mapped. The PBL Challenges provide a list of concepts related to the specific Challenge in order to limit variability, however, some instructors choose to have students use some of the provided concepts and also generate some of their own. Each PBL Challenge also includes an "expert" concept map for reference. A number of scoring methods have been proposed for concept mapping, some very complex requiring counting of nodes and scoring of propositions. The PBL Projects scoring rubric included with the sample concept map is based mainly on the validity of the propositions generated.

4.3 Problem-solving ability

Content assessments and concept mapping are effective ways of measuring student mastery of the subject matter of a PBL Challenge. Measuring problem solving ability involves both formative (in process) and summative (final) assessments, using the Whiteboards and a reflective journal called the *Final Challenge Report*. The Whiteboards are the formative assessment since as students complete them they are stating their current understanding of the problem and the

thought processes that brought them to that stage. The Final Challenge Report is completed after solutions have been submitted for peer review and the organization's solution has been revealed. Students create a detailed summary of each of the stages of problem solving as recorded in the Whiteboards, looking back at the strategies they used, what worked and what did not work, and how well their solution satisfied the company's criteria. A final reflective exercise helps students understand what strategies will work when solving future problems.¹⁵⁻¹⁷

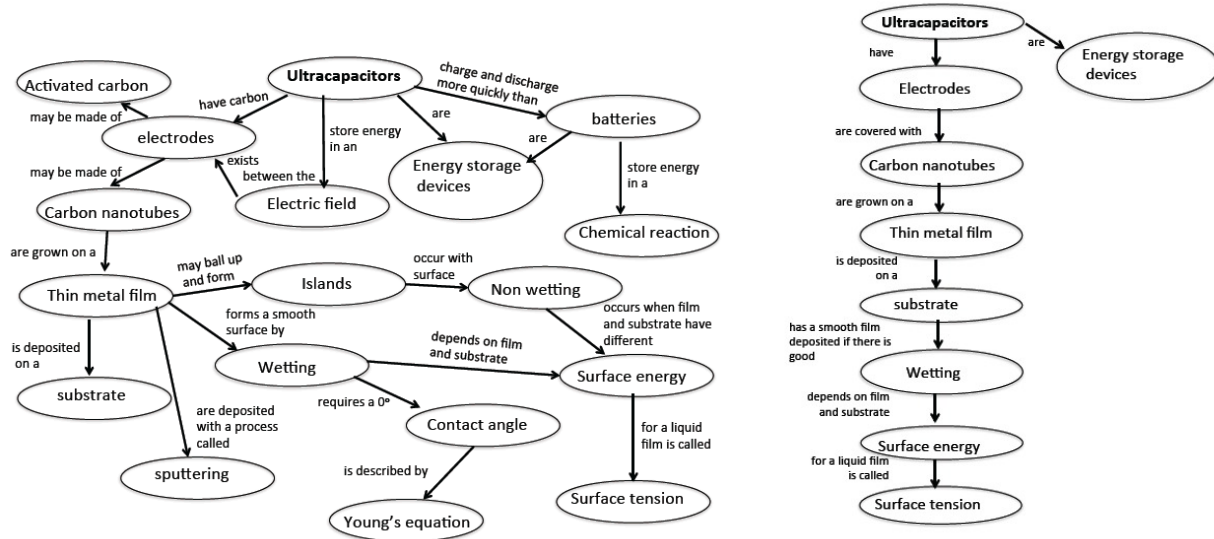


Figure 7 - Expert (left) and (simulated) novice concept maps for the FastCAP Challenge. Novices tend to use fewer concepts and arrange them in a linear fashion, rather than as a web of ideas.

4.4 Teamwork

One complaint by students about working in teams is that there are always a few students who are content to let others do the work, a phenomenon referred to as "social loafing". To counter this problem, a teamwork assessment was added during the second PBL project, STEM PBL. Adapted from work by Levi and Cadiz¹⁸, the assessment is completed by students rating their teammates and themselves on a 5-point Likert scale on five measure of project-related performance:

1. Completed tasks on time
2. Did his/her fair share of the work
3. Produced work of acceptable quality
4. Actively contributed to the team effort during class time
5. Actively contributed to the team effort outside of class time

Teamwork assessments are kept confidential and the results are counted toward each student's grade for the project. In our experience, having teammates assess teamwork of fellow students does not completely eliminate social loafing, but the loafers are inclined to admit to their failings on their own evaluations and accept that their grade should suffer because of it.

5. IMPLEMENTATION OF PBL CHALLENGES

The built-in flexibility of the PBL Challenges has allowed participants in the NEBHE PBL Projects to use PBL in a wide variety of educational settings from supplementing traditional course materials to and creating courses in which all learning was accomplished via PBL to interdisciplinary and multi-educational level extracurricular activities.

5.1 Implementation stories

In several of regional alliances, PBL was used to bring high school and college students together, allowing high school students to experience the college environment and college students to act as mentors to young learners. For example,

in 2011, students from Longview (Texas) High School worked alongside electrical engineering students at LeTourneau University to solve two STEM PBL Challenges as a supplemental after-school activity for the high school students and a graded classroom activity for college students. Alternating between high school and college campuses, The 14 participating students spent four weeks working on the PBL Challenge and then designed, built and tested their solution in the lab. More recently (2014), high school students from rural Vermont collaborated with Norwich University mechanical engineering students to solve a PBL Challenge in advanced manufacturing. According to the co-facilitating instructors, the collaboration successfully increased student engagement and encouraged deeper learning. Students gained insight into the value of PBL while working in groups of diverse ages and experience levels.

High school teachers have developed creative methods of introducing PBL into the classroom despite the demands of standardized testing. In Boston, an elective course in photonics was developed with instruction mainly through solving PBL Challenges. The teacher acted as a resource for the students but gave them little formal instruction unless they requested it. A chemistry teacher in Texas used the PHOTON PBL Challenges as a supplementary activity after the Advanced Placement test in the spring. The students knew almost nothing about optics/photonics and were able to learn a significant amount the technology as well as new problem solving strategies.

An enthusiastic Romanian practitioner of PBL introduced a Challenge to her high school class using a *Socratic Seminar*. Students were divided into two groups: an “inner” circle who participated in the discussion of the problem and an “outer” circle who observed the two-hour seminar and reported their observations. Students solved both the IPG Photonics Challenge (high power burn-in testing) and the PhotoMachining Challenge (laser wire stripping fine copper). After completing the Photomachining Challenge, students were eager to learn more about industrial lasers and were given the opportunity an online conversation with Dr. Ron Schaeffer, PhotoMachining CEO.

At the college level, PBL Challenges have been used both as supplemental course activities and as the basis for an entire course curriculum. One of the authors (JD) used PBL both in optics courses for students in a Laser and Fiber Optic Technology program and also in a traditional physics course to replace the first lab of the semester, "Density of a Cylinder". In the latter case, the chosen PBL Challenge addresses the same learning outcomes as the density lab: getting to know your lab team, taking measurements and handling data in the lab. Instead of a nearly silent classroom of students measuring cylinder dimensions, the lab was alive with teams of students arguing the benefit of various community-based methods of holding back storm water. The second author (NM) uses the PBL Challenges in several courses including *Introduction to Light and Lasers*, a freshman physics course, and *Advanced Topics in Lasers*, and a senior level laser technology course. In the Advanced Topics in Lasers course, students complete three PBL Challenges over the course of a semester. The PBL Challenges serve as a foundation for many senior capstone projects and industry-based internships by introducing students to specific technology used by sponsoring companies as well as helping to develop the problem solving skills essential for success in industry. A number of other implementation stories at the college level are documented in the *Implementation Stories* section in each Challenge.



Figure 8 - (Left) High school students build solar shed to test ideas learned in solving the SPG Solar Challenge. (Center) College students use the Whiteboards to solve a laser safety problem in the ILDA Challenge. (Right) High School and college students work together to solve a Challenge from the STEM PBL project.

In the summer of 2013, a team of middle school teachers was engaged to develop modifications of the Challenges for differentiated instruction and assessment. Working with great enthusiasm, the team revised the Whiteboards to require student-produced diagrams, solution revision based on peer suggestions and daily "checkpoints" to align with middle school instructional methods. They also modified the Final Challenge Report and suggested additional student resources for two of the STEM PBL Challenges. One of the team members subsequently joined the AM-PBL project as a participant, and has shared his experience as a new practitioner of PBL.¹²

5.2 Student engagement

Through field-testing reports and research focus groups we have collected student and teacher responses to the PBL Challenges and methodology. While students may approach the Challenges with apprehension at first, our research has shown that with increasing exposure students gain confidence in their ability to problem-solve.¹⁹ Typical student reactions include:

"My confidence increased...because unlike the task of solving textbook problems, I had the chance to learn and apply what I learned to solve something real."- Williamstown Middle and High School, Honors Physics Student, VT, AM-PBL

"I enjoyed the problem based aspect of everything. It got my mind thinking in a way I have never used it!"-Rhode Island College, Energy Systems Student, RI, AM-PBL

"PBL was a very rewarding experience for me to try out. It was way different than normal learning, so it was really exciting for me... because when you are just sitting there at your desk and people are giving you the information, it's really boring. And usually I just copy it off the screen, but when I have to find the information, it sticks with me."-Taft Union High School, Chemistry Student, CA, STEM PBL

"By the time you get to the 3rd Challenge you feel confident. You're thinking about how you can do things better versus just getting through the process. Now you're thinking, 'Wow, I could really do this this time, or pay attention to this detail next time.' You take that constructive criticism that you got and grow yourself and actually hone your craft." - Springfield Technical Community College, PHOTON PBL

Instructor reactions are positive as well:

"It's never too early for our students to begin problem-solving. By the time they've reached fifth grade, they've already started to learn the game of school—they've learned that if they just memorize some stuff, regurgitate it back on a piece of paper, they're going to skate by and be fine. But if they're given some kind of problem that requires them to come up with their own solution, that's where they struggle."-Sharon Center School, Middle School Science Teacher, CT, STEM PBL, AM-PBL

"Students were apprehensive at first but they gained confidence quickly. Overall students reacted very well to PBL and most liked it better than traditional direct instruction."- HPHS Academy of Engineering and Green Technology, CT, AM PBL

"Although the specific content does not "fit" with my curriculum, the problem solving was valuable because the science and engineering practices were all used to some extent in the problem solving. I really don't consider this to be a difficulty; I view it as an opportunity for my students to stretch their perceptions and exercise their skills." - Williamstown Middle and High School, Honors Physics Instructor, VT, AM PBL

"At first they didn't like the change from normal class process, but by the end of the Challenge, a clear majority wanted to do a second Challenge." - Cape Code Community College, Engineering Instructor, MA, AM PBL

"Students seemed to like problem-based learning! They were engaged in solving the problem, and most pushed themselves and their teammates to better understand the issues. I found that they were nervous about defining the problem incorrectly at first, but that they got past this trepidation as they dug deeper into the possible solutions. I was impressed with the solutions the student teams developed." Stonehill College, Professor of Biology, MA, STEM PBL.

5.3 "Make your own Challenge"

As of spring 2015, the NEBHE PBL team has presented dozens of short- and long-term professional development workshops with educators from middle school through university. Despite workshop presenters' reminders that "it's not about content, it's about the method" teacher participants often remark that the content presented in the particular Challenges showcased during the workshop does not apply to the courses they teach. Teachers have requested PBL Challenges on earth and space science, environmental technology, mechanical engineering and other subject areas. During the STEM PBL project a "*Create Your Own Challenge*" template was developed and pilot tested with graduate-level STEM education teachers at Central Connecticut State University to teach educators how to develop PBL Challenges on topics of their own choosing and therefore increase the offerings in NEBHE's PBL Challenge library. As a result, one of the primary goals of the current AM-PBL project is to work with participants and their local manufacturing companies to create their own Challenges.

While the online multimedia PBL Challenges developed by NEBHE have been well received in part because they capture students' attention and efficiently present the necessary information, they are time and resource intensive to develop and maintain on the web. As a simpler alternative, the NEBHE team has created two PBL Challenge design templates available to workshop participants for creating their own PBL Challenges: the preferred format is Microsoft PowerPoint, however, acceptable Challenges can also be created in narrative form as text documents. In order have their Challenges included in the NEBHE PBL library, Challenge developers are required to use the format of the templates for uniformity.

Between 2012 and 2014, the NEBHE PBL team has been providing professional development to faculty at Kennebec Valley Community College (Maine) from two academic departments, Energy Services Technology (NSF-ATE funded) and Sustainable Agriculture and Culinary Arts, funded through the U.S. Trade Adjustment Assistance Community College and Career Training Grants Program (TAACCCT). KVCC faculty were introduced to the PBL methodology and then worked with mentors to develop their own PBL Challenges to meet the instructional needs of their programs. Several new problems have been proposed and some have reached the classroom field-testing stage. The new Challenges are based on real-world issues faced by local business and industry and they illustrate the diversity of problems that can be addressed by PBL, for example, "*Under Pressure*", troubleshooting a leaky pressure release valve on a domestic hot water heater, and "*Six Sick Sheep*", determining the cause of illness among ewes grazing in the college pasture.

In spring 2015, the NEBHE PBL team also worked with Trident Community College (TTC) engineering technology faculty to help them integrate PBL into their manufacturing engineering technology curriculum. As a result of the professional development provided, TTC faculty have created two PBL Challenges focused on streamlining the manufacturing flow in a craft beer factory and redesigning an accordion-type paper air filter to minimize damage during shipping.

In 2014-2015, the NEBHE PBL team has also worked closely with the U.S. Department of Labor's YouthBuild program sites in Providence, RI, Hartford, CT, and Newark, NJ. YouthBuild provides unemployed, low-income out-of-school young people an opportunity complete their high school educations, gain the skills they need for employment, and become leaders in their communities. YouthBuild programs integrate academic skills with training in high-demand career pathways in areas such as construction, healthcare, technology, and customer service.

One of the goals of YouthBuild is to inculcate in young people the problem-solving skills needed for success on the job and in life. Working with Youthbuild represents a slight departure for the NEBHE PBL team from its focus on STEM education to providing more generic problem solving skills to a different population. Over the past year, NEBHE PBL mentors have worked closely with YouthBuild teachers and counselors to modify their existing curricula to incorporate real-world problem solving experiences and tools (the Whiteboards) into their daily activities. Although each of the Youthbuild sites has experience with student projects, the goal of the NEBHE partnership is to help faculty find the problems embedded within the projects and give students the skills to solve them.

Reactions from both teachers have been extremely positive:

"It fits my students because it provides a real-world context to learning and provides them with the choices that were missing in traditional school experience."

"(What is valuable is) to transfer that set (of skills) to young people for them to use as a tool for the rest of their lives."

6. WHAT'S NEXT?

6.1 From projects to problems with new populations of students

The NEBHE PBL team is frequently asked "What's the difference between project-based learning and problem-based learning?" Both are learner-centered approaches to education that fall under the broad umbrella of inquiry-based learning. Both PBLs focus on open-ended problems or tasks and provide authentic applications of skills and content knowledge. But while project-based learning requires the development of an end product developed according to some specifications, problem-based learning is more focused on the *process* of problem solving. In fact, problem-based learning can be thought of as the "front end" of the process, where the problem is identified and researched and solutions are proposed. That is, problem-based learning generates the criteria for project design. (See figure 9)

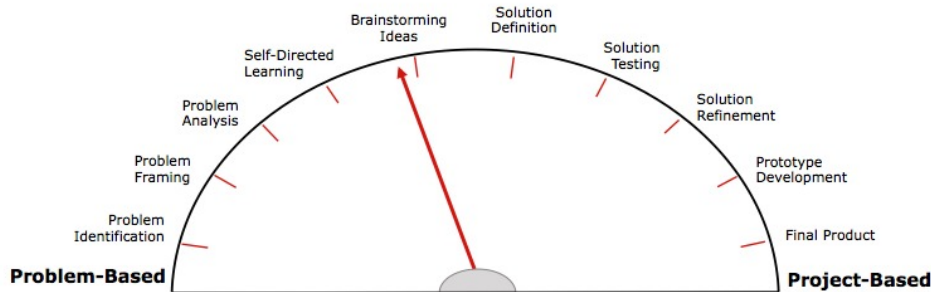


Figure 9 - The Problem-Project based learning continuum

Many educators who have attended NEBHE PBL professional development workshops have already been using hands-on projects to engage students but are now looking to take the next step to turn projects into problems integrating key 21st century skills: problem solving, critical thinking and teamwork. For example, at the time of our initial contact with the Newark, NJ YouthBuild site, the teachers were planning a project to build raised bed gardens to be located on school property. Teachers and staff had worked with an outside consultant to develop plans for students to implement. Converting the project to problem-based learning, teachers broke the large project into a series of smaller ill-structured problems requiring students to use the methodology of PBL to identify the problem and research and propose solutions.

In addition to providing an exciting educational alternative for special populations such as the overage/under credit students of Youthbuild, PBL also meets the new demands of the Common Core and Next Generation Science Standards for teaching critical thinking and problem solving as well as interdisciplinary studies, teamwork and engineering practice. Through the success, dissemination and credibility of the three PBL Projects' instructional materials and professional development model interest and demand from K-12 schools and colleges who are searching for PBL training services has grown. The PBL team is working to develop a model of structured problem-solving tools that can be customized to specific populations such as young elementary or middle school children.

6.2 Case Study: Internships and capstone projects

The NEBHE PBL team constantly asks itself "How do we improve on what we are doing now to help students further develop the real-world problem-solving skills needed by industry?" Applying our own problem solving strategies to answer this question, one of the solutions was to make the experiences provided by the PBL Challenges even more "real." To this end, one of the authors (NM) set out to develop student internship and capstone project experiences with some of the companies that sponsored the PBL Challenges, and companies involved in similar industry applications. The idea is that students who have completed several PBL challenges have already been exposed to the company, the problems they routinely face, their process for solving those problems, and would be able to "hit the ground running" in applying what they have learned in an actual real-world setting.

Over the past five years, dozens of senior students in the Laser Electro-Optics Technology program at Springfield Technical Community College have participated in onsite internships as part of their two-semester senior capstone projects at several local photonics companies. The projects selected by these companies were *real* engineering projects in which the students served as an integral part of an engineering team. A list and photos of a few selected projects is provided below in table 2 and figure 10.

Table 2 – Partial list of industry sponsored internship projects

Company	Project
Nufern, Inc.	<ul style="list-style-type: none"> • Build a compact 1-um Ytterbium fiber laser in the development of a marketable fiber laser educational kit • Design and development of a frequency-doubled Ytterbium green fiber laser • Design and development of a monochomator-based active fiber absorption test bench • Design and development of a microprocessor-based fiber optic gyro inertia measurement system • Design and development of an automated fiber laser burn-in test chamber
IPG Photonics	<ul style="list-style-type: none"> • Design and development of a 30-watt Ytterbium fiber laser demonstration unit • Design and development of a 20-watt scanning head fiber laser marking and etching system
Prima Electro	<ul style="list-style-type: none"> • Integration of a high powered fiber laser with an 1800-watt commercial CO₂ sheet metal cutting laser
FloDesign	<ul style="list-style-type: none"> • Design and development of a hybrid solar/compressed air engine vehicle
RSL Fiber Systems	<ul style="list-style-type: none"> • Design and development of a LED fiber optic tail light systems for Volvo Trucks of Brazil • Design and development of a LED fiber optic cabin lighting system for Volvo Trucks of Brazil • Design and development of a prototype LED RGB fiber optic lighting system

While anecdotal, the response from both students and industry partners has been exceedingly positive as evidenced by the hiring of student interns by sponsoring companies upon graduation. For example, in 2014, Nufern Inc. sponsored nine senior projects and hired all nine student interns. Similar hiring has occurred with all of the other sponsoring companies with extremely positive feedback. Moving forward, we intend to expand student capstone project internships with additional PBL Challenge partners and conduct research on the impact of PBL on initial job performance of PBL graduates as compared to non-PBL graduates.

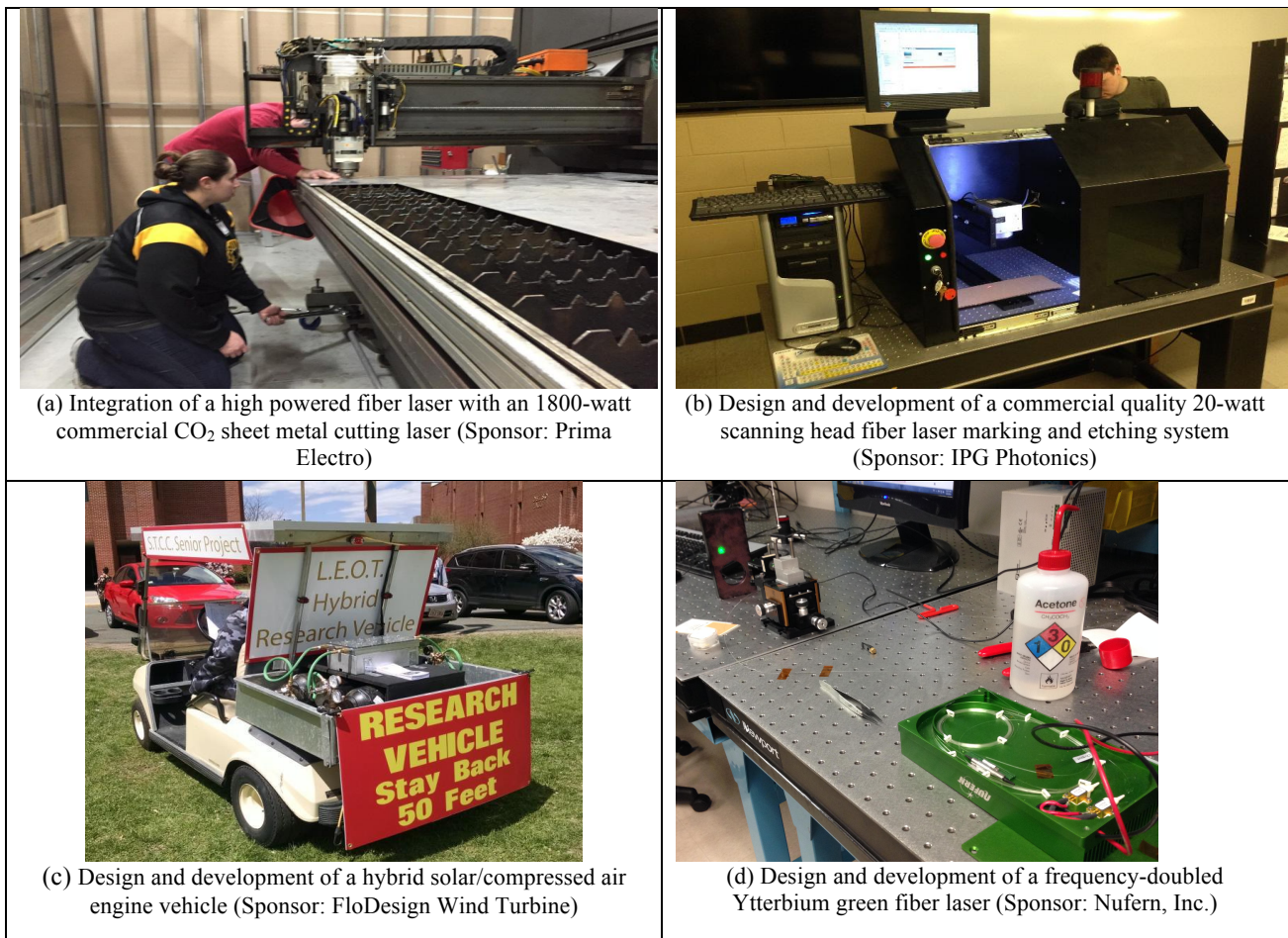


Figure 9 – Industry sponsored senior capstone projects

7. CONCLUSION

In this paper we presented a retrospective of the PBL Projects, three National Science Foundation Advanced Technology Education (NSF-ATE) projects that developed twenty interdisciplinary multi-media PBL case studies called "Challenges" in the topic areas of optics/photonics, sustainable technology and advanced manufacturing, provided faculty professional development in the use of PBL in the classroom to teachers across the U.S. and abroad, and conducted research on the efficacy of the PBL method. We described the resources built into the Challenges to scaffold the development of students' problem solving and critical thinking skills and the support provided to instructors who wish to create a student-centered classroom by incorporating PBL. Finally, we examined strategies for taking PBL to the next level through actual industry-based problem solving experiences.

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PHOTON2: Web-based Collaborative Learning for Teachers. Funded in-part by the Advanced Technological Education program of the National Science Foundation.(ATE #ATE 0302528) Principal Investigator, Fenna Hanes (Project Manager), New England Board of Higher Education; Co-Principle Investigators, Judith Donnelly, Three Rivers Community College; . Marijke Kehrhan, Neag School of Education (University of Connecticut); Nicholas Massa and Barbara Washburn, both Springfield Technical Community College

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