The Light Applications in Science and Engineering Research Collaborative Undergraduate Laboratory for Teaching (LASER CULT)-Relevant Experiential Learning in Photonics

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***Abstract*—An integrative undergraduate photonics curriculum has been developed that utilizes three active learning methods: case studies, team learning, and project-based learning (PBL). This two-course sequence at Oklahoma State University's Light Applications in Science and Engineering Research Collaborative Undergraduate Laboratory for Teaching (LASER CULT), is designed as an introduction to optics and photonics for electrical engineering students. The LASER CULT has three primary goals: make course concepts more relevant to students, provide students with training and positive experiences in functioning on a team, and introduce in-depth projects that require higher level problem-solving skills, such as evaluation and synthesis. To accomplish these goals, which are synergistic with Accreditation Board for Engineering and Technology (ABET) outcomes, LASER CULT courses use two in-depth design projects that are constructed by student teams under realistic constraints rather than focusing on hierarchical concepts. The relevance of course content to students is increased by recreating the environment of practicing engineers. Assessment data, measured through individual reflection included in team portfolios and student assessment of learning gains, demonstrate the effectiveness of this format for meeting course goals and ABET criteria and pipelining students into graduate school.**

***Index Terms*—Case studies, engineering education, lasers, optics, photonics, project-based learning (PBL), team learning.**

I. Introduction and Background

Calls for reform of undergraduate engineering education [2] are increasing, and several studies have outlined specific pathways to curriculum reform [3]–[7]. Implementation of reform can be difficult, however, particularly at large state universities. This paper outlines a two-course sequence in photonics designed for upper division engineering courses developed both to serve as a test bed for sustainable engineering education reform at a large state university and to integrate Accreditation Board for Engineering and Technology (ABET)-mandated program outcomes [8] into the electrical engineering curriculum.

Like many universities, Oklahoma State University (OSU), Stillwater, offers a traditional engineering program with a pre-engineering core curriculum followed by two years of discipline-specific engineering. The teaching methodology is primarily lecture based, and summative evaluation measuring comprehension and application of lecture material is the predominant mechanism to determine student progress. While cost effective, lecture-based instruction does not help students integrate knowledge from multiple subjects. Students take different courses from different professors at different times on different days in different rooms; they see each subject as distinct from each other rather than as different facets of electrical engineering which use the same fundamental tools and concepts. Being able to integrate knowledge is especially important in cross-disciplinary areas, such as photonics, biomedical engineering, nanotechnology, and some areas of semiconductor technology.

A second drawback of a lecture-based course format is that it may lack relevance to students. As pointed out in a recent exposé of college teaching [9], students, particularly women [10], place great stock in teaching methods that *they perceive as relevant to their lives*. Without a realistic believable scaffold on which to construct knowledge, concepts remain isolated [11], [12]. While instructors often incorporate relevance by discussing applications or examples in lecture, students often lack the requisite experience base to appreciate fully the utility of course concepts.

Attempts to use alternatives to lecture in the engineering curriculum range in size from individual courses to departmentwide efforts and regional coalition programs [5]–[7]. One widely successful model is the capstone design program used at many universities, including OSU [13], [14]. Capstone programs expose students to many of the realistic constraints faced by engineers. While data is sparse, improvements in student performance are observed in several studies [15], and capstone experiences are reported positively by graduates [14]. Replacing lecture with active learning is also effective, often by organizing courses into modular units that focus on a real-world scenario or problem [16], [17]. Relevance is emphasized since learning focuses on a real situation. A variety of methods to implement active learning have been developed, including case studies [18], design projects, guided design [19], and individual

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research projects. Several studies [16], [20], [21] have demonstrated significant student gains by using active learning; gains are often retained in follow-on **<AUTHOR: Should this be follow-up?—ed.>** courses [21]. The most striking gains are often gender specific; women improved markedly more than men [21]. A large study of engineering courses taught using active and collaborative methods reported gains of 11% in communication skills, 23% in design skills, and 34% in team skills compared with lecture courses [16] with marked improvements in the "a–k" outcomes required for EC-2000.**<AUTHOR: Please define EC-2000—ed.>**

To overcome some of the limitations inherent to lecture, the authors have developed a two-course undergraduate sequence in the multidisciplinary area of photonics, the Light Applications in Science and Engineering Research Collaborative Undergraduate Laboratory for Teaching (LASER CULT). The LASER CULT emphasizes relevance to students by using case studies as scaffolds and replacing lecture with active learning [16], [17], [22]. A common structure minimizes student discomfort induced by an unfamiliar teaching style and allows the instructor to utilize elements from one course in many other courses, reducing duplicate efforts in developing teaching resources. The thesis of this project is that lecture-based instruction is contrary to student expectations of the authentic practice of engineering and that it contributes to students' seeing course work as "disconnected" from reality [23]. The LASER CULT has the following three primary goals:

1) make course concepts more relevant to students;
2) provide students experience in functioning cooperatively on a team;
3) stimulate interest in photonics by utilizing in-depth projects that build higher level problem-solving skills, such as evaluation and synthesis [1].

Course relevance is one of the major sources of student motivation and enjoyment [24]. When course work is perceived to have relevance to students' personal or professional lives, overall satisfaction and performance in a course are often increased [25]. Students who perceive a course to be highly meaningful report significantly higher levels of intrinsic goal orientation and self-efficacy and lower levels of test anxiety [26]. Both relevance and environment play a role in students' intrinsic interest in academic tasks. While competitive academic environments often result in lower self-esteem and perceptions of competence in students [27], cooperative environments may mediate cultural differences and positively affect learning outcomes [28]. Since the educational environment has been shown to play a large a role in whether a cooperative or competitive environment is engendered [29], the authors wished to see the impact of an authentic, collaborative environment on student teams.

The remainder of this paper discusses the development and implementation of the LASER CULT. Section II covers implementation of active and project-based learning (PBL) in the LASER CULT, while Section III provides details on specific projects and case studies. Analysis of two years of assessment data is presented in Section IV, and positive and negative results discussed.

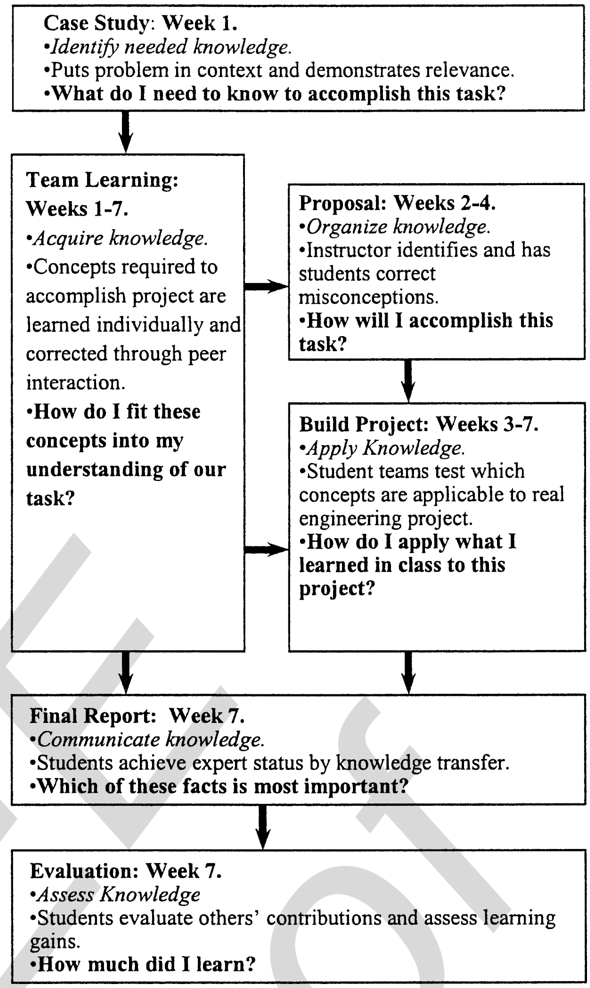

Fig. 1. Diagram of a focus area. Each block corresponds to a different teaching method or team milestone. Bullets indicate the goal, objective, and student perception of each block.

II. Structure of the LASER CULT

The LASER CULT is made up of one junior and one senior elective. The courses meet three times per week for 50 minutes at a time. Course enrollment varies from 10 to 25 students. Each individual course is divided into two *focus areas*. A focus area is an in-depth project in which students research, design, build, and test a particular photonic device. The focus area is divided into six interrelated elements, shown in Fig. 1, and integrates a case study [18], [30], modified team learning [31], and PBL [17] to provide student teams with the concepts and skills needed to design and construct the device. The case study places the project in the context of student experience, while team learning introduces concepts needed to complete the project successfully. PBL enables teams to complete a design–build–test cycle in an environment designed to mimic that of engineering project teams in industry. Each element of a focus area (Fig. 1) is described chronologically in the following paragraphs.

A focus area begins with a case study [18], [30], [32] to provide relevant scaffolding [11], [12]. The case study incorporates emerging knowledge with ethical and social issues as a story in a context relevant to students. Since students have little or no prior knowledge of the focus area being covered,

TABLE I
LISTING OF THE FOUR FOCUS AREAS THAT MAKE UP THE LASER CULT. EACH FOCUS AREA INCLUDES A CASE STUDY, KNOWLEGOS, AND PROBLEM-BASED LEARNING

Focus Areas			
Topic	**Case Study**	**Project**	**KnowLegos**
Geometrical optics	*The Zoom Lens*: A team of engineers develops a zoom lens for a movie studio in circa 1950's Hollywood	Design and build a zoom lens to maximize zoom ratio and minimize aberrations.	1] Fundamentals of geometrical optics (refractive index, Huygen's, Fermat's, Fresnel's laws); 2] Real and virtual images; 3] Thin and thick lens equations and the paraxial approximation; 4] Magnification; 5] Multiple lens imaging systems; 6] Ray-tracing software; 7] ABCD matrix formalism; 8] Calculating ABCD matrices with Matlab; 9] Cardinal points; 10] Seidel aberrations (2 KnowLegos); 11] MTF and measuring aberrations (2 KnowLegos); 12] Apertures
Spectroscopy	*Electric Storm on the Horizon*: A team of students determines threats to groundwater from a containment facility for power plant waste. *A Case of Serial Murder*: Forensic evidence analyzed by students lead to identification of a serial killer.	Detect the presence of fluorescein dye in water (electric storm) or the catalysis of fluorescin to fluorescein in the presence of blood (serial murder).	1] Particle picture of light; 2]Energy levels in atoms, molecules, and semiconductors; 3] Absorption & fluorescence; 4] Spectrometers; 5] Optical filters; 6] Optical sources- blackbody and incandescent; 7] Optical sources- LEDs; 8] Optical detectors, PMTs; 9] Optical detectors, photodiodes; 10] Phase sensitive detection and electronic filtering
Gaussian Beam propagation	*It Takes a Light Touch*: Engineers at a small startup company team up with biochemists to provide optical tweezers for engineering DNA strands.	Design and build optical tweezers from discrete components to trap ~4μm particles.	1] Safety; 2] Review of electromagnetics (two KnowLegos); 3] Coherence and Uncertainty; 4] ABCD Matrices; 5] EM field of a confined beam- derivation of Gaussian beams; 6] Propagation of Gaussian Beams (two KnowLegos); 7] Gaussian beams in optical systems (two KnowLegos)
Laser operation and design	*Death at Minus 4000 Feet*: After a tragic death of a cave exploration team in Yucatan, biologists, spelunkers, and engineers team up to undertake aerial mapping of undersea cave outlets using a custom-built laser.	Design, build, and characterize a working frequency doubled diode pumped solid state laser.	1] Beams in cavities (three KnowLegos); 2] Longitudinal modes; 3] Photon lifetime and finesse; 4] Review of differential equations; 5] Einstein A and B coefficients (two KnowLegos); 6] Line shape (two KnowLegos); 7] Optical amplification; 8] Differential equations for a cavity (three KnowLegos); 9] Example laser system: Nd:YAG; 10] Advanced topics including nonlinear optics, ASE, and Q switching

the case study includes introductory concepts with citations. Since students construct new knowledge by building upon their prior knowledge [33], analyzing the case study helps to identify unfamiliar (new) concepts and permits students to identify concepts which are "familiar" but not fully and accurately understood [33]. During class discussion of the case study, students contribute to a group understanding of the design problem, providing a context for team learning. Cooperative interaction within groups allows scaffolding of concepts and processes. Case studies improve class participation during the critical first days of a focus area since students enjoy exploring the social and ethical impacts of technology. Case studies written for the LASER CULT are fictional stories based on research publications which emphasize cross-disciplinary and emerging knowledge—often a problem encountered by young engineers at a small start-up company. A list of the case studies that have been taught in the LASER CULT is given in Table I. Cases are available on the LASER CULT Website [34] or the National Center for Case Study Teaching in Science [35].

While reading the case study, students are assigned the task of making a list of concepts with which they are not familiar and a list of important design parameters for the device. The instructor mediates the class discussion, first summarizing the case and then discussing social and ethical issues and finally specific and technical design issues. Case study discussion concludes with the creation of a list of issues and concepts that students must understand in order to undertake the design project. The instructor organizes concepts to match the topics that are covered in reading assignments and distributes this list to the class. Case study discussion permits the instructor to assess the level of student preparation in the class discussion, identify concepts that need to be covered in depth, and plan reading assignments in the following weeks.

Following the case study, a modified form of team learning, *KnowLegos*, teaches concepts and analytic skills needed to design and build the photonic device covered in the focus area. Team learning is more than students working in teams; it formalizes both individual preparation and cooperative learning by utilizing cooperative student groups and formative testing to simulate proven teaching methods, while minimizing faculty time required for implementation [31], [36]. Team learning has proven to be a highly effective alternative to lecture, resulting in dramatic increases in student comprehension [36] and enhanced group cohesiveness [37]. The standard form of team learning—in which students are given daily reading assignments and tested on comprehension both individually and as a team using multiple-choice formative examinations—has been utilized in introductory courses but not widely applied to engineering courses. Difficulties can arise both in the use of multiple-choice exams [38] and in comprehension difficulties inherent to many engineering texts.

The LASER CULT modifies team learning to assist student comprehension of mathematically based materials found in engineering texts. Teams are formed by the instructor at the beginning of the semester and consist of three to six students. Teams are heterogeneous and formed following standard practices [37]. Web-based interactive reading assignments cover specific concepts and describe how the concepts are related to the case study. These assignments are called KnowLegos and completed by each student prior to class. As with the popular toy, each KnowLego is a simple concept from which complex structures can be built. Each KnowLego contains an interactive online quiz [39], [40], which students may take multiple times [41]. The quiz is formative, guiding students to important concepts in the reading assignment with problems written in the context of the case study to highlight relevance to the focus area project. Student questions about the KnowLego are posted to a class Web log, which is monitored by the instructor or teaching assistant (TA). Use of a Web log addresses one of the major difficulties in implementing team learning: providing sufficient time to prepare responses [36] and opportunities for peer and instructor scaffolding.

By completing a KnowLego, students enter class prepared. During the class period, the instructor first answers questions submitted to the Web log, providing additional scaffolding, and lectures only if requested to do so by students. Most classes are devoted to active learning, using in-class assignments given to student teams. The in-class assignments consist of analytical, computational, and/or laboratory work to integrate concepts from the KnowLego with the focus area project and case study. In-class assignments require students to break the assignment down and divide tasks among team members rather than working in a linear, sequential manner [36], [42]. These in-class assignments focus on design or construction aspects of the focus area project, allowing feedback and supervision by the instructor. Students correct each others' misunderstandings from the reading assignment, providing scaffolding, with the instructor aiding groups when needed.

Lectures are utilized as an alternative to team learning when scores on the online quizzes indicate that students need additional explanation of the reading material. When students require three or more attempts to solve more than half of the quiz problems, a lecture is substituted for the in-class assignment. Lectures may also be given when student feedback on the discussion board indicates that there are problems with comprehension. Lecture is substituted for active learning approximately one class in six.

To focus student learning on specific quantifiable goals and to permit students to utilize knowledge acquired during team learning, the LASER CULT utilizes PBL [19]. PBL is a collection of education techniques that structures learning around a problem to be solved rather than a set of hierarchical concepts. PBL emphasizes task mastery over aptitude and ability. Environments that emphasize comparative ability and competition engender ability-focused goals in students, while cooperative environments that focus on task mastery encourage students to adopt task-focused goals [43], [44]. Students who pursue task-oriented goals tend to use deep cognitive processing strategies, to be more creative, and to continue to be interested in a task after formal instruction is completed, while the opposite holds true for students who pursue ability goals. The LASER CULT implements the authentic approach [45] of PBL in four consecutive phases:

1) project design culminating in a written proposal;
2) construction of a working prototype;
3) preparation of a written report on the project results;
4) project evaluation.

The authentic approach to PBL utilizes ill-structured problems that would be encountered in the real world and develops skills used by experts.

Midway through the focus area (Fig. 1), each team prepares a written proposal [14] that is evaluated using a rubric [46]. Submitted proposals are not graded; rather, as in research proposals, they are accepted, accepted pending mandatory revisions, or rejected. Rejected proposals and those needing major revision are revised and resubmitted until they meet the minimum evaluation criteria specified in the rubric. Proposals summarize teams' preliminary design, including data and/or modeling that demonstrates the approach is feasible. The proposal contains references to existing work to build skills in information literacy skills [47] and outlines specific responsibilities of each team member as a Gantt chart [48].

The proposal also contains a budget that lists all components and instrumentation needed to construct the project. Teams choose components from an online catalog developed for LASER CULT courses [34]. Catalog items are listed at retail prices from vendors to familiarize the students with the actual cost of their design. Preparation of the budget requires teams to choose from an array of items to construct an optimal solution, a key engineering skill. Proposal preparation ensures rigorous design rather than a trial-and-error approach to problem solving. To avoid task overload, proposals are limited to five pages in length.

Once a team's proposal has been accepted, parts requested in the budget are checked out by a TA and logged using inventory control software. Each team is assigned a cabinet for storage of parts and tools and bench space on an optical table. Teams are credited an amount equal to 20% of the requested budget to purchase additional parts, if needed. Teams assume ownership of all equipment and supplies they have checked out and are responsible for replacing items damaged through negligence. Ownership permits students to self-schedule times to work on a project, freeing up faculty time and reducing the number of required TAs. No equipment is set up by the TA or faculty, with the exception of data acquisition software. This "bare bench" approach has been previously used in photonics education [49]. A key concern is adequate safety training, especially with the optical tweezer and diode-pumped solid-state laser projects or projects using a photomultiplier tube. To ensure safety, student teams must demonstrate safe operation using low-power alignment lasers and must pass a safety review before being permitted to use potentially hazardous equipment. In addition, all students are required to undergo safety training certification by the university laser safety officer.

One disadvantage of the "bare bench" approach is the potential waste of student time on problems that are easily solved by a TA or faculty. This problem is exacerbated by having no scheduled laboratory times but mitigated by submission of a detailed design proposal. To further minimize wasted student time, each team is credited 10% of the project budget to spend on consulting. Faculty and TAs charge consulting fees to aid teams in design or construction; the faculty charge is $600 per hour, and the TA's charge is $120 per hour. Although seemingly time consuming for faculty, this method has proven extremely effective to help minimize faculty time used in teaching a design intensive course. By associating time with money, students come prepared with questions and only seek instructor input as a last resort. This cooperative approach teaches teams to exhaust their own resources before seeking outside help. While each team competes in product performance against the other teams, interteam communication is encouraged.

Project construction makes the design experience relevant and authentic by permitting students to test the validity of their conceptual understanding. Experimental design work is by nature a complex problem that serves to reinforce the value of cross-disciplinary knowledge; project completion requires skills outside those specifically addressed by KnowLegos. Students must develop effective teamwork skills since projects are too complicated for most individuals.

At the conclusion of the project, teams prepare a written report based on a rubric to ensure consistency between teams and communicate expectations [46]. While the exact format of the report varies between projects, all reports contain measured specifications and individual statements by each team member. Having students generate project specifications is a key element in effectively using PBL in the LASER CULT. By measuring project specifications, student teams quantify their project, making it concrete rather than abstract. On the day that the final report is due, teams demonstrate their projects during class, showing the project meets the reported specifications. Informal presentations are used since more formal oral presentations have been shown to impact student satisfaction negatively in courses where presentations are combined with teamwork [37]. Following the demonstration, projects are judged by the instructor based on cost and performance. Individual statements by each team member enable students to reflect [50] upon the project and their individual contributions; these statements are used to assess student attitudes and learning. The written report serves as a student-generated portfolio for assessment. Similar to academia or industry, evaluation of the success of the project is based on the written report. Teams may submit reports for instructor feedback prior to the submission deadline, as is common practice in academia or industry.

A focus area concludes with two evaluation metrics, team peer evaluations [31], and a student assessment of learning gains (SALG) [51], [52]. Peer evaluations enable each team member to evaluate the overall contributions of the other team members. An individual student's project grade is scaled by the mean rating given by their team members. Any team member who receives a peer rating of less than 70% on all focus areas fails the course. Over three years, fewer than 3% of students have failed the course because of peer evaluations. However, students are informed on the syllabus that the instructor reserves the right to modify peer evaluations to ensure fairness in grading. This step had been necessary on one team when students formed cliques. However, properly selecting teams and training students to function on teams helps avoid this dilemma. Peer evaluation is highly effective in helping equalize contributions from all team members [31]. To identify ineffective groups and aid the instructor in resolving team problems, a mock peer evaluation is performed after proposal submission. If necessary, the instructor helps resolve differences among team members. Typically, team differences are worked on during the first focus area, and teams function much more smoothly in later focus areas. The SALG, used for assessment, is discussed later.

Student grades in the LASER CULT are determined by a combination of individual and team assignments [31]. Formative quizzes from KnowLegos (15%) and a comprehensive final examination (20%) are individual grades that are not scaled by team evaluations. Team grades—the two project reports (25% each) and in-class assignments (15%)—are scaled by each student's overall team evaluation score. In team learning, grades are not "curved" [31]; however, students are allowed to adjust the relative contribution of quizzes, in-class exercises, project reports, and the final exam by $\pm 5\%$.

III. Focus Areas

The two courses that make up the LASER CULT are a junior-level introduction to photonics and a senior-level course on lasers; each contains two focus areas. Focus areas in the junior course cover geometrical optics and imaging and spectroscopy taught from Hecht's *Optics* [53]. Focus areas in the senior course cover laser beam propagation and fundamentals of laser operation taught from Verdeyen's *Laser Electronics* [54].

The focus area covering geometrical optics has student teams design and build a zoom lens. The case study [55] is based on the fictional story of a motion picture company (circa 1950 Hollywood) that is having problems with antiquated equipment. The actors and crew demand that the president of the company purchase a newly developed zoom lens; the president is concerned about the cost. The students play the role of an engineering design team at a small company. Zoom lenses, discussed in detail in [56], create a change of magnification with little shift of the image plane. While a variety of methods exist to accomplish the magnification change, the simplest to implement is an odd number of alternating fixed and movable lenses. Increasing the number of optics results in larger magnification changes at the expense of increasing complexity and aberration.

The KnowLegos associated with this focus area cover a range of topics in geometrical (ray) optics, listed in Table I. In-class exercises associated with the KnowLegos involve both analytic and laboratory exercises designed to walk teams through the zoom-lens design process, providing scaffolding. In the design phase, student teams develop a zoom lens design by first solving the polynomial equations for image plane position and magnification in Matlab [57] for the lenses available from the online catalog. A commercial ray tracing program, Optics Lab, allows teams to model the zoom system and calculate the effects of lens aberrations and aperture stops on image quality. Additional optics reduce the zoom image to fit on the “film, ” in this case a half-inch format charge-coupled device (CCD) camera.

Student teams build their lenses using commercial cage or rail systems. Images are acquired on a CCD camera and saved as electronic files. Imaging targets, including grid and line patterns, allow teams to measure the lens modulation transfer function; grids of colored light-emitting diode (LED) lights are used to measure chromatic aberration. Most teams are able to build a five lens system successfully with a zoom range of 5:1. While student systems are not of commercial quality because of aberrations and stray light, appropriate use of aperture stops permits teams to acquire images of sufficient quality to analyze the effect of aberrations.

The second focus area, an introduction to spectroscopy, covers a wider range of topics (see Table I). Two case studies are available in which student teams design and build a fluorometer to detect the presence of fluorescein dye. The first case study covers containment of toxic waste in porous karsts; dye is introduced in containment ponds to track the flow of contaminated ground water [35]. The second case study is based on forensic investigation of blood stains at a crime scene. Student teams must track down a serial killer by using their fluorometer to investigate evidence, detecting blood stains that catalyze the conversion of fluorescin to fluorescein, a common technique in forensics [58]. This progressive disclosure case explores ethical questions of relying on forensic evidence in capital cases.

Team learning covers the components of a commercial fluorometer, including light sources, detectors, filters, and phase-sensitive detection. Additional KnowLegos review fundamentals of spectroscopy, including the photon model of light and how spectrometers work. These topics emphasize how photonics interfaces with electrical engineering, particularly in developing optical filter systems based on transfer functions. In this focus area, less emphasis is placed on numerical modeling, and in-class exercises are conducted in the laboratory to allow student teams to collect preliminary data on fluorescence and filters for design proposals. Teams must demonstrate that their fluorometer minimizes detection of excitation wavelengths while maximizing throughput of the green fluorescence using an optical system that maximizes light collection.

In constructing the fluorometers, students use a variety of color glass and interference filters with both photodiodes and photomultiplier tubes (PMTs); high-voltage safety is stressed heavily before teams are allowed to check out PMTs. Teams have used both LEDs and filtered white light for excitation sources. For measurement of water contamination, the goal is to simply detect the presence of fluorescein in water. Teams mix test samples to measure the sensitivity of their instruments and determine the fluorescein concentrations of instructor-provided samples during the demonstration. Teams have access to pH and temperature sensors [59] to measure these effects on quantum efficiency. Student constructed fluorometers using LED sources have demonstrated sensitivities below 10 ppb **<AUTHOR: Please define ppb—ed.>**of fluorescein in water.

In the forensics case study, teams must determine whether evidence—including samples of clothing, wood, cardboard, and carpet—have blood on them. While student fluorometers are capable of detection of 10 parts per million (ppm) of the cow blood used for samples in solution, detection of blood on samples is more difficult because of problems of light collection. However, most teams are able to identify blood-contaminated evidence with approximately a 70% success rate.

The first focus area of the senior course covers propagation of Gaussian beams, with teams designing and building optical tweezers. In the case study, a biomedical researcher at a large research hospital seeks a way to manipulate individual DNA bases. The doctor is contacted by an old college friend about a new technique [60] that uses optical tweezers to move small spheres on which cutting enzymes have been attached to specific spots in the DNA chain. The friend works for a small start-up company that builds optical tweezers and wishes to be included in the research program but must first convince the hospital director and the medical board of the potential of this technique by demonstrating a prototype system.

Team learning covers Gaussian beam optics and propagation, using the KnowLegos listed in Table I. In-class exercises include analytical exercises and laboratory demonstrations to familiarize students with technologies used in constructing the optical tweezers. Optical tweezers make use of very tightly focused beams to exert trapping forces on small particles; the trapping strength is dependent upon the waist diameter and beam quality [61]. The proposal requires teams to design an optical system to focus an He–Ne laser beam to a minimum spot size with a 100× microscope objective by matching the beam profile and radius of curvature to either the Deutsche Industrie Norm (DIN) or Japanese Industrial Standard (JIS) standards, dependent on the objective. Data gathered during in-class exercises, such as beam profiles, lets students do numerical modeling of optical tweezers.

Rather than use modified microscopes [62], teams construct optical tweezers from discrete components. Low power ($\sim$1 mW) He–Ne lasers are used for alignment; when a team demonstrates safe operation, a 15–20-mW He–Ne is used to trap 3.7-μm latex spheres in a soap solution. Trapping is verified by collecting images of trapped spheres on a CCD camera. In constructing optical tweezers, the most common difficulty is ensuring that the minimum laser spot size and the microscope focal plane are coincident. Teams also find that distances calculated using Gaussian beam optics are not exact in practice because of focal length variations of lenses and uncertainty of measurements of the laser beam waist and curvature. Students are familiarized with the procedure for cleaning optics prior to constructing the optical tweezers. Over two semesters, the success rate of the optical tweezer project has been 100%. Teams have trapped pond organisms, E. coli bacteria, and made patterns of spheres by moving them to the surface of the microscope cover slip; images from student projects are shown in Fig. 2. E. coli bacteria make an interesting sample; since they are ovoid, the long axis rotates to align with the laser beam.

The second focus area in the senior elective class is the design and construction of a diode-pumped, solid-state laser [63]. The case study involves a team of biologists who are looking for extremophiles, organisms that live in fresh water/salt water boundaries in the deep caves in Mexico’s Yucatan peninsula.

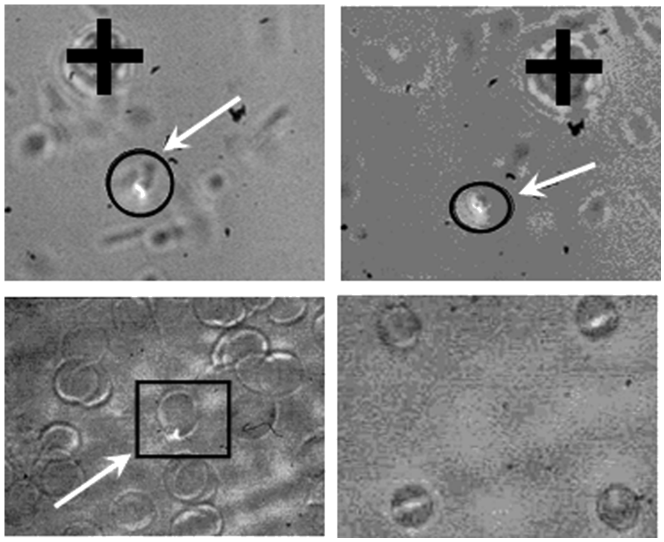

Fig. 2. Example figures from student portfolios in the optical tweezers project. The upper two figures show evidence of moving a 3.7-μm particle. The lower figures show the trapping of human red blood cells (left) and a square pattern of 3.7-μm particles made using optical tweezers.

After a fatal accident, the team leader works with an electrical engineering graduate student to design a portable laser that can be used for aerial mapping of dye released into the cave system. Mapping where the dye exits into the ocean, using an ultralight airplane, allows the researchers to map the cave system. The graduate student designs a diode-pumped, frequency-doubled, solid-state laser using neodymium-doped vanadate (Nd–YVO_4) as a gain medium and the nonlinear material potassium titanyl phosphate (KTP) for second harmonic generation.

Team learning and KnowLegos for this focus area cover design of laser cavities and modeling laser gain media through rate equations and Einstein coefficients, as shown in Table I. In-class exercises focus on solving systems of first-order coupled differential equations numerically in Matlab. Because of the difficulty of this project, the requirements for the design proposal are more stringent. Teams measure the fluorescence lifetime and spectrum of Nd–YVO_4 and the wavelength versus temperature dependence of the diode laser pump as in-class exercises to acquire data used in the design proposal. Teams' designs must determine the overlap between the diode laser pump and cavity mode, mirror reflectivities that maximize power generation, the measured values of the absorption and lifetime of Nd–YVO_4, calculation of the laser threshold, and the modeling of cavity rate equations.

Prior to constructing the diode-pumped, solid-state lasers, students receive extensive safety training. Students who violate safety regulations are penalized; the maximum penalty is receiving a grade of zero in the course. A selection of vanadate, KTP crystals, and cavity optics are available to teams. The lasers are pumped with 1-W laser diodes thermoelectrically temperature-tuned to 808 nm. Students align the cavity using a low power He–Ne laser and must demonstrate their design is safe and free from stray reflections prior to being given a laser diode driver. Achieving threshold operation of the laser cavity is not difficult, but teams have difficulty with alignment and often do not realize the importance of temperature-tuning the diode laser. A small spectrometer (Ocean Optics PC-2000), a sensitive power meter, and low-cost "night vision" viewers are used to aid in alignment. While nearly all teams achieve lasing, there is a wide range of power outputs that depend on mode matching the pump and cavity beams and the beam size within the KTP crystal.

IV. Assessment

Assessment data was collected for the LASER CULT courses from fall 2001 to spring 2003. The assessment metrics used include a SALG, student-generated portfolios containing individual reflective statements by each student, student questionnaires used for ABET, standard instructor and course evaluations, and statistical data from the WebCT quizzes (web-based formative evaluation). Changes to the course format precluded using final examinations to determine changes in student learning before and after implementation of the curriculum reforms described previously. However, this model has since been implemented in other engineering courses at OSU with slight, but not statistically relevant, increases in final examination scores. The broader implementation will be discussed in a subsequent paper.

The SALG was used to analyze student perceptions of learning on different aspects of the course (Fig. 1), including team learning, the case study, the project, written reports, and the team evaluations. Besides requesting information on learning gains and the quality of specific aspects of the course, questions gauged student opinion of LASER CULT courses in comparison to other engineering courses. SALG results were correlated with one-page statements from each student appended to the project reports. Students were asked to reflect on their individual responsibilities, what they learned from this project, the most and least valuable aspects of the project, and any problems encountered. While individual statements generally focused on technical issues, less technical themes embedded within these statements included teamwork issues, problems based on the availability of resources, and the relevance of the learning experience. A qualitative review of personal statements and SALG responses was performed to assess student attitudes and learning gains for the educational goals of the LASER CULT.

The primary goal of the LASER CULT is to enhance students' perception of course relevance, or meaningfulness, by creating an authentic learning environment. On average, 94% of the SALG respondents indicated that the case study information provided to the students was a good way of making the presented problem relevant. The use of the "bare bench" model—including ownership of parts, choosing components from a online catalog, and focus on product development—was also helpful. Overall, 78% of SALG respondents felt that this model helped make the material more relevant and promoted learning. Relevance was also a significant theme in student feedback. There were a number of comments that addressed the real-world relevance of the semester projects. Comments from students often indicated that they saw applicability of the projects to their future careers. Such comments were often tied closely to positive statements about teamwork. Other comments related that posing problems in a relevant framework helped to clarify the mathematics required in the design phase.

The second goal of the LASER CULT is to provide students with training and positive experiences in functioning on a team. Teamwork was a major theme that emerged from the student feedback in the LASER CULT. Student responses to the SALG showed that 94% of the respondents felt that they learned more from working in a team than by themselves. Since both courses are electives, the sample population could potentially be self-selected toward those students who favor a group-oriented approach. The data, collected from the start of implementation of the team-based approach over three years, does not show any increase in student satisfaction with teamwork as would be expected if students chose these courses based on the teaching style. Students made repeated references in individual statements to the benefits of a cooperative team-based approach to problem solving. Themes common to the positive responses were division of responsibility, patience with others, cooperation, and the necessity of a well-defined team structure as opposed to the amorphous groups often formed by students. There were also a significant number of negative comments about the teamwork aspects. These generally centered on one of two issues: unfair distribution of effort and language barriers.

Despite large differences in perceived efforts among team members, most students still give relatively high (>80%) peer evaluations. As students become better at team work, the peer evaluations tend to become more uniform, indicating better division of labor within the team. Averaged over three semesters of the senior course, the standard deviation of the first peer evaluation is 9.9 points on a 100-point scale, the second evaluation is 7.1, and the third evaluation is 7.8.

The third goal of the LASER CULT is to demonstrate that gains in student learning can be achieved by focusing learning on in-depth projects. Assessment analysis sought to determine whether the emphasis on a single project in a focus area affected the amount or quality of student learning and which aspect of the focus area most contributed to learning. Overall 80% of the students indicated that the focus on two projects over the semester rather than a number of smaller homework assignments did not detract from their learning. On average across courses and semesters, 85% of the students indicated that the LASER CULT format was better than a standard lecture format in terms of learning gains. The SALG results show that students feel that grades activities, including tests, quizzes, and in-class assignments, make the largest contributions to their learning.

The environment of the LASER CULT is designed to mimic that of industrial or academic research programs. Students were informed by the instructor at multiple points in the course that the LASER CULT mimics the environment of graduate research programs. To evaluate how the LASER CULT affected students' desire to pursue a graduate degree, the SALG asked students to rate, on a Likert scale ($1 =$ much less likely to $5 =$ much more likely), the impact the LASER CULT had on attending graduate school. The results, only available for one semester in the senior-level laser course, showed a mean score of 4.12 with 0% of students reporting the course had a negative impact, 38% reporting no impact, and 62% reporting positive impact. In comparison, a control sample of three junior-level courses taught using lecture had a mean score of 3.07 with a negative impact on 7% of students, no impact on 79%, and a positive impact on 14% of students.

Analysis of assessment also focused on the instructional format of the LASER CULT; course formats significantly different than student expectations may lead to dissatisfaction [64]. Student dissatisfaction with the LASER CULT arose over two items. SALG results indicated that students felt that the course TA provided little or no help to the student in terms of individual support. This situation is also reflected in the personal statements. Difficulties with equipment were also mentioned commonly in the reflective statements. These two comments most likely stem from the open-ended nature of the LASER CULT projects, making the TA's task of assisting teams difficult. The "bare bench" model means students are able to make more mistakes in setting up equipment. By purchasing from a large selection of components, poor purchasing decisions result in technical difficulties. While frustrating for students, the authors feel that such experiences reflect a realistic engineering environment and may be valuable in students' long-term professional development. Such problems would be less acceptable in introductory courses where students are less emotionally resilient. In response to student criticisms, more tutorial assistance is available, through both online tutorials [34] and how-to sessions external to class. These serve as additional scaffolding and ensure that students with little previous laboratory experience are not denied opportunities for success.

V. Conclusion

The LASER CULT is an undergraduate photonics curriculum that integrates three active learning methods: case studies, team learning, and project-based learning. The curriculum model succeeds as an introduction to optics and photonics for electrical engineering students. Student feedback is generally positive, with students self-reporting learning gains as opposed to lecture courses. Negative perceptions focus on task overload because of the open-ended problems that make up the LASER CULT. Assessment data indicate that the LASER CULT makes course concepts more relevant to students and provides positive experiences in functioning on a team through a focus on in-depth projects. The LASER CULT is synergistic with ABET outcomes, particularly "soft" outcomes (d, g, h, and i of criterion 3).

This curriculum is designed to place more of the responsibility for a student's education on the student rather than the instructor as in a traditional lecture class. The responsibility of the instructor is not lessened; however; less emphasis is placed on dispensing information and more on preparation and interaction with students. In the authors' experience, less time is taken in traditional tasks such as grading and lecturing. Rather, this time is devoted to scholarship in designing laboratories, preparing formative evaluation, and providing necessary resources for students.

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Arthur McGovern, photograph and biography not available at the time of publication.

Kay S. Bull, photograph and biography not available at the time of publication.