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Thank you for your interest in this work.

Kevin Houser

A CORE LIGHTING CURRICULUM FOR UNIVERSITY STUDENTS AND LIGHTING PROFESSIONALS

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Abstract

In collaboration with a group of lighting professionals, learning outcomes were defined, prioritized, organized, and mapped to a three-course sequence of lighting courses within a Bachelor of Science in Architectural Engineering degree program. Syllabi and educational exercises were developed to support the learning outcomes—including classroom activities, homework assignments, and design projects. The learning exercises balance the technical foundations of applied illuminating engineering with the artistic aspects of applied lighting design and are intended to promote significant and lasting learning by providing students with education that is useful and relevant to current lighting practice. The process for identifying and prioritizing lighting content is described, a process that could be adapted by other lighting educators to other pedagogical contexts. The syllabi and learning exercises are disseminated for reuse or adaptation, or for self-study by independent learners.

Keywords: Lighting Education, Learning Outcomes, Curriculum Development, Self-Study

1 Introduction

1.1 Background

Lighting is currently undergoing a significant period of transformation, creating new opportunities for educators. What was once an analogue technology, is now solid state. Software for architectural modelling and lighting design is ever evolving, including integration with tools for building information modelling (BIM), spectrally-based simulation, parametric modelling, and emerging uses of artificial intelligence. Controls technologies are rapidly changing, with greater complexity and diversity of potential solutions. Project timelines often make design-bid-build impractical, challenging conventional project workflows and demanding innovations in project delivery. As the lighting community becomes increasingly aware of how light affects physiology, the impact of light on health has become an increasingly important matter for design. While designing lighting for people, professionals must also consider the sustainability of planet earth, including collateral impacts on flora and fauna. Product sustainability is salient, including material use, embodied carbon, and circular economy solutions. Programs like LEED, WELL, ENERGY STAR, Design Lights Consortium (DLC), and others now influence design goals and equipment selections. Diversity, equity, and inclusion in lighting are increasingly recognized, and should play a larger role in design as the lighting community collectively develops understanding, tools, and techniques to address light justice. This is a lot of information to process and prioritize.

Though the contemporary context is rapidly evolving, lighting design and illuminating engineering are grounded in timeless principles. Applied illuminating engineering topics such as luminaire photometry, solar geometry, and diffuse radiative transfer are foundational, as are basic principles of design, including the integration of light with architecture and the use of light to support vision and psychological wellbeing. Against these timeless topics, however, lighting design education and practice must adapt to new technologies and knowledge, including deeper understanding of how light affects health, increased sensitivity to sustainability goals, increased awareness of ecological and social consequences of lighting design decisions, and the ability to use contemporary computational tools.

How should the breadth of all possible lighting knowledge be prioritized, organized, and delivered when developing or revising a curriculum about lighting for the built environment? What is best learned during

university studies in preparation for professional practice, versus the knowledge, skills, and abilities that could be learned on the job through lifelong learning and continuing education? These questions have no obvious answer. A universal lighting syllabus will always be elusive because prioritization will depend on factors that include academic home (*e.g.* architecture, engineering, interior design, theatre); accreditation requirements;¹⁻⁴ institutional factors that include culture, constraints, and support; instructor factors that include interests, capabilities, and availability; and expectations of regional employers.

The context for the curriculum development efforts reported in this manuscript is Oregon State University's Bachelor of Science in Architectural Engineering (ARE) program, which is housed within the School of Civil and Construction Engineering, itself housed within the College of Engineering. The ARE degree was launched in 2018 to complement two pre-existing degree-programs in the School of Civil and Construction Engineering, Civil Engineering and Construction Engineering Management. The four-year ARE curriculum is provided as **Figure 1**.

Architectural engineering is a profession where knowledge of mathematics and natural sciences are applied to the engineering design of buildings and their environmental systems. Architectural engineering degree programs that are accredited by ABET provide students with depth of knowledge in most or all of a building's engineered sub-systems, while providing depth in one or two sub-systems. ABET identifies four curricular areas as building structures, building mechanical systems, building electrical systems, and construction. Some ABET accredited architectural engineering programs also provide strong curricula in lighting and/or acoustics. In the United States, earning an ABET accredited degree is a step toward becoming a licensed professional engineer, which is distinct from other academic pathways that would lead to becoming a licensed architect or a registered interior designer.

Few would disagree with the statement that lighting is both a science and an art, but the statement invites examination.⁵ To categorize bluntly, some academic programs, companies, or individuals may more closely identify with light as an art and be drawn to the practice of lighting design,⁶⁻⁸ while other academic programs, companies, or individuals may better identify with light as a science and be drawn to the practice of applied illuminating engineering.^{9,10} Further still, some approach lighting emphasizing its effects and outcomes, which may be visual, psychological, physiological, or ecological. Others approach lighting emphasizing its technology, focusing on the light sources, optics, and controls that enable illumination of the built environment.¹¹⁻¹³ It is valid to view lighting through a lens of art, science, vision emotion, physiology, ecology, and technology—or some combination. Yet, while these are all valid proclivities, and any can be a successful framework in limited situations, none, on their own, encompasses the range of skills that are needed for the diversity of applications of light in the built environment.

For example, lighting a roadway, parking lot, or sports field to be compliant with the many available quantitative benchmarks and code requirements is facilitated by technical engineering skills. Conversely, lighting an art gallery, restaurant, or house of worship is facilitated by emotive and aesthetic design skills. Meanwhile, an outdoor pedestrian district—where effective lighting will support users visual and emotional needs while being ecologically sensitive and complying with code requirements—is an application that demands skills in both the technical and artistic domains of lighting. In practice, all common lighting design applications benefits to some degree by both technical and artistic skills, and some consideration of how design decisions will influence human vision, psychology, and physiology, and ecological impacts on non-human life.

Despite apparent tension between lighting as an art and science,^{6,14} some architectural engineering programs in the United States encourage aptitude in both the technical and artistic domains of lighting. Striking an appropriate balance between lighting as art and lighting as science was foundational to the work described in this manuscript. We aim to produce graduates that identify as both lighting designers (*e.g.*, competent with aesthetic and creative uses of light, including how light influences mood, atmosphere, and visual experience) and applied illuminating engineers (*e.g.*, competent with technical aspects of lighting to ensure proper illumination levels, energy efficiency, visual comfort, and compliance with codes and standards). Nevertheless, consistent with developing a lighting curriculum within an engineering program, and consistent with my own skills, the course sequence described herein leans slightly toward applied illuminating engineering. In the hands of a more design-oriented educator, the material presented could be adjusted to lean toward light artistry and design.

1.2 Goals

This curriculum development project was conceptualized as a catalyst for three outcomes. First, as an impetus to cement lighting education in the Bachelor of Science in Architectural Engineering program at Oregon State

University. Second, to support the needs of the professional community by inspiring students to pursue careers in lighting, thus building intellectual capacity in the art and science of applied lighting. Third, to disseminate the learning materials in a format that can be adapted and reused by other lighting educators.

In support of the first two project goals, a three-course (one academic year) core lighting curriculum was developed in consultation with representatives of the regional professional lighting community. This manuscript and a website containing supplemental material (see link in the Supplemental Material section) supports the third project goal.

Though the supplemental material contains syllabi and course exercises that could be adopted by others without modification, these materials are not proffered as definitive solutions for what or how to teach about lighting. In the next section, the methods and the underlying philosophy of the curriculum development process are described, with the belief that adopting at least some elements of the process that led to these materials will support their use and adaptation to other pedagogical contexts with resemblant priorities.

2 Methods

This project was conceptualized by the author (KH) with the *a priori* belief that collaboration with a representative group of lighting professionals would enable informed prioritization of curricular outcomes, thus contributing to career readiness and supporting the professional lighting community. Five lighting professionals were invited to collaborate—Teal Brogden (TB) (Horton Lees Brogden Lighting Design), Jason Edling (JE) (Niteo), Sean O'Connor (SO) (Sean O'Connor Lighting Design), Charles Stone (CS) (Fisher Marantz Stone), and Andrea Wilkerson (AW) (Pacific Northwest National Laboratory). Additional details about their backgrounds and the rationale for why they were invited is offered in **Appendix A**. In generously sharing their expertise, they offered the viewpoints of hiring authorities, business owners, designers, and women engineers. They shared opinions about design processes, technologies, fundamentals, and applications, all in support of developing a credible curriculum.

We developed a shared understanding of curricular priorities, which began with individual ratings of topical importance, followed by group discussion. This work made use of Bloom's taxonomy,^{15–17} which is a hierarchical model that classifies the depth of learning objectives within cognitive, affective, and psychomotor domains. A summary of the taxonomies in each of these three domains is provided in **Table 1** through **Table 3**. Bloom's taxonomy has been used by others when developing instructional objectives for lighting education.^{7,19}

In prioritizing learning outcomes and partitioning content into the three-course sequence, we also considered two learning groups. To attain breadth of knowledge in architectural engineering, and to support ABET accreditation, all students in the Oregon State University ARE program are required to take a minimum of two courses in each of the four topic areas defined by ABET: Building Mechanical, Building Electrical, Structures, and Construction. Within the ABET Building Electrical category, all architectural engineering students are required to take *Construction Engineering Management (CEM) 471 Electrical Facilities* and *ARE 361 Fundamentals for Lighting Design*. ARE 361, which is one of the three courses developed as part of this project, therefore serves two audiences with somewhat different needs. It provides breadth for students that will pursue careers in building mechanical and structural systems, and it provides foundational knowledge to be built upon for students that will pursue careers in lighting.

Our approach aligns with the concept of constructive alignment, espoused by Biggs, Tang, and Kennedy.²⁰ Constructive alignment emphasizes a three-pronged approach: 1) focus on learning outcomes first, 2) align learning activities to achieve outcomes, 3) create assessments that accurately measure how well students have achieved the learning outcomes. This manuscript emphasizes our process and outcomes for defining learning outcomes. Supplemental material provides the learning activities that support the learning outcomes. While student work examples have been archived and assessments performed, due to scope and length limits assessment materials are not described in this manuscript.

To begin to prioritize content within a Bloom's taxonomy context, a technical knowledge survey was created with these characteristics:

- Inclusion of more than 300 technical skills relevant to careers in architectural engineering and lighting, subdivided into cognitive, affective, and psychomotor domains. This list was initially developed by the author

over 20 years ago as part of a previous curriculum development effort at the University of Nebraska. The list was revised and updated for the current exercise at Oregon State University. The survey was not meant to be an exhaustive or definitive compilation, but rather a tool to prime the participants with a broad range of potential topics prior to the in-depth discussions that followed. Survey respondents were given the opportunity to add any additional topics they deemed relevant or missing from the original list, ensuring an open and inclusive approach to identifying essential skills and knowledge areas.

- By presenting a reasonably expansive list, we aimed to ensure that no major areas were overlooked from the outset, while also allowing for the identification of any gaps or redundancies during the subsequent collaborative discussions. The relationships and potential overlap between certain skills were thus addressed through the iterative refinement process that took place during discussions, where the expertise and real-world perspectives of the lighting professionals played a crucial role in shaping the final curriculum structure.
- For each topic listed, the rating scales probe the expected degree of topical mastery with reference to Bloom's taxonomy. Each rating scale was anchored at one end by "not important", then progressed through Bloom's adjectives. In the cognitive domain, a seven-item scale was employed using the words not important, remembering, understanding, applying, analysing, evaluating, and creating. Not important was assigned a score of 0 and creating was assigned a score of 6. A similar process was followed for the affective domain (*i.e.* not important, receiving, responding, valuing, organizing, and value complex) and the psychomotor domain (*i.e.* not important, imitation, manipulation, precision, articulation, and naturalization). Operational definitions for all of these adjectives are provided in **Table 1** through **Table 3**.
- The survey included responses for both non-lighting ARE students and lighting-option ARE students.
- TB, JE, SO, CS, and AW independently completed the survey. KH prepared a numerical summary, sorting the lists by mean rating (employed as a proxy for importance), and standard deviation (employed as a proxy for (dis)agreement).
- While the initial list could undoubtedly be further scrutinized, the primary objective was to provide a comprehensive foundation that could be collectively evaluated, prioritized, and refined through the experience-based insights of the practitioner group. This approach allowed for a balanced consideration of both theoretical and practical relevance in determining the core knowledge areas for the lighting curriculum.

The top sections of the survey responses for the cognitive domain responses are provided in **Figure 2** (sorted by mean) and **Figure 3** (sorted by standard deviation). The complete versions of these surveys, containing about 275 rows of topics in the cognitive domain, are provided as supplemental material. **Figure 4** provides the survey responses in the affective domain. **Figure 5** provides responses in the psychomotor domain. Refer to the supplemental material for the complete versions, including the instructions that were given to the survey respondents.

The sorted tables were not treated as a definitive prioritized ground truth. Instead, they served as a basis for group discussions, where participants examined opinions and rationales behind the ratings. Primary, secondary, and tertiary topics emerged only after these discussions, allowing for their organization into the three-course sequence. The topical prioritization discussions were collaborative, rich, and thought-provoking. While the specifics of these conversations were heavily contextualized to Oregon State University's unique situation, limiting broad generalizability, they were critical in shaping the form, structure, and content of the developed courses. A key methodological takeaway is the importance of involving professionals with relevant expertise, adequately preparing discussion participants about pedagogical concepts (e.g., Bloom's Taxonomy), giving participants time to prepare for the discussions by considering their own priorities (e.g., through a topical survey), and engaging discussions with both conviction to defend high-priority topics and openness to alternative priorities from others.

The methodology employed was rooted in the belief that creating a locally contextualized and highly relevant curriculum requires close communication, collaboration, and nuanced deliberation among a committed group of experts. A rank ordering process based solely on survey responses from a large, disparate group of practitioners would likely fail to capture the intricate considerations and institutional realities that shape an implementable curriculum.

By working closely with a small cohort of lighting professionals who possessed direct, first-hand knowledge of the regional industry landscape, academic environment, and student needs, we were able to engage in rich dialogues that went beyond mere tallying of survey responses. This approach allowed for a more holistic

integration of theoretical knowledge, practical expertise, and contextual factors specific to Oregon State University and its surrounding professional community.

While a larger-scale practitioner survey could potentially offer valuable insights in future iterations or broader studies, the primary objective of this project was to develop a curriculum tailored to the local context through intensive collaboration and discourse among a core group of deeply invested stakeholders. This focused methodology was intentionally chosen to align with the overarching goal of creating a highly relevant and impactful educational experience for students aspiring to enter the lighting profession in this region.

With the survey completed and discussed, KH began to sketch a three-course plan while also accounting for Accreditation Board for Engineering and Technology (ABET) accreditation requirements, opportunities and constraints specific to Oregon State University, and personal experience from past teaching.

To help relate the scope of this project to other pedagogical contexts, a typical course at Oregon State University comprises 10 weeks of instruction plus one week for final exams. Students are expected to spend about 12 to 16 hours per week on a 4-credit course, inclusive of in-class time and out-of-class study. Success in this three-course sequence requires pre-requisite knowledge acquired earlier in the architectural engineering program (*e.g.* mathematics, architecture studio, engineering graphics and design). Subsequently, the content in this core three-course sequence is expanded and applied in courses taken later in the program (*e.g.* daylighting, parametric modelling, capstone project).

Concurrent with my initial development of the three-course content map and outline, the consultants coordinated with their co-workers, colleagues, and staff to prepare lists of assignments, exercises, and learning experiences that they found important or memorable when first learning about light and lighting. The goal was to create a collection of activities that could serve as inspiration for how to teach the topics that we had identified as important.

To date, each of the three courses have been offered at least two times, with iteration concomitant with each offering. Students provide feedback about each course by completing a Student Learning Experience Survey that is administered by Oregon State's Office of Academic Programs and Assessment. Student responses help instructors discover ways to improve, while also identifying what went well. The courses described in the next section are current as of the dates of publication, but teaching and learning are dynamic, and no course is ever really finished. The homework assignment and design projects mentioned below and provided as supplemental material may vary from year to year. They should be viewed as representative of the topics and problems studied, understanding that continuous reassessment and revision are natural parts of pedagogy.

Throughout our discussions, the professionals stressed the importance of a general education that includes art, architecture, theatre, and knowledge of sustainability practices. Communication and professionalism were identified as critical skills. Lighting professionals draw on knowledge and experience from all their background, not just lighting-specific courses.

3 Results

This section provides an overview of the three-course sequence, including course descriptions, course learning outcomes, and mapping of course learning outcomes to ABET student learning outcomes. Homework titles are listed to concisely convey the topics covered in each course. The course learning outcomes may need to be adjusted for different accrediting bodies or academic contexts. Since it is not feasible to provide a comprehensive description of three courses covering an academic year of study in a single article, a link to external resources is provided in the supplemental material section of this manuscript. The supplemental material includes the course syllabi, assignments, survey summaries, and the full list of potential learning exercises that were provided by the lighting professionals. The listing of homework titles serves as a reference for readers interested in accessing or adapting these exercises.

3.1 ARE 361—Fundamentals for Lighting Design

This course was designed to develop introductory understanding and critical thinking about illuminating engineering and applied architectural lighting. It familiarizes students with lighting terminology, quantities, and units, the human eye and brain, basic concepts in photometry and luminous radiative transfer, lighting equipment, elementary lighting design procedures, and basic lighting calculations.

The course was designed for students studying Architectural Engineering (ARE). For ARE students that will not specialize in lighting, this course provides the breadth of knowledge for non-lighting building professionals to effectively collaborate with lighting professionals. For ARE students that will specialize in lighting, this course provides foundational breadth for the more advanced study that is needed to become a capable lighting professional.

3.1.1 ARE 361 Catalogue Description

Demonstrate critical thinking about illuminating engineering and applied lighting in the built environment. Explore lighting terminology, photometric quantities and units, the visual response of the human eye and brain, luminous radiative transfer, lighting equipment, elementary lighting design procedures, and basic lighting calculations.

3.1.2 ARE 361 Course Learning Outcomes

By the conclusion of this course, students are expected to be able to:

1. Compute and manipulate photometric quantities such as luminous flux, luminous intensity, illuminance, exitance, and luminance.
2. Analyze lighting design solutions by identifying the components of light (sometimes called “layers of light”, or luminous characteristics) that were employed in design.
3. Explain the basic performance characteristics of light sources that are relevant when matching light sources to end-use application.
4. Identify major families of luminaire types and subtypes.

3.1.3 ARE 361 ABET Student Learning Outcomes

Together with other components of the ARE curriculum, learning activities in this course support ABET Student Learning Outcomes 1 and 7:

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. [Maps to course learning outcome 1.]
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies. [Maps to course learning outcomes 2, 3, and 4]

3.1.4 ARE 361 Assignments

Assignments are intended to deepen student understanding of course material, while also supporting preparation for two midterm examinations and one final examination. Students are encouraged to work on assignments with classmates, with the belief that open discussion and the public exchange of ideas are healthy parts of the learning process and university life, understanding that this comes with an implied reciprocity. Offering and receiving guidance are both healthy parts of learning, and it is especially fruitful when students play both roles on different topics. By encouraging students to problem solve together, students are pushed to develop soft skills such as communication, planning, and leadership. It is also understood that working together is a means, not an end, and that each student is individually responsible for their own work and their own intellectual development. Assignments that were developed to support ARE 461 course learning outcomes are (see supplemental material):

- Homework #1 The Raisin Observation
- Homework #2 Lighting Image Examples, Annotations, and Critique
- Homework #3 The Language of Light and Lighting
- Homework #4 Practicing the Fundamentals
- Homework #5 Lighting Design Process
- Homework #6 Lighting Design Analysis—Psychological Impressions
- Homework #7 Light Sources

- Homework #8 Luminaires and Photometric Reports

3.2 ARE 461—Lighting Design for the Built Environment I

This course builds upon ARE 361 to advance basic understanding and critical thinking about illuminating engineering and applied architectural lighting. It builds on and extends depth in photometry, colorimetry, lighting equipment, lighting design procedures, and lighting calculations. Whereas ARE 361 focuses on fundamentals in preparation for design, ARE 461 includes a first lighting design project.

The course is designed for students that seek to learn more about lighting than the introductory material presented in ARE 361. While continuing to support breadth of knowledge in applied illuminating engineering and architectural lighting design, the course delves deeper into the design process and develops the technical and procedural skills that support decision making during the design process.

3.2.1 ARE 461 Catalogue Description

Builds upon ARE 361 to advance critical skills in illuminating engineering and applied lighting for the built environment, emphasizing integration between the lighting design process, technical fundamentals, and application to design. Extends depth in photometry by calculating illuminance with diffuse radiative transfer. Establishes design criteria, employs computer-based calculations as a verification tool, and creates solutions compliant with compulsory standards.

3.2.2 ARE 461 Course Learning Outcomes

By the conclusion of this course, students are expected to be able to:

1. Compute photometric quantities using basic radiative transfer situations, including point calculations and computation and implementation of configuration and form factors.
2. Implement the lighting design process for a space of modest complexity where there are multiple and competing design considerations and design criteria.
3. Develop design documentation comprising drawings and a lighting equipment schedule comparable to that expected in a professional context.

3.2.3 ARE 461 ABET Student Learning Outcomes

Together with other components of the ARE curriculum, learning activities in this course support ABET Student Learning Outcomes 1, 2, and 3:

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. [Maps to course learning outcome 1.]
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. [Maps to course learning outcome 2.]
3. An ability to communicate effectively with a range of audiences. [Maps to course learning outcome 3.]

3.2.4 ARE 461 Assignments

Assignments are intended to deepen student understanding of course material, while also supporting preparation for one midterm examination. Evaluation of work in the latter half of the course is based only on performance on the assignments, with nearly half of the course grade linked to a month-long design project. For assignments early in the term that have closed-form solutions, answers are often provided; students are expected to express their understanding by developing, documenting, and solving all intermediate steps. This course is an opportunity for students to develop material for inclusion in a portfolio. Students are encouraged to take equal pride in both the presentation of their work and its technical correctness, and both are considered in grading criteria. As with ARE 361, students are encouraged to collaborate with classmates. Assignments that were developed to support ARE 461 course learning outcomes are (see supplemental material):

- Homework #1 Point Calculation

- Homework #2 More Practice with Point Calculations
- Homework #3 Luminous Radiative Transfer
- Homework #4 Human-Centric Lighting, Part 1
- Homework #5 Human-Centric Lighting, Part 2
- Homework #6 Learning Styles
- Homework #7 A Good start to Design Project: Light Structures Models in AGi32
- Homework #8 Getting Started with AGi32
- Design Project #1: Light Structures Models in AGi32
 - Deliverable 1: Oral Presentation
 - Deliverable 2: Written Report

3.3 ARE 462—Lighting Design for the Built Environment II

The course is designed for students that have the desire to learn more about lighting than the introductory material presented in ARE 361 and the intermediate material presented in ARE 461. Students develop more nuanced and advanced understanding of topics previously introduced (*e.g.* design process, photometry, software) while expanding breadth and depth in new topics (*e.g.* colorimetry, parametric comparisons). Cognitive facility with the most critical skills for applied illuminating engineering and lighting design is expected to transition beyond just knowledge toward proficiency.

3.3.1 ARE 462 Catalogue Description

Builds upon ARE 461, extending lighting design skills and technical knowledge in applied illuminating engineering to produce defensible solutions to open ended engineering problems. Prioritize and balance competing criteria that addresses lighting requirements for the visual experience (*e.g.* vision, visual comfort, psychological reinforcement, colour quality) and human health, while accounting for energy use and complying with compulsory standards. Demonstrate facility with the lighting design process, luminaire photometry, applied colorimetry, and software-based simulation.

3.3.2 ARE 462 Course Learning Outcomes

By the conclusion of this course, students are expected to be able to:

1. Compute the major components of a luminaire photometric report (*e.g.* zonal lumens, luminaire efficiency, coefficient of utilization) from an IES LM-63 format photometry file.
2. Implement the lighting design process for a space of modest complexity where there are multiple and competing design considerations and design criteria.
3. Report the results of your design process orally in the form of a professionally prepared presentation and in writing in the form of a professionally prepared report.
4. Be able to perform a parametric comparison where one lighting variable is systematically varied and a dependent measure is analyzed.

3.3.3 ARE 462 ABET Student Learning Outcomes

Together with other components of the ARE curriculum, learning activities in this course support ABET Student Learning Outcomes 1, 2, 3 and 6.

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. [Maps to course learning outcome 1.]
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. [Maps to course learning outcome 2.]
3. An ability to communicate effectively with a range of audiences. [Maps to course learning outcome 3.]

6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions. [Maps to course learning outcome 4.]

3.3.4 ARE 462 Assignments

ARE 462 does not include any examinations. All assignments are project based, and intended to deepen student understanding of course material. This course provides extensive opportunities for students to develop material for inclusion in a portfolio and students are encouraged to take equal pride in both the presentation of their work and its technical correctness. As with ARE 361 and ARE 461, students are encouraged to collaborate with classmates. Assignments that were developed to support ARE 462 course learning outcomes are (see supplemental material):

- Class Preparation Assignment #1 Wall Lighting Examples
- Class Preparation Assignment #2 Five Questions about Judging the Scientific Quality of Applied Lighting Research
- Homework #1 Lighting a Plane
- Homework #2 Color Science for Illuminating Engineering
- Homework #3 Excel-Based Photometric Tool
- Homework #4 Howard Brandston Student Lighting Design Education Grant
 - Deliverable 1: Oral Presentation
 - Deliverable 2: Written Report

3.4 Ideas for Additional Learning Exercises

The consultants coordinated with their co-workers, colleagues, and staff to prepare lists of assignments, exercises, and learning experiences that they found important or memorable when first learning about light and lighting. The goal was to create a collection of ideas that could serve as inspiration for how to teach the topics that we had identified as important.

The professionals provided more than 50 potential exercises. While some of these potential exercises were incorporated into the assignments listed above, many other exercises were not incorporated into the three-course sequence. This is unrelated to their pedagogical value, and instead related only to making difficult choices about what to include in the available time. The exercises are grouped into the following categories.

- Thought exercise, emotional content, language of lighting, foundations, etc. (8 exercises)
- Sketching and imagery (8 exercises)
- Light in support of visual tasks (2 exercises)
- Communication and general lighting knowledge (1 exercise)
- Observations and analysis of light in architecture (5 exercises)
- Light play (shade, shadow, highlight, intensity, pattern, direction, etc.) (7 exercises)
- Lighting equipment (3 exercises)
- Design process (2 exercises)
- Software and coding skills (5 exercises)
- Photometry experiences and measurement (8 exercises)
- Colorimetry experiences and measurement (4 exercises)

The full list of exercises, along with brief explanations, is included as part of the supplemental material. The supplemental material categorizes the activities (*e.g.* class discussion, homework, design project, practicum, field trip, co-curricular) and estimates the expected student time commitment for each activity. Activities range from approximately 10 minutes for in-class discussion ideas, to multi-step design projects that could span 40 or more hours.

4 Discussion

Lighting educators and professionals have a long history of expressing concern with the depth and quantity of university-based opportunities in lighting education. Among the historical observations, Padgham²¹ documented the inadequacy of the number of people receiving an education in lighting in Great Britain relative to contemporaneous needs. Lynes²² noted the disconnect between what was being taught to lighting students and the skills they need to be successful (*i.e.* “we are still training people ... to do a job which is disappearing.”). In Benya et al²³ DiLaura noted that the lighting industry depends on lighting education, yet “lighting education continues to be, at best, a stepchild of the lighting industry”. Julian²⁴ shared similar sentiments, observing that “there is almost no lighting education” even though we live in a world that is dependent upon and dominated by light. Gustina²⁵ observed that technical information about lighting tends to overshadow the use of light as a design element. Scarazzato and colleagues²⁶ shared similar sentiment, noting the weak link between lighting education and the architectural design process. Indeed, the tension between light as a fundamental element of architecture (*i.e.* lighting conceptualized as an integral feature of architecture) versus light as an additive element (*i.e.* lighting conceptualized as hardware attached to architecture) is not new.^{27,28} These observations are fair and they persist to some degree to this day. They can also be viewed as constructive insofar as they serve as motivation for improvement.

It is healthy to have a benevolent push/pull relationship between industry and academia, which was an underlying belief that motivated our work. Survey responses helped identify the entry-level skills, knowledge, and abilities prioritized by the invited professionals, representing the “pull” by industry. Concurrently, academia plays a role in advancing contemporary ideas, thereby “pushing” new knowledge, philosophies, and techniques toward industry. One way that academia supports technology transitions and working practices is through the skills of graduates that enter the workforce. New graduates may have new design skills and values, learned during their studies, with the potential to improve design efficiency and design outcomes.

In U.S. higher education, academic faculty are responsible for course content and the definition, assessment, and longitudinal tracking of learning outcomes. While external input regarding curricular priorities is highly valuable, outside recommendations should be examined and weighed by the teaching faculty and balanced alongside other pedagogic, institutional, and practical considerations.

Figure 3, which summarizes topics sorted by the standard deviation of the responses, is especially useful in identifying topics that received substantially different prioritizations. It relates to the push and pull between academia and industry, and to teaching faculty as being responsible for course content. For example, topics related to luminous radiative transfer were polarizing (std. dev. ≈ 2.5) and they did not receive a high mean rating (mean ≈ 3.8 , corresponding to the “applying” category in Bloom’s taxonomy). Nevertheless, class time, a homework assignment, and exam questions are devoted to this topic based on my belief that knowledge of radiative transfer is foundational to a lighting education in an engineering context.

Graduates with different educational backgrounds (*e.g.* engineering, architecture, interior design, theatre) may have different methods and dispositions toward solving lighting problems. Even within any one of these fields, it is relevant to consider if graduates will have one or more defining attributes or specialized skills, beyond basic core competencies. At Oregon State University, a guiding principle of this three-course series has been balancing the technical (engineering) and design (artistic) aspects of lighting design. Graduates are expected to be technically capable of achieving architecturally integrated and aesthetically pleasing solutions, without falling into a trap of being overly reliant on numerical performance.

Our overarching principles are consistent with our academic home, which is a college of engineering, where problem solving based on first principles is an important attribute of an engineering education. In contrast, in an architecture or interior design program, there might be greater reliance on studio courses and visual representation of lighting design concepts and solutions, perhaps with less reliance on computations, consistent with the overarching principles of architectural and interior design education.^{25,29,30} Setting aside the specific topics, the methods of delivery (*i.e.* teaching methods) and student dispositions toward learning are salient. Alignment between teaching and learning styles is probed and discussed through the homework assignment titled “Learning Styles” (available in the supplemental material). The key point is this: While the selected lighting topics are important, they should be understood as a vehicle for developing students’ discipline-specific problem solving and critical thinking skills.

Looking beyond basic core competencies in engineering, applied illuminating engineering, and lighting design, it is relevant to consider if an academic program has the capacity to develop specific skills, and in doing so create a distinguishing identity. For example, parametric design and artificial intelligence have the potential to improve design outcomes, but with growing pains that will disrupt conventional design workflows. At Oregon State University, a parametric modelling course is offered as an elective, and all lighting students are encouraged to take this course as part of their lighting-elective sequence. Being able to bring emerging techniques into practice as entry-level employees is one way that students can distinguish themselves and market their skills to prospective employers. An academic program might consider to what degree it would be advantageous to place greater or lesser emphasis on specialized skills to complement and extend core competencies.

Daylighting is an important aspect of lighting, yet it is not substantially addressed in the learning outcomes or course activities within the three-course sequence. While students are encouraged to have a mindset of “light is light”, there are additional technical considerations specific to daylight, including computation of solar geometry, daylight availability, building massing and orientation, skylight and window design, and climate-based modelling. Daylighting design is not the same as daylighting analysis, as daylighting design requires the designer to have influence over building orientation and architectural form. In an architecture program, where students have extensive architectural theory, history, and studio experience, it may be more natural to introduce daylighting first, whereas daylighting is introduced later in Oregon State University’s ARE program. Regardless of placement in the curriculum, it is salient to consider the degree to which daylighting should be compartmentalized into its own course, integrated into a core lighting course sequence, and/or integrated into studio and capstone experiences. Within Oregon State University’s ARE program, daylighting is offered as its own stand-alone course, scheduled to be taken in the quarter immediately after ARE 462. Students then also complete a two-quarter capstone project, in which the lighting option students are expected to apply what they have learned in their four prior lighting courses (*i.e.* the three-course sequence described herein, plus daylighting).

Awareness about light’s influence on human health, sometimes referred to as human-centric lighting,³¹ or integrative lighting,³² has introduced new considerations for design practice³³ and lighting education. The supplemental material accompanying this manuscript contains two assignments related to human-centric lighting, which may offer insights into how light and health topics are presently incorporated into the lighting curriculum.

While the supplemental material to this article is extensive and includes syllabi, assignments, ranked and sorted topic lists in the cognitive, affective, and psychomotor domains, and additional ideas for learning exercises, the supplemental material does not include lecture notes. This is in part because lecture notes are intrinsically incomplete. They serve as a backdrop for interaction between the instructor and students, but they do not capture the spoken words, tone, and interactions that support moments of understanding and influence in-class learning.

Based on my 25+ years of experience as an educator, it is my firm belief that most learning, moments of insight, and skill development occur outside of the classroom. Teaching is supported by textbooks, classroom instruction, and complementary assignment, but learning requires motivation, time, thought, and the actual doing of the work.³⁴ Aptitude is supported by general intelligence, but being smart is not enough. Facility and professional competence are cultivated through concentrated effort, reflection, persistence, curiosity, self-interest, and grit. One of the most effective ways that an instructor can support achievement is by creating out-of-class assignments that encourage (and require) students to focus their effort on developing the knowledge, skills, and abilities that align with course learning outcomes, where course learning outcomes have been defined to support career readiness and enable students to achieve their professional aspirations.

The three-course sequence intentionally incorporates repeated exposure to key topics, where at each exposure students are guided (and challenged) to develop higher levels of cognition, consistent with Bloom’s taxonomy. Consider photometry. In ARE 361, students learn about luminous flux, luminous intensity, illuminance, exitance, luminance, and the inverse square and cosine laws, but most only advance to the remembering or understanding levels of Bloom’s taxonomy. In ARE 461, students explore more complex photometry and radiative transfer situations by integrating over receiving and sending surfaces to develop configuration and form factors. In ARE 461, students are also exposed to radiosity software and electronic photometry files. In ARE 462, students develop code to produce a luminaire photometric report from a photometry file, computing quantities such as zonal lumens, luminaire luminance, and coefficients of utilization. Through this sequence, students acquire progressively advanced abilities, leading to the evaluative and creating skills that are at the highest levels of

Bloom's taxonomy. The assignments that support this progressive development of skills related to photometry are available in the supplemental material.

Students enter college with preconceived conceptions of light,³⁵ which should be developed through guided exploration that fosters observation, discussion, and challenges students to acquire depth. Learning to light first requires learning to see,³⁶ and early assignments that encourage heightened perceptual awareness can be used to develop common understandings (e.g. see "The Raisin Observation" available as supplemental material). ARE students that concentrate on lighting tend to be drawn to the visual, emotional, and psychological aspects of the profession. Laboratory facilities for teaching about light and lighting support learning about light and the visual experience,³⁷ including quantities of light from bright to dim, correlated colour temperature, colour rendering, colour mixing, chromaticity, shade, shadow, highlight, key light, fill light, back light, grazing versus washing, surface materiality including diffusion and specularity, glare and visual discomfort, controls interfaces, window coverings, and shading devices. If a dedicated teaching laboratory is impossible or impractical, then local examples can be sought and documented, even assigning students to be "detectives" that identify and document local examples of lighting situations (e.g. wall washing, wall grazing, glare, view-preserving window shades, chromaticity inconsistencies). At root, engrossment is an accelerant to learning, and learning activities that invite engagement support learning outcomes.

Commercially available software should likely also play a role in lighting education.^{38,39} Pedagogically, software enables parametric comparison and can be employed to encourage algorithmic thinking and exploration of design alternatives. Practically, entry-level lighting professionals are expected to have facility with software that supports lighting design decision making, compliance with codes and standards, and enables the production of construction drawings.

Matters related to diversity, equity, inclusion, difference, power, and oppression hold significant relevance and meaning within the context of lighting design and its impact on the built environment.^{40,41} Access to quality lighting is often influenced by socioeconomic factors, with affluent communities frequently enjoying better outdoor lighting⁴² and indoor environments with natural light and views, while those in lower-paying roles are more likely to experience suboptimal lighting conditions (e.g., affluent patrons in a restaurant dining room versus workers in windowless kitchens).⁴³ These disparities highlight the importance of considering equity and inclusion in lighting design to ensure fair access to quality illumination regardless of socioeconomic status or background. The term "light justice" reflects a growing recognition within the lighting community that equitable access to quality lighting is a matter of social and environmental justice. For society to become more equitable and just, it is incumbent upon teachers and learners to address real disparities in lighting quality and their impacts on human health, well-being, and productivity. By acknowledging and addressing these issues during university studies, educators can prepare graduates to create more inclusive and equitable lighting solutions that benefit all members of society.

Converting these three courses to e-campus offerings has been considered, including packaging them into an online certificate program. Offering these courses electronically would require developing recorded lectures, which would be made available for asynchronous viewing. A notable advantage of electronic delivery is the potential to reach a larger audience, without geographical limits. Downsides include the paucity of person-to-person interactions such as group-work and in-person collaboration, and lack of access to physical facilities and laboratory demonstrations.

Well-conceived co-curricular activities support in-class learning, acquisition of professional knowledge, and the transition from being a student to becoming an early career professional. Participation in professional conferences is a highly effective co-curricular activity, for both knowledge acquisition and professional networking. In the United States, competitive travel support is consistently available through the International Association of Lighting Designers (IALD) Education Trust and Illuminating Engineering Society (IES) Emerging Professionals travel grants. Ad hoc funding can also sometimes be obtained from the lighting industry to support group travel by students.

5 Conclusions

While the curriculum development activities described in this work were developed within the context of Oregon State University's Bachelor of Science in Architectural Engineering degree program, both the process and outcomes are readily adaptable to other educational contexts. In disseminating this work, I aim to support other

educators in our shared objective of offering relevant, contextualized, and rigorous lighting education programs that support student academic development, career readiness, and the advancement of lighting as a profession. You are invited to explore and adapt the syllabi and assignments that were developed as part of this project, and which are available as supplemental material.

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Supplemental Material

Supplemental material may be downloaded from <https://blogs.oregonstate.edu/kevinhouser/> under the heading titled "Nuckolls Project". This page contains course syllabi and assignments for all three courses, the technical knowledge surveys in the cognitive, affective, and psychomotor domains (including instructions and responses), and the full list of potential learning exercise that was provided by the lighting professionals.

References

1. [NAAB] National Architectural Accrediting Board. *About NAAB*. Available at: <https://www.naab.org/about/>. (Accessed: 8 June 2023).
2. [CIDA] Council for Interior Design Accreditation. *About CIDA*. Available at: <https://www.accredit-id.org/mission> (Accessed: 8 June 2023).
3. [ABET] Accrediting Board for Engineering and Technology. *About ABET*. Available at: <https://www.abet.org/about-abet/> (Accessed: 8 June 2023).
4. [NAST] National Association of Schools of Theatre. *About NAST*. Available at: <https://nast.arts-accredit.org/about/>. (Accessed: 8 June 2023).
5. Davis W, Hu W. Architectural lighting design education: Teaching science to designers. *Education and Training in Optics and Photonics Conference 2021*; Washington, DC. 8-10 September 2021.
6. Rey-Barreau JA. 1983. A methodology for teaching interior illumination. *Journal of Interior Design Education and Research* 1983; 9(1): 43-45.
7. Brent RS. Instruction in lighting design. *Journal of Interior Design Education and Research* 1985; 11(1): 18-22.
8. Reddy SL, Stewart AH, Fortenberry SL. A case for the expansion of lighting design education. *Journal of Family and Consumer Sciences* 2021; 113(1): 56-61.
9. Ronen RS, Smith RF. Shedding light on the subject: Introduction to illumination engineering and design for multidiscipline engineering students. *Proceedings of SPIE Vol. 2525 1995 International Conference on Education in Optics*. San Diego, CA. 13 October 1995.
10. Berardi U, Pietroforte R, Il-Korchi T. Acoustics and lighting education in architectural engineering: Experience of WPI. *Journal of Architectural Engineering* 2014; 20(2): 05013003.
11. Koshel JR, Abraham V, Kim J, Liu R, Richardson S, Namnabat S, Czajkowski A, Abd El-Maksoud RH, Irvin R, Nakazawa T, Kudenov M, Dawsey M, De Leon E, Wang L, Crabtree K, Orr RM, Primeau B, Kim Y. 2009. Illumination system design in a project-based course. *Proceedings of SPIE Vol. 7423 Nonimaging Optics: Efficient Design for Illumination and Solar Concentration* 2009; San Diego, CA; 21 August 2009. 742305.

12. Bunch RM, Joenathan C, Connor K, Chouikha M. Modules to enhance smart lighting education. *Proceedings SPIE 8481 Optics Education and Outreach II* 2012; San Diego, CA. 15 October 2012. 84810B.
13. Bunch RM, Joenathan C. Lighting education and outreach at Rose-Hulman Institute of Technology. *Proceedings SPIE 10741 Optics Education and Outreach V* 2018; San Diego, CA. 14 September 2018. 1074102.
14. Boyce P. The divorce of the art and science of lighting. *Lighting Research and Technology* 2017; 49: 671.
15. Bloom BS, Englehart MD, Furst EJ, Hill WH, Krathwohl DR. *Taxonomy of educational objectives: The classification of educational goals. Handbook 1 Cognitive Domain* 1956; New York, NY: David McKay Co., Inc.
16. Krathwohl DR, Bloom BS, Masia BB. *Taxonomy of Educational Objectives: Handbook II, Affective Domain* 1964 New York, NY: David McKay Co., Inc.
17. Anderson LW, Krathwohl DR. Editors. *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives* 2001; New York, NY: Longman.
18. Dave RH. In Armstrong RJ (editor). *Developing and writing behavioral objectives* 1970; Tuscon, AZ: Educational Innovators Press. 33-34.
19. Bernecker CA. Instructional objectives for lighting education within an architectural engineering curriculum. *Lighting Design and Application* 1983; November: 23-32.
20. Biggs J, Tang C, Kennedy G. *Teaching for Quality Learning at University*, 5th edition. Open University Press/McGraw Hill. 2022. 1208 p.
21. Padgham CA. Lighting education in Great Britain. *Transaction of the Illuminating Engineering Society London* 1963; 28(3): 110-126.
22. Lynes J. Discussion of Bean AR, Pickup JF, Pritchard DC. The crisis in lighting education. *Lighting Research and Technology* 1970; 2(4): 205-219.
23. Benya J, Butler D, DiLaura D, Dombroski W, Ginthner D, Long J, Meden R, Murdoch J, Smith R. Lighting education: An overview. *Lighting Design and Application* 1985; February: 31-43.
24. Julian WA. The need for lighting education. *Proceedings of SPIE Vol. 4588 Seventh International Conference on Education and Training in Optics and Photonics* 2002; Singapore. 26-30 November 2001. 155-162.
25. Gustina C. Light fantastic: Teaching introductory lighting to interior designer students. *Design Principles and Practices*. 2011; 5(5): 521-532.
26. Scarazzato PS, de Silva Fonseca Matos JC, Franca AJGL, Pavani TD. Challenges in lighting education: A recommended practice. IOP Conference Series: Earth and Environmental Sciences. Light Symposium 2022. 1099: 012040.
27. Addleson L, Bell J. Lighting in architectural education. *Lighting Research and Technology* 1968; 33(4): 119-140.
28. Addleson L. Lighting in architectural education. *Architectural Research and Teaching* 1972; 2(2): 88-95.
29. Tural M. An approach to integrate lighting concepts into interior design studios: A constructivist educational framework. *PhD thesis in Art, Design, and Architecture* 2006; Bilkent University, Turkey. 236 pp.
30. Hedge A. People learn by doing: Introducing lighting design problem solving in a lecture class. *Proceeding of the Interior Design Educators Council 44th Annual International Conference* 2007; Austin, TX. 6-11 March 2007. 395-406.
31. Houser KW, Boyce PR, Zeitzer JM, Herf M. Human-centric lighting: Myth magic or metaphor? *Lighting Research and Technology* 2021; 53(2): 97-118.

32. Vetter C, Pattison PM, Houser K, Herf M, Phillips AJK, Wright KP, Skene DJ, Brainard GC, Boivin DB, Glickman G. A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions. *Leukos* 2022; 18(3):387-414.
33. Houser KW, Esposito T. Human-centric lighting: Foundational Considerations and a Five-Step Design Process. *Frontiers in Neurology* 2021; 12: 630553.
34. DiLaura DL. Lighting education. *Leukos* 2006; 2(4): 232-234.
35. Watts MD. Student conceptions of light: A case study. *Physics Education* 1985; 20: 183-187.
36. Brandston HM. *Learning to see: A matter of light* 2008; New York, NY: Illuminating Engineering Society. 138 p.
37. Buddharuksa B. The development of an interior lighting demonstration module. Master of Arts Thesis 1994; California State University Long Beach. 160 pp.
38. Sarawgi T. Survey of the use of lighting design software in architecture and interior design undergraduate education. *International Journal of Architectural Computing* 2006; 4(4): 91-108.
39. Valdez MMT, Agreira CIF, Ferreira CMM, Barbosa FPM. PBL implementation in a lighting design course. *44th International Universities Power Engineering Conference (UPEC)* 2009; Glasgow, UK. 1-4 September 2009.
40. Bartholomew E, Loeffler M. With Good Lighting and Justice for All. *Lighting Design + Application* 2021; 51(9): 48-51.
41. Bartholomew E, Loeffler M. Light + Justice in Action. *Lighting Design + Application* 2022; 52(2): 42-48.
42. Creatura I. Public Lighting and the Urban Wealth Gap. *Brown Political Review* 2017; Available at: <https://brownpoliticalreview.org/2017/02/public-lighting-urban-wealth-gap/> (Accessed 10 February 2024).
43. Bartholomew E, Loeffler M, Osborn LS. Achieving Equitable Indoor Lighting. *Lighting Design + Application* 2023; 53(12): 46-49.

Appendix A

Teal Brogden (TB), Jason Edling (JE), Sean O'Connor (SO), Charles Stone (CS), and Andrea Wilkerson (AW) were invited to participate because, individually and collectively, they had the capacity to provide deep insight into what lighting education should and can be within an architectural engineering degree program. In particular:

1. It was considered important to build regional connections between lighting education at Oregon State University and the nearby community of professionals. When this project started, all five professionals were based (primarily) on the west coast of the United States—CS and JE in Seattle, AW in Portland, TB and SO in Los Angeles.
2. Collectively, this group has a desirable mix of educational backgrounds enabling them to provide a richness to discussions about curriculum and learning outcomes. TB and JE have degrees in Architectural Engineering from the University of Colorado – Boulder. CS got his start in theatre, with a degree in English. SO's background is in Architecture and Art History. AW has degrees in Architectural Engineering from the University of Nebraska (BS and MAE) and Penn State (PhD).
3. As design principals and firm owners, TB, JE, CS and SO are directly involved in hiring. They know what a lighting design business needs from entry level employees and they understand the characteristics that lead to career progression. TB, JE, and SO are professional members of IALD and CS is a fellow of IALD.
4. When this project began, AW was the Secretary and Treasurer of the IALD Education Trust and a Lighting Engineer at the U.S. Department of Energy Pacific Northwest National Laboratory (PNNL). Through her work at PNNL and involvement with IALD Education Trust, AW is on the leading edge of advanced lighting technologies while having a broad view of the lighting education landscape.

5. TB and AW are women with engineering degrees. This is important because they could offer the perspective of a woman as an engineering student. TB brought the perspective of a woman business owner.
6. SO was involved in an effort to develop an MFA in Architectural Lighting degree at Otis College of Art and Design in Los Angeles. TB is involved with the University of Colorado – Boulder, including as a faculty member in the Rocky Mountain Institute. AW was involved with lighting education outreach through Project CANDLE, and she taught a course at Penn State. CS is familiar with lighting education at Penn State through his involvement in Project CANDLE. This group can offer wisdom and counsel about lighting in higher education.

The group was kept small to encourage participation in conversation. Insightful commentary was prioritised over trying to converge on consensus by averaging (and thus diluting) opinionated and sometimes conflicting priorities.

Table 1. Descriptions of the major categories in the cognitive domain.^{15,17}

Category	Description
Remembering	Knowledge is defined as the remembering of previously learned material. This may involve the recall of a wide range of material, from specific facts to complete theories, but all that is required is recalling the appropriate information. Knowledge, or remembering, represents the lowest level of learning outcomes in the cognitive domain.
Understanding	Understanding is defined as the ability to grasp the meaning of material. This may be shown by translating material from one form to another (e.g. words to numbers), by interpreting material (e.g. explaining or summarizing), and by estimating future trends (e.g. predicting consequences or effects). These learning outcomes go one step beyond the simple remembering of material and represent the lowest level of understanding.
Applying	Application refers to the ability to use learned material in new and concrete situations. This may include the application of such things as rules, methods, concepts, principles, laws, and theories. Learning outcomes in this area require a higher level of comprehension than just understanding.
Analyzing	Analysis refers to the ability to break down material into its component parts so that its organizational structure may be understood. This may include the identification of the parts, analysis of the relationships between parts, and recognition of the organizational principles involved. Learning outcomes here represent a higher intellectual level than understanding and application because they require comprehension of both the content and the structural form of the material.
Evaluating	Evaluation is concerned with the ability to judge the value of material (e.g. statement, novel, poem, research report, product design, lighting design solution) for a given purpose. The judgments are to be based on definite criteria. These may be internal criteria (e.g. organization) or external criteria (e.g. relevance to the purpose) and the student may determine the criteria or be given them. Learning outcomes in this area contain elements of the other categories, plus conscious value judgments based on clearly defined criteria.
Creating	Synthesis refers to the ability to put parts together to form a new whole. This may involve the production of a unique communication (e.g. theme or speech), a plan of operations (e.g. research proposal), or a set of abstract relations (e.g. scheme for classifying information). Learning outcomes in this area stress creative behaviors, with major emphasis on the formulation of new patterns or structures.

Table 2. Descriptions of the major categories in the affective domain.¹⁶

Category	Description
Receiving	Receiving refers to the student’s willingness to attend to particular phenomena or stimuli (e.g. classroom activities, textbook, music). From a teaching standpoint, it is concerned with getting, holding, and directing the student’s attention. Learning outcomes in this area range from the simple awareness that a thing exists to selective attention on the part of the learner. Receiving represents the lowest level of learning outcomes in the affective domain.
Responding	Responding refers to active participation on the part of the student. At this level the student not only attends to a particular phenomenon but also reacts to it in some way. Learning outcomes in this area may emphasize acquiescence in responding (reads assigned material), willingness to respond (voluntarily reads beyond assignment), or satisfaction in responding (reads for pleasure or enjoyment). The higher levels of this category include those instructional objectives that are commonly classified under “interest”; that is, those that stress the seeking out and enjoyment of particular activities.
Valuing	Valuing is concerned with the worth or value students attach to a particular object, phenomenon, or behavior. This ranges in degree from simple acceptance of a value (e.g. desire to improve group skills) to more complex commitments (e.g. assumes responsibility for the effective functioning of the group). Valuing is based on the internalization of a set of specified values, but clues to these values are expressed in the student’s overt behavior. Learning outcomes in this area are concerned with behavior that is consistent and stable enough to make the value clearly identifiable. Instructional objectives that are commonly classified under “attitudes” and “appreciation” would fall into this category.
Organization	Organization is concerned with bringing together different values, resolving conflicts between them, and beginning the building of an internally consistent value system. Thus, the emphasis is on comparing, relating, and synthesizing values. Learning outcomes may be concerned with the conceptualization of a value (e.g. recognizes the responsibility of everyone for improving human relations) or with the organization of a value system (e.g. develops a vocational plan that satisfies personal desires for both economic security and social service). Instructional objectives relating to the development of a philosophy of life would fall into this category.
Characterization by a Value or Value Complex	At this level of the affective domain, the person has a value system that has controlled behavior for a sufficiently long time to have developed a characteristic “life style.” Thus, the behavior is pervasive, consistent, and predictable. Learning outcomes at this level cover a broad range of activities, but the major emphasis is on the fact that the behavior is typical or characteristic of the student. Instructional objectives that are concerned with the student’s general patterns of adjustment (e.g. personal, social, emotional) would be appropriate here.

Table 3. Descriptions of the major categories in the psychomotor domain.¹⁸

Category	Description
Imitation	Observing and patterning behavior after someone else, such as copying work or replicating another's actions. Performance may be of low quality.
Manipulation	Being able to perform certain actions by memory, or by following instructions and practicing. At this level, tasks can be performed from written or verbal instructions.
Precision	The ability to perform actions with a level of expertise that does not require help or intervention from others. The work is refined and more exact. Few errors are apparent.
Articulation	Coordination of a series of actions, achieving harmony and internal consistency. At this level, skills are so well developed that movement can be modified to fit special requirements or adapted for novel situations.
Naturalization	Having high level performance becomes natural, without needing to think much about it. Performance of actions is automatic and intuitive, with little physical or mental exertion. Performance has become second nature.

Year	Fall			Winter			Spring		
	Course No.	Cr.	Course Title	Course No.	Cr.	Course Title	Course No.	Cr.	Course Title
1st	ENGR 100	3	The OSU Engineering Student	ENGR 102	3	Design Engineering & Prob Solving	ENGR 103	3	Engineering Computation
	MTH 251	4	Differential Calculus	MTH 252	4	Integral Calculus	MTH 254	4	Vector Calculus
	CH 201	3	Chemistry for Engineering Majors	CH 202	3	Chemistry for Engineering Majors	GEOG 240	3	Human Dimensions of Climate Change
		2	EL: Fitness	CH 205	1	Laboratory for CH 203		1	EL: Fitness
	WR 121Z	4	Writing Composition I	COMM 111Z	3	Public Speaking		3	EL: Western Culture
2nd	PH 211	4	General Physics with Calculus	PH 212	4	General Physics with Calculus	PH 213	4	General Physics with Calculus
	MTH 264	2	Intro to Matrix Algebra	MTH 256	4	Applied Differential Equations	ST 314	3	Intro to Statistics for Engineers
	MTH 265	2	Intro to Series	WR 227Z	4	Technical Writing	CCE 203	3	Intro to Virtual Design in Construction
	ENGR 211	3	Statics	ENGR 213	3	Strength of Materials	ART 323	3	Italian Renaissance Art & Architecture
	CCE 207	1	Civil & Const Engr Seminar	CCE 201	3	Civil & Const Engr Graphics & Design		3	EL: Difference, Power, & Discrimination
		3	EL: Cultural Diversity						
3rd	ARE 310	4	Architecture Studio	CE 381	4	Structural Theory I	CE 382	4	Structural Theory II
	ARE 311	4	Fluid Mechanics	ARE 361	4	Fundamentals for Lighting Design	CCE 321	4	Civil & Const Eng Materials
	CEM 471	4	Electrical Facilities	ARE 341	4	Fundamentals of HVAC	ENGR 201	3	Electrical Fundamentals I
	CEM 442	4	Bldg Construction Management	CEM 472	3	Mechanical Facilities	ARE 461	3	Ltg Dsgn For Built Environ I
							ARE 499	3	ST: HVAC Design I
							CE 372	4	Geotech Engineering I
4th	ARE 451	4	Advanced Bldg Const Methods	ARE 418	4	ARE Prof Practice (Capstone I)	ARE 419	3	ARE Design (Capstone II)
	CE 383	4	Design of Steel Structures	CCE 422	3	Green Building Materials		3	EL: Science, Tech & Society
	CE 420	4	Engineering Planning		3	EL: Difference, Power & Discrimination			
	ARE 462	4	Ltg Dsgn For Built Environ II	ARE 499	4	ST: Daylighting	ARE 499	4	ST: Parametric Design in ARE
								3	EL: Contemporary Global Issues
	ARE 499	4	ST: Bldg Energy Modelling		3	EL: Contemporary Global Issues	ARE 499	4	ST: Indoor Air Quality
								4	Mechanical Tech Elect
	CE 481	4	Reinforced Concrete I	CE 484	4	Wood Design		3	Structures Tech Elect
							3	EL: Contemporary Global Issues	

Key	
	Course for all ARE concentrations
	Courses for LIGHTING concentration
	Courses for MECHANICAL concentration
	Courses for STRUCTURES concentration

Notes:
 ST = Special Topic (awaiting permanent course number)
 EL = General Education Elective in Category Listed

Figure 1. Oregon State University's Bachelor of Science in Architectural Engineering curriculum. The courses that are the subject of this manuscript are in **bold** text.

	Non-Lighting ARE Students						Lighting ARE Students							
	Not Important	Remembering	Understanding	Applying	Analyzing	Evaluating	Creating	Not Important	Remembering	Understanding	Applying	Analyzing	Evaluating	Creating
263 Oral communication skills						6.5	6.5						6.5	6.5
264 Presentation skills						6							6.4	
128 Computer Calculations and Computing Skills				4.5	4.5								6.33	
256 Non-Technical Professional Skills				5									6.33	
155 Design creativity (divergent thinking skills)			3										6.2	
54 Photometric reports			2.8										6	
147 Lighting Design Skills			3.5	3.5									6	
148 Lighting design process			3.25										6	
149 Design criteria development			3										6	
156 Conceptualization of luminous compositions			3.2										6	
209 Color and Colorimetry			3.5	3.5									6	
211 Spectral power distributions (SPDs)			3.4										6	
258 Written communication skills						6							6	
153 Design criteria prioritization			3.2										5.8	
154 Development of preliminary/schematic design concepts			3										5.8	
162 Hand sketching			3.2										5.8	
210 Color vision fundamentals			3.2										5.8	
64 Outdoor photometric reports			2.6										5.75	
69 Material properties			3										5.75	
85 Light sources			3.25										5.75	
96 Solid-state lighting			3.5	3.5									5.75	
157 Design development			3										5.75	
161 Presentation drawings				4.25									5.75	
261 Graphical communication skills						5.75							5.75	
231 Luminaire Design			2.75										5.67	
6 Fundamental seeing factors (i.e., lum., contrast, size, time, age)			2.8										5.6	
55 Luminous intensity		2.4											5.6	
68 IES photometry files		2.4											5.6	
73 Lamp efficacy (lumens/watt)			3										5.6	
74 Luminaire efficacy (lumens/watt)			3										5.6	
150 Task analysis			2.8										5.6	
214 CCT				3.8									5.6	
215 Chromaticity			3										5.6	
257 Preparation of a portfolio showcasing work					4.6								5.6	
259 E-Mail communication					5.2								5.6	
24 Lighting Standards, Industry Guidelines, Regulatory Compliance			3.25									5.5	5.5	
46 Photometrics			3.5	3.5								5.5	5.5	
47 Fundamental photometric units and concepts			3									5.5	5.5	

Figure 2. Upper portion of the list of skills in the cognitive domain, sorted by cognitive domain learning level for students concentrating on lighting. The full list contains about 300 items. Embolden text represents topic headings, under which there were subcategories. Values appear in two columns when the mean is exactly between the two columns; otherwise, the value appears in the nearest column. Given the small sample size, the categorical binning by column is considered more relevant than the numerical values. Refer to the supplemental material for the sortable Excel file, instructions for completing the form, and additional comments.

	Not Important	Remembering	Understanding	Applying	Analyzing	Evaluating	Creating	Std. Deviation
143 Python	2			1			1	2.87
125 Form factors	1	1	1			1	1	2.59
126 Interreflected calculations (flux balance models)	1	1	1			1	1	2.59
140 Excel	1			2			2	2.51
274 Personal financial literacy	2		1			2		2.51
142 Matlab	2		1	1			1	2.49
124 Configuration factors	1		2			1	1	2.45
122 Point calculations	1		1	1		1	1	2.39
115 Connected Lighting		1	1		1		1	2.22
272 Time sheets	3		1			1		2.19
164 Working drawings	1		1		1	2		2.17
260 Formal report preparation	1		1		1	2		2.17
123 Radiative transfer	1		1	1		2		2.12
273 Lighting design as a business	2		1	1		1		2.12
146 Unreal Engine	1	1			1			2.08
33 Non-Lighting Sections	2	1	1			1		2.07
133 ALFA	2			1	1			2.06
43 NFPA 70 National Electric Code		1	2	1			1	1.92
130 DIALux	1	1		1	1			1.83
26 IES Lighting Library			2	1		1	1	1.82
36 ASHRAE/IES Standard 90.1 (Energy Standard for Buildings)			2	1		1	1	1.82
114 Sensors (e.g., occupancy, vacancy)			3		1		1	1.79
232 Aesthetic design of luminaires		2		1	1	1		1.79
109 Controls and control gear			1	2			1	1.73
116 Power over Ethernet (PoE)		1	2			1		1.73
137 Climate Based Annual Daylight Modeling	1			2	1			1.73
165 Specification of product criteria			1		1	1	1	1.71
168 Establish and work within design constraints			1		1	1	1	1.71
190 Climate-based annual daylight modeling		1		1	1	1		1.71
4 Anatomy and physiology of human visual system		1	1	1		1		1.71
132 Parametric modeling (e.g., Grasshopper, Rhino, Ladybug)			2		2		1	1.67
234 Optical design of refractors		1		1	1	2		1.67
118 Zonal cavity method	1		1	1	2			1.67

Figure 3. Upper portion of the list of skills in the cognitive domain, sorted by standard deviation of the survey responses, for lighting concentration ARE students only. The full list contains about 300 items. The integers in the body of the figure are the number of responses. Topics such Python, Excel, form factors, and interreflected calculations were polarizing, with some of the professionals believing these topics to be highly important, others rating them as not at all important, and some ranking them in the middle. Refer to the supplemental material for the sortable Excel file and additional comments.

	Non-Lighting ARE Students						Lighting ARE Students					
	Not Important	Receiving	Responding	Valuing	Organizing	Value Complex	Not Important	Receiving	Responding	Valuing	Organizing	Value Complex
1 Mental Library of Light and Lighting		2										5
2 Artistic and Aesthetic Appreciation			2.75									4.75
3 Professional Attitude				4								4.75
4 Ability to Find and Use Appropriate Resources			3						4.33			
5 IES Lighting Library (RPs, TMs, DGs)		2.5	2.5						4.25			
6 CIE Standards		2						3.5	3.5			
7 Web-based resources			3						4.5	4.5		
8 Manufacturer's literature			3						4.5	4.5		
9 Non-Technical Professional Skills					5							5
10 Written communication skills					5.25							5.25
11 Tone of e-mail communications					5.25							5.25
12 Manner on phone/video calls					5.25							5.25
13 Intrinsic Motivation					5							5.25
14 Attitude toward receiving constructive criticism					4.75							5

Figure 4. Full list of skills evaluated in the affective domain. Values appear in two columns when the mean is exactly between the two columns; otherwise, the value appears in the nearest column. Given the small sample size, the categorical binning by column is considered more relevant than the numerical values. Refer to the supplemental material for the sortable Excel file, instruction for completing the form, and additional comments.

	Non-Lighting ARE Students						Lighting ARE Students					
	Not Important	Imitation	Manipulation	Precision	Articulation	Naturalization	Not Important	Imitation	Manipulation	Precision	Articulation	Naturalization
1 Measurement Techniques		1.75										3.75
2 Illuminance measurement		1.75										3.75
3 Luminance measurement		1.5	1.5									3.75
4 SPD measurement		1.5	1.5									3.75
5 Colorimetric measurements		1.25						3.5	3.5			
6 Reflectance measurement		1.5	1.5					3.25				
7 Goniophotometry		1.25						2.75				
8 Integrating sphere photometry		2						3				
9 Design Communication			3.25							4		
10 Hand Sketching			3.25							4		
11 Preparing design documents				4						4		
12 Commissioning of lighting equipment in field settings		1.75						3				
13 Luminaire aiming		1.75						3.5	3.5			
14 Controls commissioning		1.67						2.75				
15 Model building / craftsmanship				4						4		

Figure 5. Full list of skills evaluated in the psychomotor domain. Values appear in two columns when the mean is exactly between the two columns; otherwise, the value appears in the nearest column. Given the small sample size, the categorical binning by column is considered more relevant than the numerical values. Refer to the supplemental material for the sortable Excel file, instructions for completing the form, and additional comments.