Abstract – Two modules related to home energy use that have been developed for a freshman level engineering course are introduced. These modules are intended to introduce concepts in sustainability; serve as an introduction to the profession; and prepare students for the sophomore year, where formal design and communication instruction will occur. Brief overviews of the classroom instruction, laboratory set ups, assignments, and assessment rubrics used for one of the modules in the course, as well as a discussion of the general framing of the modules in the context of preparing students for future coursework are provided.

Keywords: Energy, Lighting, Project Based Learning, Sustainability.

INTRODUCTION

Each semester, Rowan University’s engineering students take an Engineering Clinic [1-2]: a project-based class where subjects from traditional classes are introduced or reinforced, and the so-called professional skills defined by the ABET A through K outcomes [3] are developed. This paper discusses a spring semester Freshman Engineering Clinic that uses sustainability in the context of household energy use as a theme for projects and classroom instruction. Two main modules are presented in the class. The first is based on lighting, and the second is based on heat transfer. Each module starts with traditional classroom instruction that introduces the underlying governing principles, a lab activity that incorporates the governing principles and measurements to assess household products, and a design challenge with a carefully limited scope. In the Spring 2011 semester, one section was taught by Dr. von Lockette, and one section was taught by Dr. Riddell. In the Spring 2012 semester, one section was taught by Dr. Riddell. Furthermore, in both semesters, Dr. Riddell’s class was one of two honors sections of Freshman Engineering Clinic II that was offered.

The project-based aspect of the Engineering Clinics progress in authenticity from Freshman to Senior years. The Freshman and Sophomore Engineering Clinics tend to be carefully structured experiences that are repeated from year to year, while the Junior and Senior Engineering Clinics are one-time experiences, typically based on externally funded projects. The Freshman Engineering Clinics (FEC I and FEC II) serve as an introduction to the profession, with emphasis on measurement and product evaluation. The Sophomore Engineering Clinics (SEC I and SEC II) introduce technical communication coupled with formal design instruction. In the Junior and Senior Engineering Clinics, students interact with sponsors to solve real engineering challenges, and final deliverables make an observable impact on practice. Given the progression, and the high expectations placed on junior and senior students through interaction with actual practice, an essential goal for Freshman Engineering Clinics is to help the students begin to extend from the focus, scope and expectations of traditional high school science laboratories, to successful performance on engineering design tasks encountered in engineering practice.

The authors have had extensive experience (over 10 years combined) teaching the Sophomore Engineering Clinic courses. Development of these courses was strongly influenced by various ideas from the literature [4-6], and has been described in detail elsewhere [7-10]. In SEC, design instruction is based on a model that considers design to be a process that involves creativity, collaboration, problem solving, and informed decision making [7,8].

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Incorporating this model into Sophomore Engineering Clinic I resulted in a noticeable and measureable improvement in the students’ design [8]. The concept of convergent and divergent problems and thinking, as described by Dym, et al. [4], is especially important to the model. Convergent questions have truth value, while divergent questions deal with concepts. Convergent thinking is characterized by making design decisions that move one closer to the optimal design and involves predictions of performance based on physical laws and assessment of designs, including the collection and analysis of data. Divergent thinking is characterized by making design decisions that do not necessarily move directly to the optimum design, but are instead meant to widen the design space. While a design challenge is fundamentally a divergent question, the process of design requires sequences of divergent tasks and convergent tasks, and transitioning between these tasks is an important skill for designers.

Using this framework to evaluate students’ design abilities, a common weakness in the Sophomores had been identified. While students tend to be strong at both performing calculations, i.e., convergent thinking, and developing potential design solutions, i.e., divergent thinking, they often have a hard time using convergent thinking to refine, optimize or choose between potential design solutions [10]. In other words, the ability to deftly and appropriately switch between convergent and divergent thinking throughout the design process is extremely difficult. Without direct intervention, students are unlikely to use calculations to inform design decisions.

It was anticipated that completion of design challenges that are simple enough to give a high chance for success, yet capture essential aspects of design thinking, would help prepare freshman engineering students for future design experiences. Two modules were developed, with a similar progression through each. The first part of each module is essentially convergent in nature: a laboratory experience that is designed to evaluate and assess household items. The second report is based on a design challenge that is limited in scope, but strongly dependent on proper design thinking: identification of constraints, and criteria; identifying initial concepts as potential solutions; and using a mathematical model based on governing principles to optimize or determine the best solution.

### COURSE CONTENT

In recent years, there have been multiple sections of Freshman Engineering Clinic II (the spring semester) offered. Each section has between 16 and 25 students, and is led by a faculty member. The course has one fifty minute class, and one two hour and fifteen minute lab period each week, and counts as 3 credit hours. While each faculty member has a great deal of latitude in how the class runs, there are some specific requirements. The spring semester has a nominal common theme of engineering assessment. Furthermore, several topics are required to be covered: ethics, introductory statistics, and engineering economics. Finally, students are required to make an oral presentation, and give a poster presentation, although the topics for these are left to the individual instructor.

The two authors collaborated in developing course content for their sections of FEC II, with the goal of a class that met the pedagogical goals via a study of energy use in the household. It was felt that this topic would allow fundamental concepts of sustainability to be introduced in a setting to which all disciplines of engineering could relate. Two modules on household energy use, lighting and heat transfer, were the most significant aspects of the course. Other topics covered during the semester included ethics, statistics, and numerical integration. Typically, students in this class have taken College Composition, Chemistry, and Calculus I prior to this semester, and are taking Calculus II and Introduction to Mechanics (i.e., Physics I) concurrently. The modules are taught assuming that students have no background in optics or heat transfer prior to this course. Each module consisted of a series of fifty minute classes, a laboratory experience based on assessment of performance, and a design challenge. A significant portion of the laboratory periods were left free for group work.

In each module, a preliminary lab is used to assess the performance of commercial products. In the lighting module, the efficacies of various light bulbs are assessed. In the heat transfer, the efficiency of various refrigerators, freezers, hotplates and ovens are assessed. These laboratory experiences are used to answer convergent questions. The second module was focused on design – answering a divergent question. As the students have not received formal instruction in design, the design challenges were intended to be very simple. However, the challenges are posed in a manner such that they cannot be solved explicitly. In the lighting module, the type, number and placement of lamps is designed for a hallway to satisfy lighting level requirements while minimizing lifecycle costs. In the heat transfer module, home water heaters are selected to satisfy the various students’ own household water use requirements, while minimizing lifecycle economic costs. Details of the lighting module are now presented.

The lighting module includes classroom instruction in various topics related to optics and lighting, as summarized in Table 1. For each class, a handout describing key words, objectives, and in some cases Greek symbols was passed out to the class. This information is included in Appendix A. Although class notes are intended to be sufficient for
the students to learn the material well enough to complete the design challenge, a textbook on architectural lighting [11] was used to develop the material, and is available to the students on reserve in the university library.

Table 1. Classroom topics in lighting module

<table>
<thead>
<tr>
<th>Class Title</th>
<th>Topics Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Light and Energy</td>
<td>Electromagnetic radiation, photons, energy, work and power</td>
</tr>
<tr>
<td>Measurement of Light</td>
<td>Luminous Flux, Luminous Intensity, Illuminance</td>
</tr>
<tr>
<td>Electric Sources of Light</td>
<td>Human perception of light, Metrics for light (correlated color temperature, color rendering index, lumens), Principles behind lamps (incandescent, fluorescent, LED)</td>
</tr>
<tr>
<td>Calculating Illuminance</td>
<td>Illuminance on inclined surfaces, integration of illuminance to find luminous flux</td>
</tr>
</tbody>
</table>

The students use the initial laboratory experience to assess various household light bulbs that are commercially available. Incandescent, compact fluorescent, and light emitting diode (LED) lamps that use a traditional household light fixture are available for evaluation. The students are given manufacturer-supplied data on lumens, correlated color temperature (either an actual temperature, or description such as “warm white”) and color rendering index, as well as purchase price for each lamp.

Students were tasked with measuring the illuminance from various lamps at different angles from the central axis of the lamp, and measuring the electricity use. A side view schematic of the laboratory setup is shown in Figure 1, and a plan view is shown in Figure 2. Each group has a light meter with which to measure the illuminance at a fixed distance and varying angles from the lamp. The distance from the lamp to the light meter, \( r \), is obtained using a string of known length, and trigonometric principles. The angle is found using a protractor. Sample data from an experiment is shown in Figure 3. For these data, illuminance was measured at a distance of 0.56 meters from a 13-Watt LED bulb. Polynomial curves are then fitted to illuminance data, to develop a continuous expression for \( E_v(\theta) \). The polynomial coefficients are shown in Figure 3 for the data presented.

Equation 1 is integrated numerically to find the luminous flux, \( \Phi_v \), (in lumens) over a sphere of radius, \( r \), for each lamp. For a given lamp, this value is independent of \( r \), and characterizes the brightness of the lamp. WattsUp? meters were used to measure the electric power drawn by each lamp, allowing the efficacy (lumens/Watt) to be determined. The first report was returned with comments, but not graded.

\[
\Phi_V = \int_{\theta=0}^{\pi} E_v(\theta) 2\pi r^2 \sin\theta \, d\theta
\]  

(1)

Figure 1. Side view of experimental setup.
The second report addresses the design challenge, which consisted of designing a lighting strategy for a hallway, based on the measured performances of the lamps. The scope of the design was limited to placing fixtures along the centerline of a hallway that is 10 meters long and 2.5 meters tall. A minimum illuminance of 100 lux is required along the entire centerline of the floor of the hallway. Students were tasked with specifying the type, number and location of lamps to satisfy the minimum illuminance, while minimizing the lifecycle cost over ten years. The lifecycle cost was present worth cost of electricity used to light the hallway for 8 hours per day over 10 years, and the initial and replacement bulbs that might be needed.

Consistent with the model for teaching design in SEC I [7], this design challenge requires non-trivial calculations. The illuminance at a given floor location resulting from a single lamp can be found using Equation 2.

\[
y = -51\theta^2 - 9L - 0.07\pi^2 - 0.0006\pi^2 - 0.0892\pi^2 + 5.0492\pi + 3.4014
\]

where \( E_{V,\text{floor}} \) is the illuminance on the floor at a given location, \( \theta \) and \( R \) describe the location of the given point with respect to the light, as shown in Figure 4, \( E_v(\theta) \) is the polynomial fitted to experimental observations (see Figure 3), and \( r \) is the distance used to develop \( E_v(\theta) \).
The illuminance resulting from light output from multiple lamps can be found using superposition. The power
drawn for each lamp (in terms of hours of service) was taken from the experimental values, the cost per lamp was
the purchase price, and the lifetime of the lamp was provided by the manufacturer. The authors were anticipating
that the student teams would develop and employ a rational design strategy. Although there are potentially many
approaches that could be utilized, one strategy would be as follows. First, develop an excel spreadsheet that allows
a user to vary the location of lamps and evaluate the illumination along the entire length of the hallway. Second, use
the spreadsheet to determine optimal spacing for a single type of lamp in the middle of the hall (away from edge
effects) – ideally this would provide just the minimum illuminance required. Then, determine the adjustments
needed to light the ends of the hall, until an optimal solution is found for that lamp type, which would be a candidate
for the final design. This process would be repeated for all lamp types, establishing several candidate final designs.
Finally, use economic analysis to determine the lifecycle costs for each candidate final design, which identifies the
best possible solution. This approach requires correct calculations of illuminance; checks that the constraint, i.e.,
minimum lighting level, is satisfied; rigorous searching of the design space for each lamp type; and then correct
economic analysis for each candidate design to allow the best design to be selected.

![Figure 4. Single lamp source incident on floor.](image)

In addition to the design information, the final report for the project includes the original assessment report, with
changes made based on the initial comments. The students were asked to use engineering economics to account for
initial purchases, replacement purchases, and electricity costs to establish a present worth cost for each design. The
assessment was then included as part of the final report for the module, which was graded according to the rubric
presented in Appendix B.

**ASSESSMENT**

One goal of this work was to address the ABET A-K outcomes assessment criteria [3], summarized in Appendix C
for review. As structured, the lighting and water modules’ emphasis on performing convergent analysis using
physical laws and mathematics, conducting experiments, designing an energy- and cost-efficient solution, and
coupled with the course’s team-based structure, documentation requirements, and emphasis on ethics are well
situated to provide an experience conducive to outcomes A-H and J-K directly. Given successful completion of the
course, students would achieve at least an exposure level to these outcomes. More formal assessment can be seen
from assessment of the documentation using the grading rubric.

Average grades for the design reports from the three sections of the course are shown in Table 2. The two authors
have significant experience grading reports from Sophomore Engineering Clinic I, and have found that their grades
using similar rubrics are in reasonable agreement [9]. From von Lockette’s section the lighting module reports,
which were completed first, showed that almost all student teams were able to perform calculations of required
lighting levels and cost measures and to select lowest cost design solutions. However, most teams were not
effective at rigorously investigating the design space of all possible hallway lighting solutions to choose the global
optimum and teams often incorporated engineering economics in only part of their cost calculations (e.g., for
periodic replacement lamps but not operating costs or vice versa). In addition, the multiple arenas of convergent
analysis (illuminance calculations, numerical integration, and engineering economics) required appeared to cause
some level of difficulty. It appeared that students had difficulty integrating all objectives, focusing on individual
aspects of convergent analysis and design separately, while focusing less on divergent design concepts, e.g., not
examining options that digressed significantly from their initial design choices. In general, Riddell’s section did a
better job in the design aspect. These teams all appeared to perform the convergent analyses correctly, and were able to select the lowest cost design from the pool of candidate designs identified. As with von Lockette’s section, in Spring 2011, few teams in Riddell’s section were rigorous in their investigation of the design space for each individual lamp type. Many of the “optimal” designs presented for a given type of lamp were clearly over-lit. As a result, the type of lamp a team selected for the final design was a function of how well optimized that particular search of the design space had been, rather than how efficient that lamp could be. As a result of these observations, teams in the Spring 2012 semester were given additional guidance to ensure that each of their candidate designs were optimal for that particular lamp type. The average scores on the design section of the rubric improved did improve from 15.2 out of 20 in the Spring 2011 semester to 16.4 out of 20 in the Spring 2012 semester.

<table>
<thead>
<tr>
<th>Project</th>
<th>Average Score</th>
<th>Von Lockette</th>
<th>Riddell</th>
<th>Riddell</th>
</tr>
</thead>
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<td>Lighting</td>
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<td>80.8</td>
<td>80.0</td>
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</tr>
<tr>
<td>Heat Transfer</td>
<td>82.2</td>
<td>82.8</td>
<td>82.8</td>
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</table>

**SUMMARY AND CONCLUSIONS**

The larger goal for the project was to introduce students to design via design challenges that are rich enough to require all the essential aspects of design thinking, yet simple enough to accomplish in the freshman year. The authors contend that the course modules are well structured to provide a framework for students to develop their convergent-divergent thinking skillsets: the various modules contain the required elements. However, student outcomes suggest that while students were able to perform convergent analysis to evaluate design outcomes and make selections, they were less facile with integrating multiple levels of convergent analysis and mapping that analysis onto multiple, possibly divergent, design solutions. As a result, it appears that freshman would benefit from explicit design instruction, even for relatively simple (but rich) design challenges.

**REFERENCES**

William T. Riddell
Dr. William Riddell received his B.S. in Engineering from the University of Massachusetts at Amherst, and his Ph.D. from Cornell University. He is an Associate Professor of Civil and Environmental Engineering at Rowan University, with research interests in mechanics of materials and sustainability. Prior to Rowan, he worked at the John A. Volpe National Transportation Systems Center in Cambridge, MA, and the Mechanics of Materials Branch at NASA Langley Research Center in Hampton, VA.

Paris R. von Lockette
Dr. Paris von Lockette received his B.S. in Engineering Science from Trinity University in San Antonio Texas and his Ph.D. from the University of Michigan, Ann Arbor. He is an Associate Professor of mechanical engineering at Rowan University, Glassboro, NJ with an expertise in active materials, mechanics, and polymer physics. Dr. von Lockette has a strong interest in design pedagogy and has taught design-related courses at Rowan University for over 10 years. He also has a lengthy record of developing outreach programs, especially to underrepresented groups (such as the STEM Academy at Rowan – STAR program).
APPENDIX A: STUDY GUIDES FOR FOUR CLASSES IN LIGHTING MODULE

Introduction to Light and Energy

Key Words:
Photon  Wavelength  Energy  Frequency  Joule
Newton  Watt  Kilowatt  Horsepower  Power

Objectives:
● Perform basic unit conversions
● Cite two models for light
● Calculate the energy in a photon as a function of wavelength
● Explain the difference between work and power
● Relate watts, kilowatt-hours and cost for electricity

Measurement of Light

Key Words
Radiometry  Photometry  Optics  Luminance  Emittance
Illuminance  Luminous Flux  Lumen (lm)  Efficacy  Luminous Intensity
Steradian  Candela  Radian  Lux (lx)  Footcandle

Objectives
● Explain the difference between radiometry and photometry.
● Relate luminous flux, luminous intensity and illumination.
● Calculate the efficacy of an electric light source.
● Estimate the % of total power used that an electric bulb can convert to light.

Greek Letters
Φ  (phi)

Electric Sources of Light

Keywords
Cones  Incandescent  Halogen  Fluorescent  Light Emitting Diode (LED)
High Intensity Discharge  Correlated Color Temperature (Color Temperature)
Color Rendering Index  Filament  Ballast

Objectives
● Explain how humans perceive the color of an object
● Describe three parameters used to describe an electric light source
● Cite 5 types of electric lights
● Explain how incandescent, fluorescent, and LED lights work
● Discuss operational considerations of incandescent, fluorescent and LED lights

Calculating Illuminance

Keywords
Illuminance  Luminous Intensity  Lumen  Steradian  Angle of Incidence

Objectives
● Derive the r² relationship for illuminance vs distance
● Derive the cos² relationship for illuminance vs angle of incidence
● Calculate illuminance for an arbitrary surface for one or more given light
# APPENDIX B: RUBRIC FOR FINAL LIGHTING MODULE REPORT

<table>
<thead>
<tr>
<th>Section</th>
<th>Score</th>
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<tbody>
<tr>
<td>Cover Page</td>
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<td>□ Includes initialed statement by editor</td>
<td></td>
</tr>
<tr>
<td>Executive Summary</td>
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</tr>
<tr>
<td>□ Briefly summarizes report for a high level reader</td>
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<tr>
<td>Introduction</td>
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</tr>
<tr>
<td>□ Orient reader to the entire document</td>
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<tr>
<td>□ Clearly identifies problem statement</td>
<td></td>
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<tr>
<td>□ Includes helpful figure</td>
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</tr>
<tr>
<td>□ Defines constraints</td>
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<tr>
<td>□ Defines criteria</td>
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<tr>
<td>Assessment of Lamp Types</td>
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</tr>
<tr>
<td>□ References example calculations in an appendix</td>
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</tr>
<tr>
<td>□ Describes experiments well enough for reader to reproduce results</td>
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</tr>
<tr>
<td>□ Uses appropriate graphics to convey information</td>
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</tr>
<tr>
<td>Design Process</td>
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</tr>
<tr>
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<tr>
<td>□ Explains how experimental data were used to inform design</td>
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<tr>
<td>□ Clearly presents preliminary designs, and explains how they were developed</td>
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<tr>
<td>□ Graphically shows that preliminary designs all meet the constraints</td>
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<tr>
<td>□ Presents results of engineering economics analysis in a table</td>
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<tr>
<td>□ Clearly identifies and defines final design</td>
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<tr>
<td>□ Makes strong argument for choice of final design</td>
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<td>Summary and Conclusions</td>
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<td>□ Summarizes design process</td>
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<td>□ Clearly states final design and resulting costs</td>
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<td>Follows Document Specifications</td>
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<td>□ Includes exact copies of original data sheets</td>
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<tr>
<td>□ Example calculations allow reader to reproduce results reported in main body of report</td>
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APPENDIX C: ABET ENGINEERING CRITERIA PROGRAM EDUCATIONAL OUTCOMES

A. an ability to apply knowledge of mathematics, science, and engineering
B. an ability to design and conduct experiments, as well as to analyze and interpret data
C. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
D. an ability to function on multi-disciplinary teams
E. an ability to identify, formulate, and solve engineering problems
F. an understanding of professional and ethical responsibility
G. an ability to communicate effectively
H. the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
I. a recognition of the need for, and an ability to engage in life-long learning
J. a knowledge of contemporary issues
K. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice