Engineering Design Modules as Physics Teaching Tools

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Pre-engineering is increasingly being taught as a high school subject. This development presents challenges as well as opportunities for the physics education community. If pre-engineering is taught as a separate class, it may divert resources and students from traditional physics classes. However, design modules can be used as physics teaching tools that can seamlessly integrate technology, engineering, and math into high school physics using a variety of teaching styles. This paper discusses a rationale for using design modules as tools for teaching physics. As an illustration, an example of an engineering design module is presented. This example module is appropriate for an algebra-based physics class that covers Ohm’s law.

Motivating rationale for using design in physics classes

Improved science learning & equity:

Physicists and engineers share many common characteristics. Experimental physicists perform engineering tasks while designing and troubleshooting an experimental apparatus. Most practicing engineers took at least one year of calculus-based physics. Finally, some graduate and undergraduate physics students become practicing engineers.

Recently, pre-engineering has increasingly been taught as a high school subject. Often, pre-engineering is taught by high school technology teachers. Yet, due to the strong ties between engineering and physics, the high school physics classroom is a natural place to introduce engineering design modules in a way that enhances high school physics education, in addition to teaching engineering design principles.

Simultaneously, design has increasingly been shown to be an effective pedagogy for science education. One of the pioneers in using design as a science teaching tool has been Janet Kolodner. Kolodner’s Learning by Design (LBD) has been applied to middle school science. Kolodner reports that students using the LBD methods “learned science content as well or better than those learning under more traditional methods.” Further, LBD students performed “as well as or better than honors students who have not been exposed to LBD, while LBD honors students perform the targeted skills and practices like high school or college students.”

Another positive aspect of using design as a pedagogical method for teaching science is related to enhancing science education of underrepresented minorities. Christian Schuun et al. of the University of Pittsburgh’s Learning Research and Development Center have demonstrated that using design as a pedagogy for teaching science results in “superior performance in terms of ... achievements in core science concepts, engagement, and retention.” They found that using design as a pedagogical method for teaching science was “most helpful to low-achieving African-American students.”

A similar study demonstrated that the positive effect of using design benefited girls slightly more (though not by a statistically significant difference) than boys.

Akins and Burghardt have demonstrated that using engineering design enhances mathematical thinking. They studied seventh- through ninth-grade students who applied math in the context of engineering design. According to the authors, the results were “nothing less than remarkable.” They reported that the lowest-scoring students showed the most gain in mathematics as a result of using engineering design as a context for mathematics.

One of the more innovative means of incorporating student design into physics is the Investigative Science Learning Environment (ISLE) method developed by Eugenia Etkina and Alan Van Heuvelen. The ISLE is a comprehensive method of teaching physics where, among other tasks, students design experiments to test predictions that are based on observations. One of the benefits of using the ISLE method is that it facilitates transfer and learning at a later time.

However, many physics instructors do not incorporate the findings of Physics Education Research into practice. Specifically, student design is one of the least used reform-based physics pedagogies.

One means for introducing engineering design into the science curriculum is through discrete engineering design modules. Cantrel et al. introduced three engineering design modules into the physical science curricula of eight Nevada middle school classrooms. They found that by using engineering design modules to teach physical science, “achievement gaps were reduced dramatically for Hispanics and Black students.”

Apedoe et al. used an engineering design module on heat transfer in high school chemistry classes involving 380 students. They found that students using the engineering design modules made substantial gains in knowledge of chemistry. They also reported that participating teachers said they had been able to cover more chemistry content after completing the design module because students had “a stronger grounding in the core ideas of chemistry.”

Beyond the design experience, the process of working in teams to construct and troubleshoot a design prototype provides substantial additional educational opportunities. Specifically, constructing and troubleshooting a prototype encourages many of those skills advocated by The Partnership
A typical problem associated with circuit analysis in an algebra-based physics textbook could be finding the voltage at node a in Fig. 1. However, this circuit is likely not based on a real circuit because 35-kΩ and 65-kΩ resistors are generally not mass produced.

Rather, resistors are generally mass produced with values that are (nearly) equally spaced on a log scale. For example, the (EIA-E24) standard-based resistor values between 10 kΩ and 100 kΩ are limited to: 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, and 100 kΩ. Such limitations (design constraints) are common in engineering design problems.

The circuit illustrated in Fig. 1 may be adapted into an open-ended engineering design problem. All engineering design problems have design goals and constraints. A specific example of a design goal for designing a voltage divider is asking students to design a circuit so that a circuit node is at 6.5 V ± 0.2 V.

Design constraints are often based on logistical, financial, or technological limitations. In addition, design constraints may also be based on legal, ethical, or societal expectations. A specific example of design constraints for designing a voltage divider is:

1) Use up to three resistors.
2) Resistor values are limited to the following: 1 kΩ, 1.2 kΩ, 1.5 kΩ, 1.8 kΩ, 2.2 kΩ, 2.7 kΩ, 3.3 kΩ, 3.9 kΩ, 4.7 kΩ, 5.6 kΩ, 6.8 kΩ, 8.2 kΩ, and 10 kΩ.
3) Use a 10.0-V (or other supplied) dc power supply.

One aspect of engineering design problems is that they usually have more than one solution. For example, two schematics associated with acceptable designs corresponding to a 10-V power source are illustrated in Fig. 2.

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Student designs for this module may be readily fabricated using inexpensive resistors, solder-less breadboards, volt/ohmmeters, and a dc power supply. In the appendix are specific suggestions for implementing this module including: a) a discussion of resistor variability; b) a suggestion for an inexpensive and “green” dc power source; and c) potential variations in the design goal and constraints.

**The voltage divider as an engineering design module**

This section illustrates the modification of a typical physics example or homework problem into an engineering design module. This particular module involves a voltage divider and is appropriate for students who:

- have completed at least one year of high school algebra, and
- have studied Ohm’s law, including resistors in series and in parallel.

![Fig. 1. A typical textbook problem on circuits.](image1)

![Fig. 2. Schematics for two designs: $V_b = 6.36$ V, and $V_c = 6.48$ V.](image2)
Experiences with engineering design in the physics classroom

This module (with minor modifications), as well as a similar module, was implemented in a high school physics class for juniors and seniors at St. Ursula Academy in Toledo, OH. Students worked in teams of about three. After preparing a design for the circuit, student teams implemented their design using electronic breadboards. Their initial attempts at implementation were not always successful. However, these temporary failures facilitated higher-level learning skills such as analysis and troubleshooting. Finally, a sense of victory prevailed when all teams eventually attained a successful prototype.

Coauthor and teacher Jackie Kane observed teamwork, discussion, and a freedom to explore new ideas in student teams. Since there was no single right answer, just a goal, students worked within the design constraints, calculating, testing, and troubleshooting their designs. They did not always gravitate toward the easiest solution, but often strived to build an intriguing combination, as well as to beat out the other teams.

Students appeared excited to work with electrical components. Many developed an interest in the engineering process in a way that connected with their own high-tech lives. One student, whose father is an engineer, revised her career interest to consider engineering. Those already interested in engineering became confident leaders in the class.

Conclusion

Pre-engineering is increasingly being taught in high schools. This trend may be used to the advantage of physics programs by introducing open-ended engineering design modules as a physics teaching tool. A voltage divider was used to illustrate how a typical physics problem can be modified into a design module that seamlessly integrates high school physics and math with engineering design.

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Appendix: Resistor Variability

Obtaining quality resistors is important to the success of this project. The nominal (color-coded) tolerance of many ¼-W resistors is 5%. If the variation in the resistors were actually as large as 5%, this would add another level of difficulty when students compare predicted voltages with the measured voltages.

To check if the resistors used had variability as high as 5%, a sample of resistors was tested. Results of this inspection are given in the table below. Based on these samples, the actual variability of these resistors is likely much less than 5%.

<table>
<thead>
<tr>
<th>Nominal Resistance</th>
<th>Number Tested – n</th>
<th>Min/Max Values</th>
<th>Mean Resistance</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 Ω</td>
<td>31</td>
<td>988.3/1015.5 Ω</td>
<td>997.19 Ω</td>
<td>0.55%</td>
</tr>
<tr>
<td>10 Ω</td>
<td>31</td>
<td>9.998/10.156 kΩ</td>
<td>10.075 kΩ</td>
<td>0.40%</td>
</tr>
</tbody>
</table>

It is expected that most recently manufactured ¼-W resistors will have similarly low deviations from the nominal (color-coded) values. Regardless, manufacturing processes are variable. Hence, prior to implementing this design module, it may be wise to randomly test the resistors for variability and deviation from the nominal values.

The resistors used should not have too large of a resistance or some low-end digital multimeters may not render an accurate voltage reading across that resistor. The author (DO) has found that limiting resistors to the range of 1.0 kΩ ≤ R ≤ 22 kΩ seems to work well.

A source of inexpensive carbon film resistor kits that are well suited for classroom use is Small Bear Electronics (www.smallbearelec.com).

An inexpensive and ‘green’ power supply source

Each student group will need access to a low-voltage (~6 to 20-V) dc power supply. An inexpensive (and environmentally friendly) way to obtain power supplies is to recycle surplus dc power adaptors. These adaptors may be modified into dc power supplies by replacing the connector at the end of the wire with a red (positive) and a black (ground) alligator clip. A photo of such a recycled power adaptor is illustrated in Fig. 3.

One of the problems associated with using many small power adaptors as dc voltage sources is that they have an internal resistance and are able to produce only low current near the maximum voltage. If this internal resistance is not considered, the calculated voltages may not match well the actual circuit voltages. This problem may be substantially remedied by one of the following:

1. **(Suggested remedy)** Testing individual transformers and using only transformers that do not exhibit a significant voltage drop when a load is applied. For example, newer Motorola™ 5.0-V transformers deliver a nearly constant dc voltage, even at relatively large currents.

2. **(Alternate remedy)** The relative effect of this drop in source voltage may be substantially reduced by using only transformers with a peak voltage of about 16 to 20 V – then assigning only low target voltages (say 2 to 4 V).

3. **(Alternate remedy)** Using design criteria so that the goal is a specified fraction of the power source instead of a specified voltage.
4. **(Alternate remedy)** Have students graph the voltage delivered by a transformer as a function of the total resistance load (in ohms). Students should use this graph to estimate the value of the actual source voltage corresponding to the total resistance in the voltage divider.

**Potential modifications to the design goals and constraints**

There are many perturbations that can be made to the design goal and constraints. Consider the two potential solutions illustrated in Fig. 2. It is not clear which is best. The circuit on the right has a voltage that is closer to the target voltage of 6.5 V. However, the circuit on the left uses only two resistors and is likely a less expensive design to manufacture. Potential design criteria modifications include:

- Allow for the use of more than three resistors, designing the voltage divider to minimize a specified function such as
  \[ f = n(V_{\text{node}} - 6.5 \, \text{V})^2, \]
  where \( n \) is the number of resistors used (this criterion considers both cost and precision);

- Allow for the use of more than three resistors, establishing two target voltages at two different nodes, for example, 6.5 V at one node and 3.5 V at another node; or

- Allow a broader range of resistors.

**References**

13. See, for example, Overview of 21st Century Skill at www.21stcenturyskills.org.
15. See, for example, Amy Prevost and Mitchell Nathan, “The Integration of Mathematical into Precollege Engineering: The Search for Explicit Connections,” AC 2009-1790, ASEE Conference, Austin, TX (June 2009).
18. For a description of common resistor values, see www.pc-control.co.uk/resistor-eia.htm.

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