

Work InProgress: Infrastructure Live! An Electric Experience on a Single Mobile Chalkboard

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Abstract

The offering of broad-based infrastructure engineering courses has grown considerably over the last decade, with the energy sector – and specifically electricity – being a critical topic. Although students' lives are inextricably dependent upon electricity, and the practice of civil engineering both relies on and creates electrical infrastructure, personal experiences generally do not provide for direct, physical, or visual observation of the fundamental concepts underlying our electrical infrastructure. Consequently, educators have a challenge when it comes to building upon existing knowledge of energy and electricity in the classroom. To help address this challenge and grow essential knowledge of energy infrastructure in civil engineering students, the authors leveraged multiple tenants of the Excellence in Civil Engineering Education (ExCEED) model of pedagogical theory to develop a novel hands-on demonstrator for the direct observation of a typical household electrical system using a single chalkboard on wheels. This demonstrator facilitates the study of a wide variety of concepts, including the difference between energy and power, alternating current and voltage, the function of key safety features and their limitations, balancing loads, code requirements and the reasons behind them, and more. In service for over a decade, this simple, single demonstrator has stood the test of time and helped educate over 2,300 students. In this work-in-progress paper, the authors present the pedagogy of using the demonstrator, to include learning objectives, classroom activities, and a model script for a 50-minute experience, as well as a parts list and instructions for constructing the demonstrator. The authors also present the use of the demonstrator within the context of an infrastructure engineering course within a civil engineering program. Lastly, the authors present their plan to assess the demonstrator's effectiveness in helping students achieve identified learning objectives.

Introduction

Civil engineers are responsible for designing the infrastructure society requires. The large investments on civil works projects made by local, state, and national governments require trained professionals who understand the interdependencies between various sectors of infrastructure and how nearly every facet of society depends upon the built environment. Prior to 2008, civil engineering educators discovered a major void in curriculum as few, if any, courses existed to teach students how to identify, assess, protect, rebuild, or maintain infrastructure [1]. Electrical power infrastructure – ubiquitous, complex, and essential to meeting sustainability goals – is particularly essential to the infrastructure landscape, and early civil engineering students broadly lack a basic understanding of the functioning of this critical element.

Over the past ten years, there has been a growth of broad-based infrastructure survey courses at the college level, especially within civil engineering programs. Early coursework on

infrastructure focused on the history behind the development of modern-day industries and engineering [2]. This evolved into infrastructure courses focused on engineering for the fundamental needs of society, with major topics including network modeling, water and wastewater, energy and electricity, and transportation [3]. Further work developed models, or mental frameworks, for students of infrastructure to understand the interdependencies of the various sectors of infrastructure [4]. Additionally, some courses focus on sustainable design for infrastructure and life cycle analysis, to include planning, design, construction, operation and maintenance, and either rehabilitation or replacement [5]. It has even been argued that infrastructure is core knowledge that all disciplines should study as a part of a broad-based, liberal arts education that prepares graduates to become informed decision-makers and collaborators in society [6]. Such broad-based courses on infrastructure empower students to understand the complexities of networks and metasystems, assess systems under both normal and disrupted conditions, identify and classify stakeholders of infrastructure projects or failures, and identify requirements for infrastructure to remain resilient in serving the needs of society.

Similar to survey-type courses like history and art, introductory infrastructure courses typically cover a wide variety of topics, and enduring themes have emerged as critical content, to include energy, water, and transportation [7]. For many students, water's basic properties are well-understood. Direct observation and physical interaction with water concepts like pressure and flowrate result in an innate knowledge upon which deeper understanding can be built. Similarly, transportation is readily observable and understood by students, many of whom have been licensed drivers for several years and have physically used various modes of transportation. Conversely, the properties of energy – especially electricity – tend to pose special challenges. Unlike a bus or a river, the fundamentals of the electro-magnetic world are only indirectly observed. Students use electricity every day, but their daily experiences tend to be restricted to flipping a light switch on and off or plugging a cord into an electrical outlet. Such experiences do not provide for direct, physical, or visual observation of fundamental concepts or the underlying physics of electricity.

Not understanding the basics of electricity is a major gap in civil engineering education that can be overcome through learning objectives in infrastructure courses. Civil engineering education must prepare graduates to meet the future needs of society, and the National Academy of Engineering asserts that restoring and improving urban infrastructure is a “grand challenge” for the 21st Century, specifically stating that solutions “must be designed for sustainability, giving proper attention to environmental and energy-use considerations” [8]. Nearly everything civil engineers design and construct relates to the energy infrastructure sector in some form or another, from hydropower generation at dams to transmission towers to buildings that use electricity. Further, the American Society of Civil Engineers' (ASCE's) Vision for Civil Engineering in 2025 calls for civil engineers to “serve as Master Builders... leaders in the discussions and decisions shaping public environmental and infrastructure policy,” a vision that calls for deep understanding of the generation, transmission, and use of electrical power in order to be effective members of integrated design teams – particularly those seeking to address sustainability challenges [9]. Civil engineers must have a foundational knowledge of the basics

of energy and power and, as such, civil engineering educators must have a mechanism to facilitate the visual observation and understanding of common electrical equipment.

To address this need, the authors leveraged multiple tenants of the Excellence in Civil Engineering Education (ExCEED) model of pedagogical theory to develop a hands-on “power demonstrator board” for the direct observation of a typical household electrical system consisting of common electrical equipment mounted on a mobile chalkboard. The demonstrator allows for the study of a wide variety of electric power concepts, including the difference between energy and power, alternating current and voltage, balancing loads, and the function of key safety features and their limitations – to include circuit breaker operation, ground-fault and arc-fault circuit interrupters (GFCIs and AFCIs), polarized plugs, grounding, code requirements, and more. Mobility increases the demonstrator’s flexibility and use; it is easy to move from room to room, and it can be stored in a small space. In service for over a decade, this simple, single demonstrator has helped educate over 2,000 students.

Others have developed similar demonstration boards in recent years, though the primary functions of those demonstrators are different. For example, Dr. Jeff Galapon Pereyra developed a smaller “electrical wiring installation trainer” board for teaching Industrial Technology majors in Electrical Technology at the College of Technology, Pangasinan State University, Lingayen Campus [10]. The purpose of this board, however, was to help students learn procedures for wiring single-phase distribution for lighting and outlets. The PBS TV series, “Ask This Old House” utilized a similar concept to show how GFCIs and AFCIs function during an episode that originally aired in January 2023 [11]; that demonstration board was made to look like what a homeowner might find at home with a circuit breaker panel neatly installed and surrounded by drywall. These demonstration boards differ in scope from the one developed for use by students of infrastructure and discussed herein. This power demonstration board is specifically designed to be presented by a trained and certified laboratory technician who, in concert with the instructor, can show students what the system looks like behind the drywall. Beyond understanding how to properly wire a system, this board uses measurements of voltage, current, power, and resistance to show, in real-time, how an electrical system responds to loads.

Initial Development and Pedagogical Approach

The power demonstrator board is used to facilitate a deeper understanding of the use phase of electricity, a major component of the energy sector of infrastructure [4]. Organizations like the U.S. Energy Information Administration (EIA) trace energy consumption from source (petroleum, natural gas, renewable energy, coal, & nuclear) to end-use sector (transportation, industrial, residential, and commercial) [12]. Nearly 38% of primary energy in the United States is used to produce electricity, ultimately servicing every end-use sector. To meet society’s sustainability goals, emerging initiatives to reduce carbon emissions often rely on electrifying all end uses of energy and producing that energy using clean, renewable resources [13]. With the proliferation of electric vehicles, solar panels, home battery storage, etc., it will be imperative for civil and other engineering graduates to demonstrate adequate understanding of the basics of

electricity as a key component of the energy sector and, perhaps, the burgeoning future of infrastructure development worldwide.

Consequently, topics of instruction within the energy block of an infrastructure course should include energy fundamentals (like the difference between energy and power); gravimetric and volumetric energy density of fuels; energy efficiency, conversion losses, and conservation of energy; circuitry basics (resistive, inductive, capacitive); basic relationships between Direct Current (DC) and Alternating Current (AC) voltage, current, resistance, and power; generation of three-phase electricity; high-voltage transmission; substations; distribution; and use in either industrial and commercial applications with three-phase power or residential with split, single-phase power. This is a long list of topics, many of which will be new to the student; to help students identify and categorize these topics and the many components of electrical energy infrastructure, a mental model or framework is used with the mnemonic: Grizzly Bears Don't Use Water Closets, which is for Generation, Bulk transmission, Distribution, Use, Waste, and Coordination [14]. The power demonstrator board was specifically developed to support student understanding of the “use” phase of electrical energy infrastructure.

Josiah F. Bumstead, in his 1841 treatise *The Black Board in the Primary Schools*, wrote that, “the inventor... of the blackboard deserves to be ranked among the best contributors to learning and science, if not among the greatest benefactors of mankind” [15] [16]. The power demonstrator board leverages the age-old black board in a new way. One instructor of an early infrastructure engineering course met with a laboratory technician to discuss the problem he was having with getting students to understand the use phase of electricity. He knew that experiencing engineering is a great way to learn engineering, so he wanted to do something beyond drawing circuit breaker schematics on the blackboard to help his students “see” how the system works.

Utilizing “scaffolding” (the pedagogical concept of temporary adaptive support often attributed to Lev Vygotsky, David Ausubel, David Wood, and/or Jerome Bruner and others), the instructor and technician team desired to leverage students’ innate understanding of electricity in a household as a means of building a larger framework of understanding [17]. To brainstorm the development of a demonstration aid, the instructor grabbed a mobile chalkboard from the hallway and rolled it into the laboratory. There, they proceeded to outline a circuit breaker on the side with four quadrants labeled kitchen, living room, dining room, and basement with the associated 120V or 240V outlets, lightbulbs, switches, and electrical appliances commonly associated with each room. The team then had a stroke of brilliance: why not just develop the demonstration aid right there on the mobile chalkboard, thereby creating an easily movable tool that could be used, stored, and reused in future course offerings? Figure 1 shows an early version of the power demonstrator board.

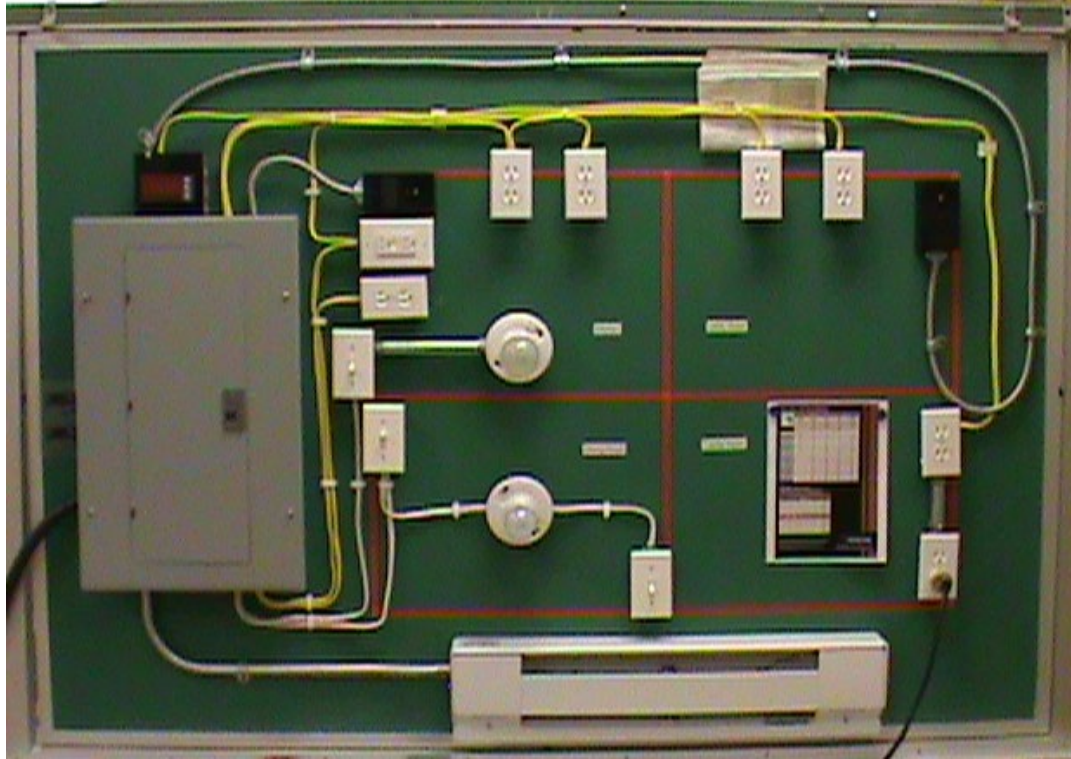


Figure 1: An early version of the power demonstrator board, 2011

Engineering faculty should leverage different instructional methods and strive to have their teaching informed by the literature on “what works.” The Excellence in Civil Education (ExCEED) teaching model is a well-documented framework in use since 1999 that has been adopted by ASCE and taught in annual one-week workshops to hundreds of college professors. The ExCEED Model establishes the teacher as a role model who leverages structured organization; engaging presentation; enthusiasm; positive rapport with students; frequent assessment of student learning; and appropriate use of technology to achieve exemplary teaching [18]. Although the power demonstrator board supports multiple facets of the ExCEED Model framework, it primarily supports “structured organization” by providing a varied, active learning technique to “appeal to different learning styles” and meets identified “learning objectives,” and also supports “engaging presentation” as a “physical model and demonstration” [18].

The power demonstrator board is an example of an active learning technique, which can be defined as any instructional method that engages students in the learning process [19]. “In short, active learning requires students to do meaningful learning activities and think about what they are doing” [20]. Although active learning is not the cure for all educational challenges, there is generally broad support in literature for the elements of active learning. Students are likely to benefit from hands-on learning in addition to traditional lecture formats. Theoretical discussions in the classroom are valuable in establishing a foundation for the material by establishing relationships and providing guiding principles and formulas. However, using demonstration aids that mimic, or even reproduce, real systems can be both unique and invaluable educational experiences [21]. Active learning activities, therefore, provide useful alternatives to traditional classroom presentations that faculty can add to their repertoire of instructional techniques [22].

The power demonstrator board is used to meet the following learning objectives within the infrastructure engineering course:

1. Sketch and explain the functioning of a standard light circuit, receptacle circuit, and circuit breaker panel.
2. Compare and contrast GFCIs and AFCIs.
3. Explain how a circuit breaker works and what causes it to “trip.”
4. Determine when and why a load is “balanced.”
5. Estimate the design electrical load in a residence in terms of voltage, phases, current, and power.

These learning objectives are specific to the power lab lesson and support the overall infrastructure engineering course objectives, which in turn support the overall civil engineering program educational objectives and student outcomes, which in turn support the university’s overarching academic program goals. Although the power demonstrator board can facilitate a deeper understanding of much more, these five objectives represent the focused expectation for student learning achievement during this exercise.

Finally, the power demonstrator board facilitates an engaging presentation as part of a designed learning experience. As described by Ken Bain in his book, *What the Best College Teachers Do*, “highly effective teachers design better learning experiences for their students in part because they conceive of teaching as fostering learning” [23]. One such technique is to use the power demonstrator board as a part of a three-part lesson delivery. The first part begins with a traditional classroom experience, leveraging a chalkboard to draw schematics of commercial and residential delivery and use of electricity, like the examples shown in Figure 2.

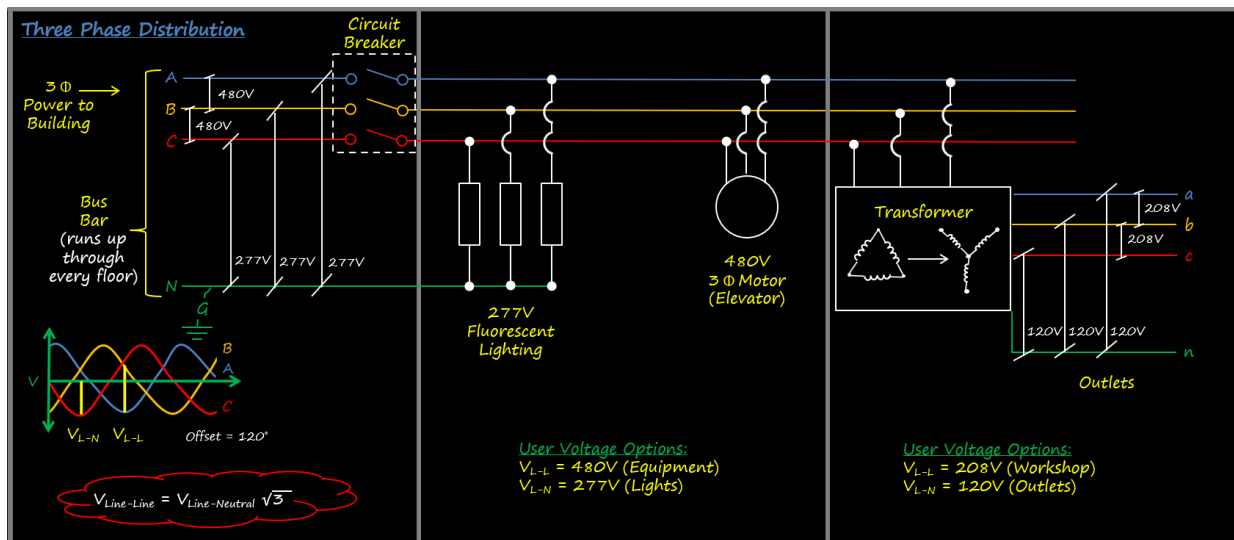
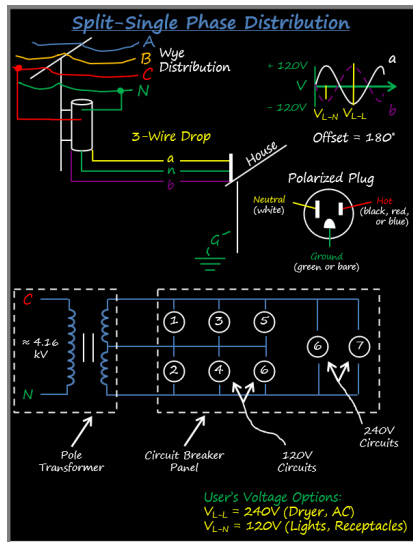


Figure 2: Example classroom boards illustrating residential and commercial distribution and use of electricity

Following the pedagogical concept of bringing drama to the engineering classroom as discussed by multiple authors such as Wankat and Oreowicz, Lowman, and Estes, the instructor then delivers a performance by taking the class on a suspenseful, “top secret” mission to the electrical closet [24] [25] [26]. There, students open those mysterious doors in the hallway that are always closed to reveal a world of large circuit breakers, humming transformer boxes, and bus bars running vertically up through every floor of the building. Having just done the boards in the classroom, the students feel empowered to – without touching anything – start tracing conduit from the bus bars to the circuit breaker panel boxes, like the one shown in Figure 3. The students read labels aloud to their classmates, identifying both voltages and what is being serviced by each breaker (e.g., lights, outlets, HVAC, etc.). They can even determine the input and output voltages of the transformers.



Figure 3: Example a building’s circuit breaker panel with the protective cover temporarily removed

After this short stop at the electrical closet, students arrive in the laboratory to walk through the power demonstrator board with the technical leader of the lab. Utilizing multimeters, current clamps, and built-in digital displays, the laboratory technical leader goes through a pre-planned script of short experiments, especially focused on elements and wiring common to residential electrical systems. Students get to pass around a cut-away GFCI that shows its internal components and learn how it works as the laboratory technical leader causes one to trip with a special mis-wired plug. Throughout the demonstrations, students have a handout with basic queries listed to guide their questions, catalog answers, and take notes.

Throughout this three-part lesson delivery, students are actively engaged across a variety of learning modes. From taking notes in the classroom to exploring an electrical closet to observing how a circuit breaker panel and related safety features work in real-time, the students are constantly varying their learning modality and actively engaging with the material that supports the identified learning objectives.

Methodology: Building the Power Demonstrator Board

The Power Demonstrator Board is mounted on a standard four-foot by six-foot reversible, easel-style chalkboard on a frame with wheels. This allows for the demonstrator to be wheeled from room to room and to be shared as needed. When not in use, the demonstrator board can be stored in a training aids room with minimal space required. Although its total “footprint” may be about two-feet wide by six-feet long, its thin profile allows for other materials to be stacked inside the legs or even underneath the board. Ancillary components, like heat guns, shop vacs, multimeters, current clamps, oscilloscopes, etc. need not be dedicated to the demonstrator; they can serve their

purpose in other courses and then be collected to be used with the demonstrator as needed. Table 1 outlines a suggested bill of materials for a basic power demonstrator board to include items, quantity, and cost, while Figure 4 illustrates how the board has evolved over time.

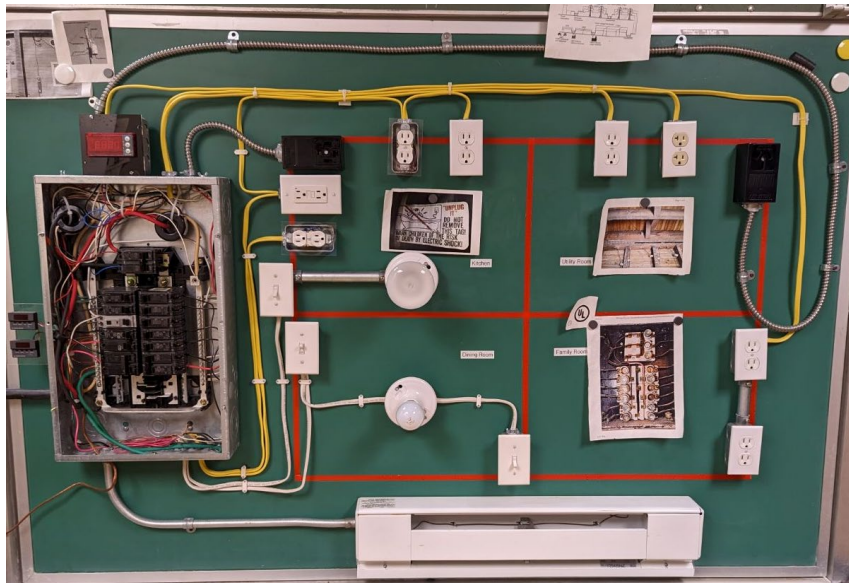


Figure 4: An evolved version of the power demonstrator board in storage with the breaker panel cover temporarily removed to show wiring and instrumentation, 2023

An important note is that the board described in this paper relies on the availability of two power phases. A typical residential system has split single-phase power where two phases offset by 180 degrees, or perfectly opposed, are available. In the example case, three-phase power typical of commercial and industrial settings was the only power available, so two phases offset by only 120 degrees are used to energize the board. This has little impact on typical single-phase devices (fans, vacuums, toasters, etc.) but delivers significantly different voltage potential to two-phase devices like baseboard heaters. This difference has not posed a problem for laboratory exercises, but it must be accounted for in discussions and/or if looking at phase-to-phase power on an oscilloscope.

Table 1: Bill of materials for a basic power demonstrator board

Item	Quantity	Cost Each	Item Cost
100 Amp 24-Space 48-Circuit Indoor Main Breaker Plug-On Neutral Load Center with Cover	1	\$120.00	\$120.00
100 amp Amp 2-Pole Circuit Breaker	1	\$68.00	\$68.00
30 Amp 2-Pole Circuit Breaker	1	\$17.00	\$17.00
20 Amp 2-Pole Circuit Breaker	2	\$17.00	\$34.00
20 Amp Circuit Breaker	4	\$7.00	\$28.00
15 Amp Circuit Breaker	3	\$7.00	\$21.00
20 Amp Arc Flash Circuit interrupter	1	\$59.00	\$59.00
15 Amp Residential Grade Grounding Duplex Outlet, White (10-Pack)	1	\$7.00	\$7.00
20 Amp Commercial grade grounding Duplex Outlet, White	1	\$7.00	\$7.00
20 Amp Self-Test SmartlockPro Slim Duplex GFCI Outlet, White	1	\$21.00	\$21.00
30 Amp 125-Volt/250-Volt Shallow Single Flush Mounted Outlet, Black	1	\$8.00	\$8.00
30 Amp 125/250V, NEMA 14-30R Flush Mount Power Outlet, Single Straight Blade Range and Dryer Outlet Grounding, Black	1	\$10.00	\$10.00
Decora 1-Gang Midway Nylon Wall Plate - White	1		
White 1-Gang Single Outlet Wall Plate	2	\$3.00	\$6.00
1-Gang White Duplex Outlet Wall Plate (10-Pack)	1	\$4.00	\$4.00
1-Gang Midway Toggle Nylon Wall Plate, White	2	\$1.00	\$2.00
15 Amp 3-Way Toggle Switch	1	\$3.00	\$3.00
15 Amp Single-Pole Toggle Light Switch, White	1	\$1.00	\$1.00
4 in. H x 2 in. W x 1-7/8 in. D Steel Gray 1-Gang Drawn Handy Box with Ten 1/2 in. KO's and Raised Ground	12	\$1.00	\$12.00
4 in. W x 2-1/8 in. D Metallic 2-Gang Two-Device Square Switch Box with Eleven 1/2 in. KO's and Six 3/4 in. KO's	1	\$9.00	\$9.00
4 in. W x 1-1/2 in. D Steel Metallic Drawn Octagon Box with Eight 1/2 in. KO's and Raised Ground	2	\$3.00	\$6.00
3/8 in. Flexible Metal Conduit (FMC) Combination Clamp Connector (5-Pack)	4	\$5.00	\$20.00
1/2 in. Electrical Metallic Tube (EMT) Set-Screw Connectors (5-Pack)	1	\$4.00	\$4.00
1/2 in. x 10 ft. Electric Metallic Tube (EMT) Conduit	1		
10 ft., 12/2 Solid CU MC (Metal Clad) Armorlite Modular Assembly Quick Cable Whip	1	\$17.00	\$17.00
15 ft. 12/3 Solid Romex SIMpull CU NM-B W/G Wire	1	\$50.00	\$50.00
50 ft. 12/2 Solid Romex SIMpull CU NM-B W/G Wire	1	\$78.00	\$78.00
15 ft. 14/2 Solid Romex SIMpull CU NM-B W/G Wire	1	\$22.00	\$22.00
15 ft. 14/3 Solid Romex SIMpull CU NM-B W/G Wire	1	\$27.00	\$27.00
15 ft. 10/3 Solid Romex SIMpull CU NM-B W/G Wire	1	\$65.00	\$65.00
600-Watt 250-Volt White Outlet Box Lampholder	2	\$3.00	\$6.00
75 Watt 680 Lumens A19 Incandescent Rough Service Shatterproof Light Bulb, 2-Pack	1	\$7.00	\$7.00
Dimmable LED Bulb, 65W + 680 Lumens, Soft White, 2 Pack	1	\$10.00	\$10.00
AC Power Meter, AC 80-300V 100A LCD Display Panel, Digital Voltmeter Ammeter with Current Transformer	2	\$18.00	\$36.00
Single Phase kWh Meter, Pass-Through, 2 or 3-Wire, 120V up to 120/240V, 100A, 60Hz		\$133.00	\$0.00
24 in. 240/208-volt 350/262-watt Electric Baseboard Heater in White	1	\$42.00	\$42.00
1/2 bussings	5	\$1.00	\$5.00
1/2 1/2 in. Rigid Chase Conduit Nipple	5	\$1.00	\$5.00
cable clips (100 pack)	1	\$4.00	\$4.00
insulated staples (100 pack)	1	\$3.00	\$3.00
Rolling Magnetic Blackboard 96 x 46	1	\$500.00	\$500.00
		Total:	\$1,344.00

** Disclaimer: hire a licensed electrician to ensure the board is built correctly, safely, and to code **

Applying the Learning Models to the Power Demonstrator Board

One of the most challenging aspects of using the power demonstrator board is staying on target with the identified learning objectives. Experience has shown there is so much that can be discussed and illustrated that it is very easy to veer off topic and end up rushing through the demonstration at the end of the class period. The laboratory leader must have a plan. Using pre-identified timing way-points is a helpful technique to ensure one stays on track.

A specific goal of using the power demonstrator board is to provide students with a baseline understanding of how the various components help keep them safe. Emphasis is placed on multimeters and outlet testers to check if components are energized or if wiring is incorrect. These basic tools are generally available at any major home improvement retailer or hardware store. Though not a specific learning objective, teaching students to verify the correctness of the electrical distribution systems in their home or workplace can ultimately save lives and/or property damage caused by improperly installed electrical components that could lead to failures. These specific elements also help to emphasize the importance of a well-regulated electrical infrastructure system.

At the core of the demonstration are students being able to correctly identify and describe key components. They should understand how basic circuits are wired, how breakers get balanced between phases, and why breakers, especially GFCIs and AFCIs, trip. A highlight of the demonstration is passing around a cut-away circuit breaker that can still operate mechanically. Students can see the bimetallic strip and the switch that comes open when the circuit breaker trips. A short explanation of how to reset a breaker is key, including how one must shut it off before resetting the circuit.

Students are asked to identify components, like the two-phase outlets and the two-pole breakers, which then leads the facilitator to host a discussion on why the equipment or connections are the way they are, with special emphasis placed on code. Students gain an appreciation for when to use certain materials – like non-metallic sheathed electrical cables within the walls or wire in conduit when in garages or basements – and how common problems can be quickly identified – like an outlet in the kitchen that is inoperable because it is wired in series and protected by another GFCI outlet that has tripped.

Care must be taken by the instructor and/or laboratory technician when removing the protective panel from the circuit breaker to expose the bus bars and wiring inside. This should only be done while the board is unplugged from the wall and completely deenergized. It is best to first orient students to what is behind the cover, then replace the cover and plug the power demonstrator board in to energize it and read values from installed meters. This way, the students know what it is they are seeing, yet the facilitator who is managing the board remains safe. Students should not touch the board while it is energized; only a trained facilitator should conduct the demonstrations.

Household appliances can be used to investigate current, voltage, and power. Students can read the labels on an appliance before the facilitator plugs it in, turns it on, and then allows students to compare the rated power, voltage, and current from the appliance's data plate to the actual

power, voltage, and current shown on the board's instrumentation. They can also explore technological advancements, like the difference between using incandescent, compact fluorescent, and light emitting diode (LED) lightbulbs. Students are often surprised to discover that, even though they may have the same light output measured in lumens and are on the same circuit at 120 volts, the bulbs use drastically different amounts of power (watts).

To illustrate the use of the power demonstrator more fully, Appendix A includes a model script for an instructor and/or laboratory technician to walk through with the students.

Student Handout

Figure 5 is an example student handout with questions (in **bold**) for students to write answers (in *italics*) on during the demonstration:

1. Why are wires colored differently? Does it matter?

The color of the wire is typically used to indicate what the wire is connected to; i.e., red, black, or blue = hot; white = neutral; green = ground. However, this color-coding system only matters if the person who installed the wires followed it. Consequently, it is important to always check with a multimeter or tester to ensure wires are not energized before performing any work.

2. Why are wires sized differently?

Wires are sized to properly handle the current (amperage) they are designed to carry. You can check the code via a chart to see what size wire is needed for a designed amperage. Larger wires can handle more amperage. You can always put a bigger wire on a smaller breaker, but you can never put a smaller wire on a bigger breaker.

3. How does a circuit breaker work? How is it different from a fuse?

Circuit breakers have a switch that is either connected to a bimetallic strip or an electromagnet. At currents exceeding the rating for the breaker, temperature will build in the bimetallic strip, which expands at different rates due to the different metal properties, causing the bimetallic strip to bend, which moves the linkage and breaks the circuit. The electromagnet type works in a similar fashion, where increasing current boosts the electromagnet's magnetic force until it is strong enough to open the switch and break the circuit. The circuit breaker is different than a fuse, which blows when current exceeds its limit. The circuit breaker can be reset, whereas the fuse must be replaced. This is why people who did not understand the inherent safety risk would replace a blown fuse with a higher rated fuse, thereby creating an unsafe condition and possibly causing an electrical fire.

4. How does a Ground Fault Circuit Interrupter (GFCI) work?

If the current returning on the neutral does not equal current on the hot, the GFCI will trip (because that means current is going somewhere else and could cause electrocution). You can have multiple plain receptacles wired in series with one GFCI, so if an outlet does not seem to be working properly, especially in a kitchen, look for an outlet with a tripped GFCI.

5. How do we protect wires?

Never use uninsulated wires. Insulated wire needs to be behind walls, and metal plates are put on the wood studs to protect homeowners from drilling or nailing into wires (they also flag where the wires are when using certain types of stud finders). We use conduit (flexible or rigid, metal or PVC) for wire on the outside of walls, like in basements or garages.

Figure 5: Example student handout for use during the power demonstrator board presentation

As with any teaching technique, it is important to continuously assess how the learning activity can be improved. Over the past decade, new technologies have burgeoned and become commonplace in the home, and the power demonstrator board can be updated to reflect and integrate those technologies. For example, many electrical outlets now are integrated with USB and USB-C ports to eliminate the need for charging plugs. Bluetooth enabled LED lights and thermostats that control everything from common outlets to electric resistance heaters can also be incorporated. Additionally, updated oscilloscopes can be built into the board at various locations to show the voltage waveform (AC) or level (DC) depending upon location within the system and device used. Finally, data loggers can be included on the board to track power requirements, start-up power for inductive loads, and overall energy consumption of various appliances.

Assessment Strategy

The most important question regarding the power demonstrator board is this: is it a worthwhile educational tool? To answer this question, the authors have developed the assessment plan detailed in Figure 6. Each semester, approximately 90 students take the Infrastructure Engineering course with about five sections of 18 students each. Each section will be randomly split into two groups. Before the Power Demonstrator Board lesson, both Group 1 and Group 2 students will be asked to take a survey with approximately five short answer type questions specific to the lesson’s learning objectives, but only Group 1 will also be asked to complete five Likert scale questions to assess their level of confidence in each learning objective. After the lesson, both Group 1 and Group 2 students will be asked to take a survey with the same five short answer type questions, as well as three Likert scale questions to assess their feelings about the benefits of the Power Demonstrator Board to their learning. This time, however, only Group 2 students will receive the five Likert scale questions to assess their level of confidence in each objective.

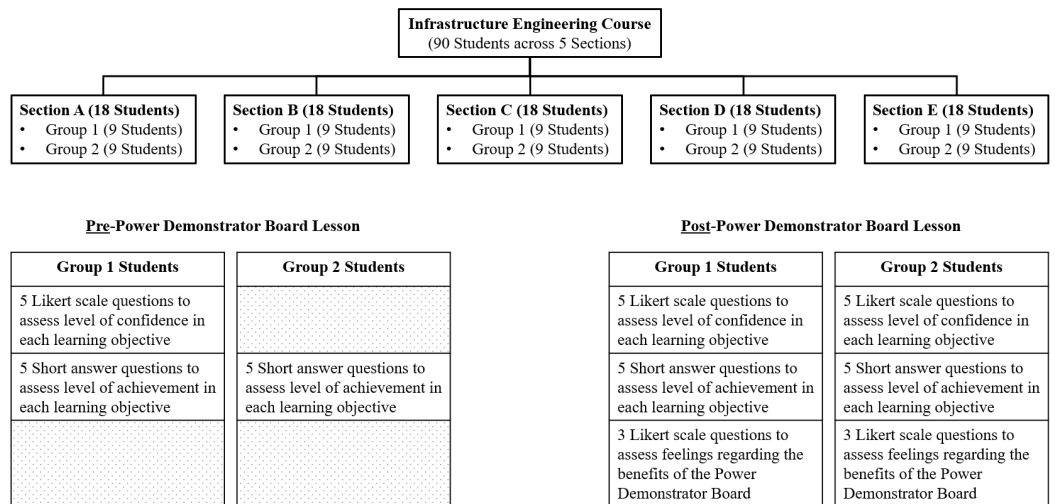


Figure 6: Assessment strategy during each semester’s offering of the course

The intent behind splitting the students into two groups is to assess if there is any bias in how students answer the Likert scale questions assessing their level of confidence. It is hypothesized that if students take both a pre- and post-lesson survey with the same questions, they are likely to believe they should demonstrate increased confidence post-lesson from what they reported pre-lesson. By randomly dividing the students into two groups, asking these questions of only Group 1 students pre-lesson and both Group 1 and Group 2 students post-lesson, the authors hope to assess if there is any bias in confidence level reporting.

The intent behind splitting each section into even groups is to help eliminate any influence on results that might arise based on how one instructor or another teaches the lesson.

The five short answer questions provide the authors a mechanism to score and compare levels of achievement for each learning objective. Assessing all students' scores both pre- and post-lesson will provide another valuable means of comparison.

The three Likert scale questions post-lesson provide insight into student feelings regarding the effectiveness of the Power Demonstrator Board toward their learning progress.

The authors anticipate results will show increased confidence levels for each learning objective due to using the Power Demonstrator Board. As students have a range of learning styles, the authors suspect results will show the Power Demonstrator Board is received more positively by some students than others.

Conclusion

As argued in the introduction, an understanding of electrical power infrastructure is an essential element of a civil engineer's education towards becoming a Master Builder, as envisioned by ASCE. As of the writing of this paper, over 2,300 students, many of them civil engineers, have been trained on this single power demonstrator board! The same board has been in use for over a decade and is still fully functional, with the monetary investment rapidly approaching \$0.50 per student and falling each time the course is taught. The power demonstrator board is a relatively low-effort, high-payoff, educational tool that can be used with other existing laboratory and workshop equipment to create a meaningful learning experience. It is easy to use and maintain, and it provides flexibility for instruction. The board can also be updated with new components and materials as technology changes and codes are updated.

Integrated into a carefully designed learning experience, the power demonstrator board can provide active learning for students to foster curiosity and teach safety. By allowing students to see what is hidden behind the walls all around them, they gain a new appreciation for electricity and safety equipment, as well as for the broader reach of the unseen infrastructure that surrounds them daily. Since the demonstrator is outfitted with meters to display current, voltage, and power readings within circuits in real time, it clearly demonstrates critical electrical concepts right in front of the students' eyes. It becomes instantly clear when the load on a circuit has exceeded its allowed capacity when the audible "click" of the circuit breaker is heard and all the equipment running on that circuit and causing the overload is immediately shut off. Demonstrating safety

features like the GFCI develops students' appreciation of building codes, teaching them to see the safety provided and not just an inconvenience caused. Trust is built between the student and the instructor as theory is shown on the blackboard and then followed up with real-time observation of matching numbers and experimental results on the power demonstrator board.

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Disclaimer

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Appendix A: Demonstration Script

The following script is meant to be used in the “Socratic style” with a dialogue between the instructor and/or laboratory technician and the students. The general flow is provided by numbered steps with questions (Q) and answers (A). Whether it is the instructor/ laboratory technician or the student asking the questions or providing the answers does not matter – it is the active conversation and engagement that matters.

1. Turn off main breaker to start.

Q: What is a closed circuit?

A: A closed circuit is like a circular road with a drawbridge over a river. When the bridge is down, the roadway is complete (closed), and cars can flow on the roadway. When the drawbridge is up, traffic stops. A closed circuit similarly allows electrical energy to flow along the wire – a current. For example, when a light switch is in the off position, the drawbridge is up, but when it is in the on position, the drawbridge is down. The circuit is complete, the current can flow, and you have a closed circuit.

Q: What is the difference between AC and DC?

A: Household outlets are AC, whereas car and phone batteries are DC; AC has a sinusoidal voltage that cycles 60 times a second in the United States, and DC has a constant potential. The advantage of using AC voltage comes with long-distance bulk transmission of electricity from the power plant. Since we may be a long way away from the power plant, we could experience line loss. For example, we do not use an extension cord that is 500 feet long. Since power is a function of current times voltage, you can deliver the same power with much lower current if you increase the voltage. Additionally, since power loss in lines is given by the resistance multiplied by the square of the current, we can significantly reduce power loss in the lines by increasing the voltage and decreasing the current while still delivering the same power. That is why we use high-voltage transmission lines and then transformers at substations to drop down the voltage for distribution to our buildings.

Your computer and cell phone charger converts AC from the wall to DC for use by your device. The plug transformer steps down AC voltage to a desirable voltage, and then four diodes and a capacitor converts the low-voltage AC to DC. Converting DC to AC is more complicated but can be done with pure sine wave inverters.

2. Use a multimeter to test potential for incoming voltage to the bus bars, which should read 0V.

Q: The main breaker is off, and I just used my multimeter to show that the voltage is zero – does that mean everything is deenergized and safe to touch?

A: No! If the board is plugged in, then power is still coming to the main breaker, just not beyond. In such a case, the panel should not be energized, but the line coming to the panel would be.

3. Turn on main breaker and use a multimeter to test the voltage potential between hot “a” and ground / neutral; should get about 120V. Test between “b” and ground/neutral; should get about 120V. Test between “a” and “b”; should get about 208V.

Q: In a real residential, split-single phase system, what should the line-to-line voltage be?

A: 240V

Q: Why is it just 208V here? Where is the power feeding the board coming from?

A: In a residential building, we use split-single phase with $V_{L-N} = 120V$ and $V_{L-L} = 240V$. This power demonstrator board has a $V_{L-N} = 120V$ and a V_{L-L} of 208V because we are pulling from the three-phase system in our academic building. For residential power, there is likely a pole-mounted transformer (or a transformer in a large green box for buried cables) outside the home that reduces high voltage to a desirable voltage for use inside your house. You have three wires (likely colored black, red, and white) coming into your house. The black and red wires will have voltages that are 180 degrees out of phase, but they are only 120 degrees out of phase here on our board because we are drawing from the academic building's three-phase power. That is why, in your house, the line-to-line voltage will be 240V, but here it is just 208V. The white line is your neutral, and a fourth line (the green line) is connected to a copper wire that is hammered into the ground with a grounding rod. If you ever take apart a household device, you may see where it has a ground screw that is attached to the metal. Everything in your house is bonded, thus you have zero potential difference. Grounding provides a low impedance path to the earth to prevent dangerous voltages and current flowing through other materials, like metal framing or pipes or the people who might touch those things. Bonding simply joins two electrical conductors together to bring them to the same electrical potential. For example, the Army uses field generators with a grounding bar and a bonding strap. The bonding strap is used to bond several generators together and bring them to the same potential. The grounding bar is hammered deep into the ground (about four feet) to provide that low impedance path for stray current back to the earth.

4. With the panel unplugged, investigate the circuit breaker panel with the students and identify the major components, e.g., the main breaker and the individual circuit breakers, and show them how the circuit breakers connect to the bus bars. Pull a one-pole breaker and show how the staggered teeth contact the bus bars. Pull a two-pole breaker and show how it is composed of two breakers one on top of the other, which hits both bus bars and is thus line-to-line.

Q: What is the purpose of a circuit breaker panel?

A: It allows us to safely distribute power to where it is needed, to organize and consolidate wires, and to protect the system. The main breaker protects wires “a” and “b” whereas the individual circuit breakers protect everything beyond the panel. The main breaker feeds two bus bars which are hot. The buses are engineered to feed each breaker. The breaker mechanism has a switch with a set of contacts. When you close the switch, current flows through the wire and through a bimetal strip and out to the wire that runs through your house. The bimetal strip has two metal types with different thermal expansion rates, so when it heats up too much, it bends enough to separate the contacts and trip the breaker.

Q: How can we have multiple circuit breakers with amperages that sum to more than the main breaker?

A: Not all will be used at maximum capacity at one moment in time. If the entire system reaches over 100 amps, then our main breaker will trip.

Q: Why do we use 15amps for lights and 20amps for the outlets?

A: We balance need and cost in construction. We can safely use the smaller wires for lighting but need larger wires for the outlets to accommodate whatever you might decide to plug in.

Q: What does it mean to balance loads?

A: Appliances draw different amounts of current (amps) that return on the neutral, and the bus bars, or legs, supplying the current are 180 degrees out of phase. Thus, when current returns on the neutral, what is returned from “leg a” will either cancel out or add to what returns from “leg b.” For example, let’s say our house has a refrigerator in the kitchen that draws 8 amps and a chest freezer in the basement that draws 7 amps. Let’s neglect their duty cycles and assume they run constantly all the time. If we were to wire our house such that the outlets servicing these items were drawing from the same leg, say leg a, then they would be returning $8 + 7 = 15$ amps on the neutral. However, if we balanced them and had them on separate legs, the refrigerator would return 8 amps on one leg, say leg a, and the chest freezer would return 7 amps on the other leg, leg b, which are 180 degrees out of phase, meaning the total current on the neutral would be $8 - 7 = 1$ amp. Since the bus bars are set up with staggered teeth, a one-pole breaker stacked on top of another one-pole breaker will be connected to the opposite leg. For system efficiency, it’s best to keep the loads as balanced as possible, though it is rather difficult to do in a home where what is in use at any given time may vary widely.

5. Point out the different types of wires, and talk about when to use non-metallic sheathed electrical cable vs wire running through conduit.

Q: What is the importance of wire size, or gauge?

A: It determines how much current can safely pass through the wire. For example, we can use 14 gauge for 15 amps, 12 gauge for 20 amps, and 10 gauge for 30 amps. Note the gauge goes down as the wire size goes up. Non-metallic sheathed electrical cable, commonly called “Romex” is the yellow cable, and is named for the Rome Cable Corporation of Rome, New York, which originally produced the cable. It is used indoors and inside walls. The armored cable (in the metal conduit) can be used in the garage or basement where the wire is not behind the wall. Conduit cable is good for outdoor applications and it can be waterproofed.

6. Identify the 20-amp plug.

Q: What is this outlet – why does it look different?

A: It is a 20-amp outlet used for special items, like an air conditioning unit. A regular 15-amp rated plug can connect to either a 15-amp or 20-amp receptacle, but a 20-amp rating plug cannot connect to a 15-amp receptacle, which protects us from connecting a load that would be too high. You rarely see a 20-amp receptacle at home these days.

7. Identify the GFCI and, with the board plugged in, test it with the special cord that has the ground and neutral wires reversed. Note: instead of current returning on the neutral wire, it returns on the ground, so the GFCI notices the problem and trips.

Q: How does a Ground Fault Interrupter Circuit work?

A: It senses a difference (as little as 5mA) between current flowing out on the hot leg and current flowing in on the neutral leg, i.e., meaning that electrons are going somewhere else. For example, if a hairdryer is dropped into the sink and electrons flow out into the water, the GFCI will sense this and shut off. The ground fault is any failure – perhaps from damaged wiring, faulty power tools, etc. – that allows unintended connection of power circuit conductors with the earth. It is frequently the result of insulation breakdown. It will trip if the amount of current going in does not match what is coming out. The code requires that you must have GFCI within six feet of a water supply

8. Pass around the AFCI.

Q: What is an Arc Fault Interrupter?

A: It is a special circuit breaker that recognizes arcing faults in a wire and trips the circuit. These save thousands of fires each year due to pierced wires in walls or items such as electric blankets where arcing currents catch adjoining materials on fire. An arc occurs when electric current flows through an air gap between two conductors. The AFCI breaks the circuit when it sees an electric arc, thereby preventing electrical fires.

9. Show the hairdryer and the heat gun cords. Identify polarized plugs and explain that typically electronics require current flow to be in a certain direction, so current must flow from hot to the appliance to neutral. In purely resistive loads however, like light bulbs, it does not matter.

Q: Would this make a difference for a purely resistive load, like a light bulb?

A: No. The current can flow in either direction and it will not matter.

Q: How about electronics, like a stereo system?

A: Yes!

Q: Why is the hairdryer not grounded?

A: It has a plastic case, whereas the heat gun has a metal case. Should a hot wire in the heat gun come in contact with the metal case, the user could receive electric shock.

10. Identify the four-socket receptacles.

Q: Which circuit breakers are connected to the big, four-socket receptacles?

A: The 240V, two-pole breakers.

Q: Do we have to balance the two-pole breakers?

A: No, they are already balanced because each leg provides 120V to make the total 240V for the circuit.

11. With the board plugged in, overload a circuit and identify the amp and watt meters. Watch for spikes of transient current, especially when starting an inductive load.

Q: What types of loads are there?

A: There are resistive loads, like lightbulbs, where the voltage and current waves appear simultaneously and two are in a phase. You can also have inductive loads, like motors, reactors, and transformers. When you turn them on, they need to work harder before they get going. It is not steady, and the breaker can handle the initial surge, but if you consistently pull high current the breaker will eventually trip. The voltage wave is ahead of the current wave, so the voltage appears first and then the current.

12. Use the mini-tester to look for faults. Identify the outlet where the hot and neutral are switched. Discuss how this is a good thing to check when you rent or buy a new home.

13. Point out the incandescent light bulbs and contrast them with the light emitting diode (LED) bulbs.

Q: Why does an LED bulb using 9W produce the same amount of light as an incandescent bulb using 60W? Where is all that extra power going in the incandescent bulb?

A: An incandescent bulb can also work as a small heater. In fact, the Easy-Bake Oven that first came out for kids in 1963 used to use a 100W lightbulb for heat. An incandescent lightbulb basically produces 90% waste heat and 10% light. The LED lightbulb produces about 90% light and 10% heat.

14. Identify the three-way switch.

Q: What is a three-way switch and why would we want to use one?

A: A three-way switch is used to control a light fixture from two different locations, like in a room with two entrances or exits.