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Potentially Electric: An E-Textiles Project as a Model for Teaching Electric Potential

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Electric potential is one of the most challenging concepts taught in high school physics classes due to the abstract nature of the concept.[1] When taught, electric potential is often taught using a poorly triangulated set of instructional analogies, each possessing different strengths and limitations. Within this paper we share our learning from a two-week electronic textiles (e-textiles) unit designed to help students in an AP high school physics course improve their understanding of electric potential through the construction of a project entitled "The Slouching T-shirt" (STS) (Fig. 1). The STS project was part of a larger instructional unit on electricity and energy that seeks to make connections between energy, electric potential, and computer programming central to student learning.

Electric potential is the amount of electric potential energy per charge, whereas *voltage* is the difference in electric potential between two different positions. The abstract nature of potential and potential difference makes it an even more challenging concept to teach. While most students recognize the term "voltage" from everyday use, they lack understanding of the relationship between energy and electric potential.[1] Moreover, the concept of voltage is often emphasized within the context of Ohm's law in relation to current and resistance through didactic teaching techniques.[2-4] Because voltage is a key conceptual component to understanding circuits through qualitative reasoning techniques,[5] the cognitive tasks within this unit focus on voltage and electric potential. Traditionally teachers engage one or more analogical models if they teach electric potential.[6] Analogic models are models that are based in a descriptive analogy to explain a relationship within science. For example, when teaching electric potential, teachers engage the gravitational analogy. In this analogy, positively charged particles will move from high electric potential to low electric potential similar to the way that a ball on a hill top will "want to go" from a high gravitational potential to a low gravitational potential, turning potential energy into another form of energy in the process. When analyzing the potential drop across a circuit component, energy transfer occurs in the amount equal to the potential difference quantity. However, none of the existing analogies for teaching electric potential provides a full explanation of the phenomena. Although not without its limitations, the gravitational analogy develops student understanding around series and parallel circuit comparisons in relation to energy, helps students to view the battery as a potential energy supplier rather than an electron supplier, and is a stepping stone towards the more explanatorily accurate electric field model. Because modeling leads to deeper understandings[7] and provides a better scaffold upon which to build understanding, electric potential proves an ideal candidate for a model-based, technology-integrated project. The project described in this paper focuses on developing and teaching students with a new instructional analogy.

Fig. 1. (a) "Slouch-sensing" e-shirts sewn with an Arduino Lilypad (b) and (c) Adafruit Circuit Playground, (d) an accelerometer, a buzzer, and LEDs, and (e) an artistic design cover.

Mapping the differences in electric potential

With the goal of explicating these differences, we embarked on teaching students about electric potential through a hands-on learning model with computer code connections. To begin, students need be aware of the atomic model as well as the concepts of conductors, insulators, and basic charge interactions. This project is sequenced for students having already been taught about gravitational potential energy from an energy unit. The teacher introduces students to electric potential by setting up the analogy to gravitational potential energy. Just as gravitational potential is the amount of potential energy *per amount of mass*, electric potential is how much potential energy *per amount of charge*. Similar to gravitational potential, electric potential is an issue of relative positioning. While the electron's potential does not depend on height, it does depend on relative position within a system of charges; students can use height as an analogous way to view electric potential. Students use the height analogy to create models of the electric potential "height" variations for a given circuit (Fig. 2).

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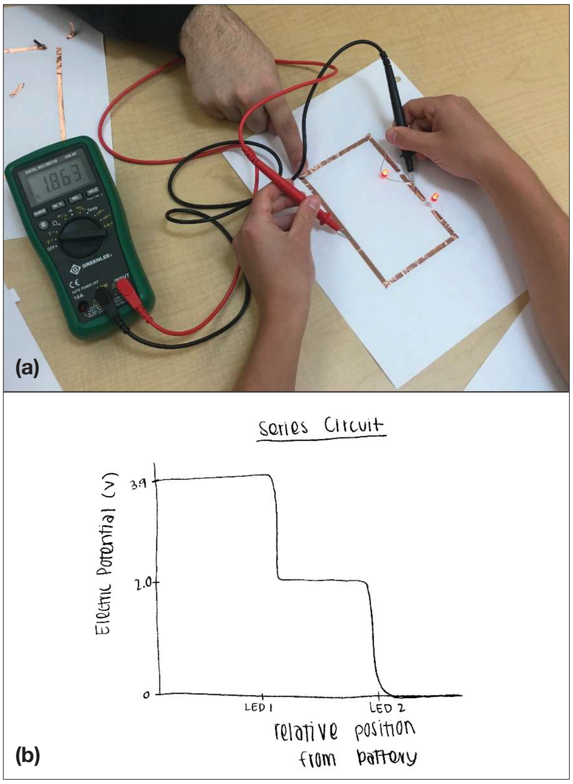

Fig. 2. (a) Students measuring electric potential around series circuit. (b) A student-drawn electric potential "height" map for a two-LED series circuit.

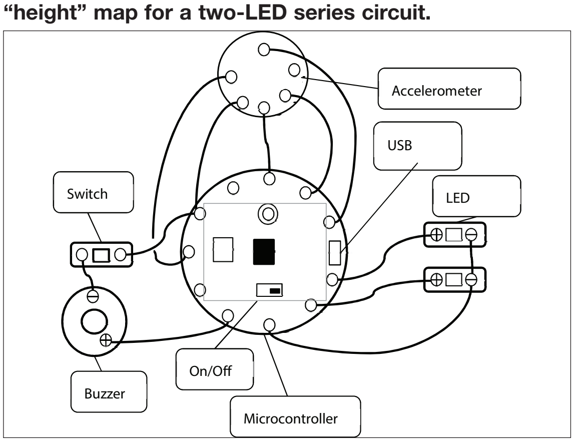

Fig. 3. Example of slouching-shirt circuit design with components.

Students work in pairs to build a sequence of circuits beginning with a simple circuit and progressing to series and parallel circuits. Using copper tape, LEDs (with small threshold voltages), paper, a 3-V coin battery, and a multimeter, students explore the differences between series and parallel circuits by building a three-LED circuit of both types.

Teachers start by explaining that the unit of electric potential is the *volt*. One volt is the equivalent of one joule of energy per one coulomb of charge. This is similar to the analogy established using gravitational potential. Then, using the multimeter, students explore how it measures *potential differences (or voltages)* between two positions—one potential being relative to the other—between LEDs. Students also investigate the voltage of the battery by measuring it with the multimeter; by connecting one lead to the negative terminal of the battery and the other to the positive terminal, one measures a value nearing 3 V. Student explorations with the battery may include keeping one multimeter lead fixed to the positive end of the battery and touching the other lead to the same end to get 0 V. The students can continue to keep one lead fixed, placing the other lead on other students' battery terminals near them. A discussion should be had as to what *zero potential* means and what the multimeter measures (only a *potential difference*). Students should be probed to come up with ways the multimeter could measure only the *potential* and not the *potential difference*. They'll likely come up with several different solutions, with the simplest to call the negative terminal the zero potential as a reference point where one lead will touch. Clarify that wherever the other lead touches is the potential at that point in the circuit system relative to the first lead's potential instead of an absolute single electric potential value. Show this as the reason the negative is often called 0 V although the negative terminal could have been –1.5 V and the positive +1.5 V and still produce a potential difference of 3 V.

The students are then shown how to place the copper tape and LEDs down to make a series and parallel circuit. Students use these to measure the potential at as many points as they can along the three-LED series and parallel circuit paths and record the results on the circuit papers. Students start their measurements touching one multimeter lead to a fixed position on the copper wire closest to the positive terminal of the battery. The other lead is moved around the circuit to measure electric potential differences as the electric potential drops across each component. Each potential value is likened to a height value along a hill that may or may not have different heights as the one lead is moved away from the starting position [Fig. 2(a)].

When students are finished making their models of the potential "heights" around the circuit, they discuss why the LEDs were brighter when in parallel as opposed to being dim when in series. As educators we know that every time the electric potential drops, it means the electrons lost energy, but this should be made explicit for students. Analogously, when a mass falls and changes height, it means it lost gravitational potential energy as a transfer of energy into something else. Have the students record on their circuit where the energy went for every time the electric potential dropped on their potential "height" map [Fig. 2(b)]. By the end of the modeling, it is best to lead a class discussion on potential differences across each LED for a series circuit and a parallel circuit. Explain that the word "voltage" should only apply to a potential difference but is often confused for *electric potential*, which is also measured in volts. The greater the potential difference (drop) across the component, the bigger the amount of energy being transferred into that component. In the case of the LED, the higher potential drop across the LED meant a brighter LED.

T-shirt project description

The STS project allows students to collect data on the changes that occur when the upper body, or back, tilts beyond a determined slouching threshold. Using a codable microprocessor such as an Adafruit Circuit Playground or Lilypad

```
void setup() {
  pinMode(10, OUTPUT);
}
void loop() {
  digitalWrite(10, HIGH);
  delay(1000);
  digitalWrite(10, LOW);
  delay(1000);
}
```

(a)

```
void setup() {
  pinMode(10, OUTPUT);
}
void loop() {
  digitalWrite(10, HIGH);
  digitalWrite(11, LOW);
  delay(1000);
  digitalWrite(10, LOW);
  digitalWrite(11, LOW);
  delay(1000);
}
```

(b)

Fig. 4. (a) Code for Blink example when LED is connected to pin 10 (positive) and the negative pin (negative). (b) Code for Blink example when LED is connected to pin 10 (positive) and pin 11, which is assigned as either positive or negative.

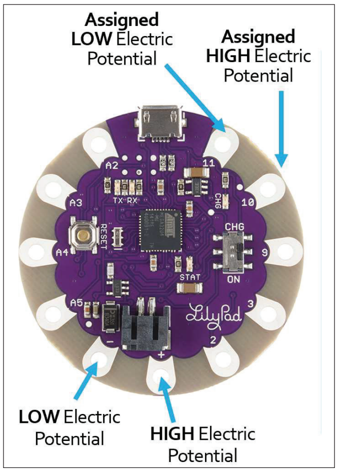

Fig. 5. Lilypad Arduino board with possible assigned and built-in electric potential configurations.

Arduino, students sew the microprocessor, some LED light bulbs, and an accelerometer to a t-shirt (Fig. 1). After construction, students program the t-shirt to engage different responses to different angles registered on the accelerometer. Step-by-step directions for constructing the t-shirt project can be found at http://teachprojectstitch.blogspot.com/. The construction process takes about four 50-minute class periods. A significant portion of that time is the design and planning aspects of the project. Some teachers assign this design process for homework to conserve class time. Figure 3 showcases a model design with components connected to the negative pin in parallel.

The microprocessor possesses pins (also called ports) that can be coded and pins that are already coded. The coded pins are designated positive or negative so that they are usable within a parallel circuit. It is from this point that teachers are able to engage students in learning about electric potential through the use of code as a novel analogic model for discussing electric potential. Figures 4(a) and (b) show code that students use to turn their light bulbs on and off in a blinking pattern. While discussing these pieces of code, the teacher notes that the code uses the terms HIGH and LOW to refer to turning a light ON and OFF. In discussing why those words are used, instead of ON and OFF, the teacher notes that the words HIGH and LOW refer to the electric potential of the pin (Fig. 5). Students learn that the accelerometer needs to be connected to a pin that is assigned a low potential (or negative pin) and a higher potential (positive pin) to have power. The other pins on the accelerometer sensor are for sending a voltage to the processor as an input signal. In fact, any of the pins on the microprocessor can be programmed later as either "HIGH" potential of 3.3 V or "LOW" potential as 0 V.

When students realize any of the microprocessor pins, including the non-numbered pins, can be assigned a potential, they can be as creative as they'd like for the placement of components and optimization of circuit design (see Fig. 1 for examples). The design task provides a great assessment opportunity to determine whether each student understands how to provide the proper potential difference across each component and can differentiate between conceptual differences of series and parallel circuits. Students will transfer their revised

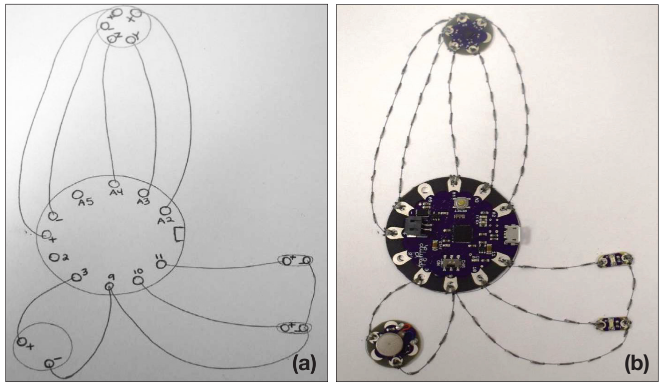

Fig. 6. (a) Diagram of circuit design on felt. (b) Sewn t-shirt felt with all components.

Table I. Approximate project timeline.

Timeline		Content Taught
Week 1	Day 1	Create paper circuits and measure potential to create electric potential maps. Develop and relate concepts of charge, electric potential, electric potential energy, and voltage.
	Day 2	Introduce students to programming environment with Arduino board.
	Day 3	Develop design for felt circuit and transfer to felt.
	Day 4	Sew felt circuit with all components.
	Day 5	Finish felt circuit sewing and artwork.
Week 2	Day 1	Connect microprocessor to computer, download code, alter code, and upload to microprocessor.
	Day 2	Test e-shirts and troubleshoot.

Table II. Materials used.

Slouch-Sensing E-Shirt	Paper Circuits
• Lilypad Arduino USB – ATmega32U4 Board or Adafruit Circuit Playground Classic • Lilypad Vibe Board • Lilypad LEDs (red and green) • Conductive thread • Lithium ion battery for Arduinos, 3.7 V • Felt fabric (assorted colors) • T-shirt • Embroidery thread (assorted colors)	• White paper • 3-V coin battery • 5-mm diffused LEDs (green, red) • ¼-in conductive copper foil tape

```
int AccelX = A2;  // Pin the x-acceleration is connected to
int AccelY = A3;  // Pin the y-acceleration is connected to
int AccelZ = A4; // Pin the z-acceleration is connected to
int VibeBoard = 3;  // Pin the VibeBoard is connected to
int Ground = 9;   // Pin that is set to Ground
int GreenLED = 10;  // Pin for Green LED
int RedLED = 11;    // Pin for Red LED
int MY_LED = 13;  // Built-In LED
```

(a)

```
// Check if the accelerometer is "slouching" past 50 degrees
int slouch = 50;
 if (angleYZ < slouch)
  {
   digitalWrite(GreenLED, LOW);  // GREEN LED OFF
   digitalWrite(RedLED, HIGH);   // RED LED ON
   digitalWrite(VibeBoard, HIGH);   // VibeBoard ON
  }
 else if (angleYZ > slouch + 10)
  {
   digitalWrite(GreenLED, HIGH);  // GREEN LED ON
   digitalWrite(RedLED, LOW);    // RED LED OFF
   digitalWrite(VibeBoard, LOW);    // VibeBoard OFF
  }
```

(b)

Fig. 7. (a) STS code showing assignments of pins based on circuit drawing's configuration. Code following "//" signifies code comments and is not needed to run properly. (b) STS code showing output assignments for the potential of each pin. HIGH indicates +3.3 V and LOW indicates 0 V. Code following "//" signifies code comments and is not needed to run properly.

design over to a piece of felt [Fig. 6(a)]. Drawing the schematic directly onto the felt helps students avoid "wire" crossover during the sewing phase. Once drawn, the conductive thread is used to sew along the lines [Fig. 6(b)]. It's important to help students understand that none of the positive wires can touch the negative wires or what's known as a short-circuit will occur causing the circuit to overheat or malfunction.

Conclusion

Although there is little consensus as to which educational analogy is best to use with electric potential,[6] the new coding analogy builds off the gravity analogy. Within the programming language used (Arduino) microprocessor pins are designated as "HIGH" or "LOW" electric potential and coded using those words. Gravitational potential proves a more robustly understood concept that students intuit more easily. By high school, students' firsthand experience of things falling or rolling from high locations to lower ones makes this concept more visible and concrete. Electric potential is less visible and thus more often misunderstood. Physics students often misinterpret electric potential as being synonymous with electric potential difference, commonly known as voltage. The ability to code a microprocessor in a way that reflects the physical science behind electric potential presents an engaging way for students to develop their conceptual understanding around voltage while constructing a personally meaningful artifact for their classwork.

The teacher has involved students in this activity for the past two years, finding students were more engaged and vocal about the physics of electric potential than in previous years. For example, when deciding how to troubleshoot a non-functioning circuit, many students took the self-initiative of using multimeters to locate zero and nonzero voltage drops to isolate the problem. In addition, some students used the code to troubleshoot circuit components by adjusting a pin's electric potential through code rewriting instead of circuit rewiring. It was also evident to the teacher that students made the contrast between electric potential and electric potential difference. To illustrate, when a student was asked why she thought her LED wasn't turning on at the right time, the student looked through her code and said, "These two pins that the LED is connected to are both 'HIGH' electric potential, so relative to each other, there is no potential difference to turn on." Through this project, the students demonstrated a better understanding of relating the electric potential to references to make sense of voltage and potential energy than in years past.

Acknowledgments

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