Low-cost sensing to teach energy for everyone

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Abstract

Given the urgency to revamp our global energy system due to the combined threats of climate change, fossil fuel depletion, and increasing global energy use, everyone needs a basic understanding of energy use in their lives and society. Yet as Robin Millar wrote about the U.K., "It is not an overstatement to say that the teaching of energy is in a mess". We are developing an after-school curriculum in the United States that aims to teach students a coherent, physics-based model for energy that also relates energy use in their daily lives to energy use in the national and global economy. The conceptual physics models are based on the *Karlsruhe Physics Course* from Germany, *Energy and Change* from the U.K., and *CASTLE* from the U.S. The curriculum introduces low-cost sensing using the US$30 Arduino open-source electronics prototyping platform. Students take temperature measurements in a small model house to learn about home heating, and voltage/current/power measurements in circuits to learn about energy sources and loads. By feeding data from Arduino into Processing, an open-source programming language created for visual artists, we are able to display dynamic visual representations of the incoming data. Both Arduino and Processing have well-supported documentation and user communities, and we teach the basic ideas behind these tools to start looking inside how the data interface works. Pilot testing of the materials occurred this past spring, and further testing will continue in the fall. All materials will be made available for free online.

Keywords: Probeware, thermodynamics, modeling.

Resumen

Dada la urgencia de reformar nuestro sistema energético mundial debido a la amenaza combinada del cambio climático, el agotamiento de combustibles fósiles, y el creciente uso de la energía global, todo el mundo necesita un conocimiento básico del uso de energía en sus vidas y la sociedad. Sin embargo, como Robin Millar escribió sobre el Reino Unido, "No es una exageración decir que la enseñanza de la energía es un caos". Estamos desarrollando un plan de estudios después de la escuela en los Estados Unidos, que tiene como objetivo enseñar a los estudiantes un enfoque coherente, basado-Física modelo de energía que se relaciona también con el uso de energía en su vida cotidiana para el uso de energía en la economía nacional y mundial. Los modelos de la Física conceptual se basan en el curso de *Física de Karlsruhe* de Alemania, *Energía y Cambio* en el Reino Unido, y el *CASTILLO* de los EE.UU. El plan de estudios presenta bajo costo de detección con los EE.UU. $30 Arduino plataforma de código-abierto de prototipos electrónicos. Los estudiantes toman las mediciones de temperatura en una casa modelo pequeño para aprender a cerca de calefacción de los hogares, y de tensión/corriente/potencia en los circuitos para aprender a cerca de las fuentes de energía y cargas. Por la alimentación de los datos de Arduino en Processing, un lenguaje de programación de código abierto creado para artistas visuales, que son capaces de mostrar dinámicas representaciones visuales de los datos entrantes. Ambos Arduino y Processing han apoyado bien la documentación y las comunicaciones de usuarios, y enseñar a las ideas básicas detrás de estas herramientas para empezar a buscar dentro cómo funciona la interfaz de datos. Las pruebas piloto de los materiales que se produjeron la pasada primavera, y más pruebas continuarán en el otoño. Todos los materiales estarán disponibles gratuitamente en Internet.

Palabras clave: Probeware, termodinámica, modelado.

I. INTRODUCTION

The use of "probeware" in science education has a long history, dating back to the 1960s [1]. The personal computer revolution of the 1970s and 80s led to a large increase of researchers studying "microcomputer-based labs", including a 1992 NATO conference in Amsterdam [2]. A number of commercial companies such as Vernier and PASCO now sell sensors, interface hardware, and software for such labs, but the cost remains high.

Tinker and colleagues have created a "do-it-yourself probeware" guide that recommends several low-cost sensors and simple circuits [3]. But their setup still requires each sensor to have a US$61 Vernier Go!Link USB interface box and a specialized connecting cable, which quickly becomes prohibitively expensive for a class set [4].

Meanwhile, open-source electronics prototyping platforms have been developed by people interested in helping non-technical beginners use microcontrollers. One platform, Arduino, is based around a hardware board (see Fig. 1) that costs US$30 and allows up to six simultaneous analog inputs. Arduino has a large and growing community [5]. Google has also recently adopted Arduino as the foundation of the Android Open Accessory Development Kit [6].
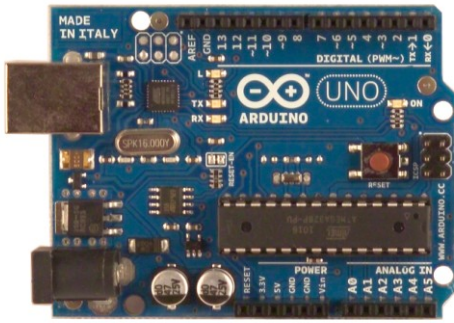

FIGURE 1. The Arduino Uno costs US$30 and allows six analog inputs.

To display the incoming data from the Arduino we use Processing, another open-source project designed for helping beginners "sketch" on the screen using some simple programming [7].

In our National Science Foundation-funded project called CELL (Clean Energy Learning and Leadership), we have used Arduino as the interface box, connecting low-cost sensors to computers where their data output is displayed on a rolling graph, combined with additional graphical representations. Our goal is to use these sensors in hands-on experiments that teach an "alternative model" [8] for thermodynamics towards a "functional science literacy" [9] about energy in students' lives.

II. ARDUINO (HARDWARE INTERFACE)

Arduino has analog inputs with 1024-bit analog-to-digital converters that can be referenced to 1.1V, 3.3V, or the default 5V range. We use the internal 1.1V for both of the sensors we're using -- a TMP36 temperature sensor, and a current-sense resistor/voltage divider combination used as a power meter.

A. Temperature sensor

Each TMP36 temperature sensor costs US$1. They are powered by 2.7-5.5V, and output a voltage that depend on temperature, as shown in Fig. 2 [10]. By using the 1.1V reference in the Arduino, the maximum temperature is limited to 63°C, which is high enough for measuring the tmperature increase in a model house heated by a light bulb.
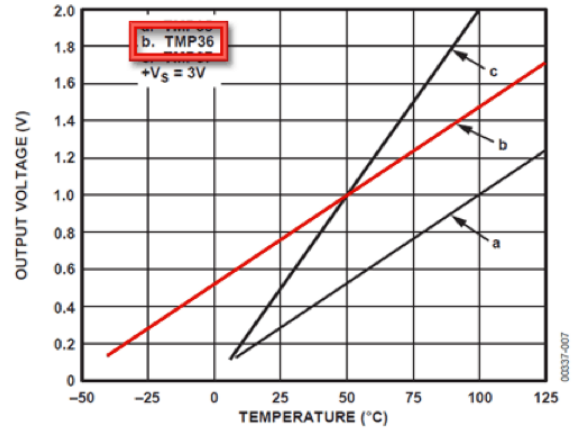

FIGURE 2. Temperature vs. outputvoltage chart for the TMP36 (highlighted in red), adapted from the data sheet [10].

B. Power meter

The traditional approach to power is to measure the voltage and current separately, and multiply them together to get the power. But it is possible to do both simulatenously using a 5.1kΩ/1kΩ voltage divider to measure the voltage, and a 1Ω, 1% resistor to measure the current. This arrangement is shown in Fig. 3.
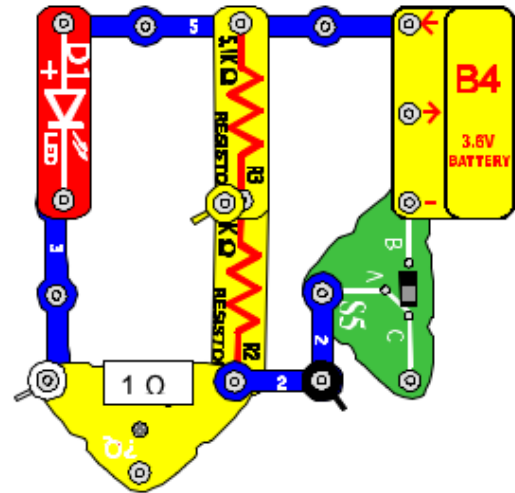

FIGURE 3. Power meter circuit built with Snap Circuit parts [11]. It uses a voltage divider (5.1kΩ/1kΩ) to measure voltage from a source (here a 3.6V battery in the upper right) and a the 1Ω, 1% resistor to measure current through a load (here a red LED in the upper left. Three snap-to-pin wires connect this circuit to the Arduino's Analog 0 (midde of voltage divider), Analog 1 (current sense resistor), and Ground (at negative terminal of source) ports.

This meter is inspired by the U.K. Science Enhancement Programme's Energymeter [12]. The idea to use a 1Ω resistor as "good enough" for current sensing comes from John Gavlik [13].

III. PROCESSING (SOFTWARE INTERFACE)

Processing is a platform for creating computer visualizations. We use a graphing library from gwoptics to display data from Arduino on a rolling graph [14] (see left side of Fig. 4). Based on an idea from Tinker [1], we also use "input" representations (thermometers and meters) so the rolling graph looks like it is "tracing" out over time, thus giving the time axis greater meaning (see the center of Fig. 4).

Beause Processing is so visual, it allows alternate representations to be dsplayed. For temperature sensing, a schematic diagram is included of the house and surroundings, and colors are mapped to each based on the temperature reading from each of the sensors (see the right side of Fig. 4).
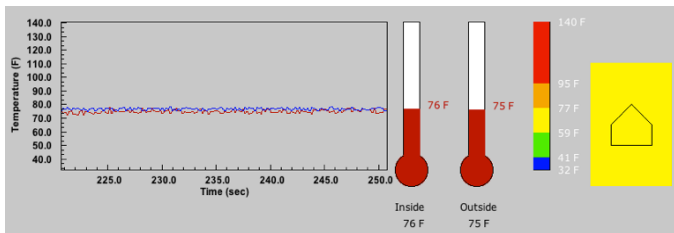

FIGURE 4. HotRoller program in Processing, with rolling graph (left), "input" representations (center), and color-coded schematic house diagram (right).

For power measurement, not only can power be shown as a direct measurement, an alternative representation called a "box diagram" can also be drawn instatenously [15] (see the right side of Fig. 5). The box diagram is a geometric representation of the power equation

$$P = I \times V, \tag{1}$$

where the height of the box represents the voltage V, the width represents the current I, and the area represents the power P. The left side of Fig. 5 shows how the three quantities are displayed on the same rolling graph, just like in the temperature display, with the three meters in the center being traced. We have focused on the box diagrams during instruction and not the graph, but another curriculum does focus on the graph [16].
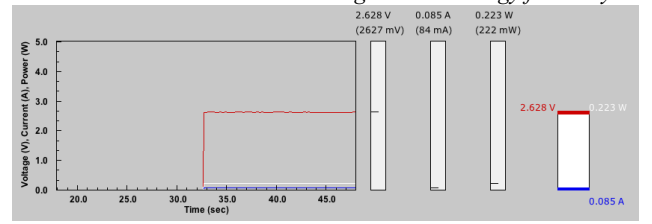
FIGURE 5. PowerRoller, with rolling graph and three meters (left) and dynamic box diagram (right).

IV. ENERGY FOR EVERYONE

The probeware and alternate representations are used to support teaching the "Energy for Everyone" model [17]. This model draws on three main curricula: The Karlsruhe Physics Course [18], Energy and Change [19], and CASTLE [20]. The Lesh translation model [21] is used to see how different ideas in the model fit together (see Fig. 6).
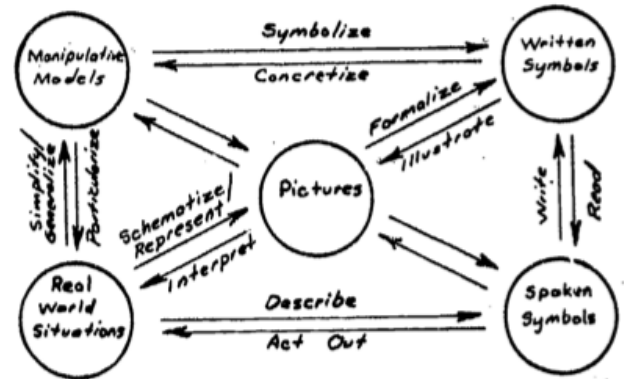

FIGURE 6. The Lesh Translation Model [21] moves between multiple representations to help students "understand" the content.

In the "Energy for Everyone" model, our goal is to help students understand real world situations -- primarily home heating, heat engines, and the the electric grid. To put the real world on a student scale, we have them build a cardboard house, an aluminum can Hero's engine, and a circuit from sources and loads in the Snap Circuits Green toy [22]. In moving from the physical models to the represntational ones, we start to draw on ideas from the three curricula.

Energy and Change [17] has some very nice phrases -- spoken symbols -- for thinking about energy: "Differences drive change and differences tend to disappear", and "It takes a difference to make a difference". This is in contrast to the idea that "energy makes things go," since energy is a constraint on what can happen, not a cause [OGBORN].

The Karlsruhe Physics Course [18] uses an analogy between the branches of physics such that in each branch, an intensive difference (temperature, pressure, voltage) drives an extensive flow (entropy, fluid, charge), and energy always flows simultaneously with at least one

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extensive flow. In this regard, energy is like a "universal word" in a dictionary that lists each branch as a separate entry (see Table I). This linguistic pattern supports a mental model that embraces a fluid-like picture of extensive quantities (including energy).

TABLE I. A "dictionary" of intensive and extensive quantity pairs that define the branches of physics.

Difference	Quantity flowing	Along with
temperature	entropy	energy
pressure	fluid	energy
voltage	charge	energy

The pictures we use include the schematic representation of home heating and the box diagram discussed above. Written symbols include the color coding system that is taken from CASTLE [20], where red represents a value of an intensive quantity that is "high above normal", blue is "low below normal", and between them are orange, yellow ("normal"), and green. This scale, and its use, can be seen in Fig. 4: both the inside and outside of the house are the same temperature and color, and therefore nothing is changing. Color coding is used in CASTLE for drawing directly on schematic diagrams of circuits and reasoning about voltages [20]. Since we are more focused on energy and power than on basic circuits, we make more use of color coding in home heating and engines than in circuits.

We introduce additional mental models to make the invisible visualizable. We represent a heated house as a leaking bottle, where water represents heat, and the two chocies to reduce the leak are to plug the holes (add insluation) or lower the water level (turn thermostat down) [23]. We represent an engine as a waterwheel, extracting energy from falling water, much as an engine extracts energy from falling entropy [24]. We represent charge in a circuit as a hula hoop, with the teacher acting as the source and a student acting as a load, transferring energy from the source to load via the charge [20].

Any of these models can be made quantitative, and additional written sumbols --equations-- can be introduced. Since our goal is to build intuition towards functional science literacy, we don't teach the equations much, though there is good parallelism between Ohm's Law, Fourier's Law, and Pouisselle's Law [25].

V. CONCLUSIONS

A pilot test of this approach was conduted in Spring 2011 in three high schools in Oakland and Emeryville, California. We are still analyzing our data, and revising for another trial in Fall 2011. Students were engaged and initial reviews were mostly positive regarding the hands-on activities. We are working to bring the patterns revealed by the Lesh Translation model out more, so that the models students construct are better related to each other. All of our materials will be available online at cleanenergy.pbworks.com, or by contacting us directly.

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