ZAP!, Student Electricity Experiments Done in their Rooms

Jerome PINE
Physics Dept, Caltech
Pasadena, California 91125, U.S.A.

ABSTRACT

An electricity laboratory course has been created at Caltech that is based on students doing experiments in their rooms, using parts and tools from a kit they receive at the start, for work during 20 weeks of the school year. The first laboratories are at a very basic level and the complexity increases over time. In the final experiment the students make a microwave transmitter and receiver and study radiation and detection by dipole antennas. During the course the physics of all the Maxwell equations is studied as well as circuit design and basic transistor electronics. Most of the students have little or no electronics knowledge at the start and they exhibit solid long-lasting learning.

Keywords: education, circuits, electricity, electronics, hands-on

INTRODUCTION

Several years ago, John King and Phil and Phyllis Morrison at MIT developed an electricity course for freshmen called ZAP! It included laboratory experiments to be done by students in their rooms, elegantly invented by John King, and able to be done with relatively simple materials. Jerry Pine at Caltech built on the MIT course, made some adaptations and additions, and made it part of a first year elementary physics course taken by engineering and science students. The Caltech version described here is taught for twenty weeks in parallel with a standard electricity textbook course. There is a student book, about 110 pages long, to guide them through one experiment each week, intended to require on average about four hours of work. The experiment subject matter parallels the textbook, but the sequence of chapters studied is modified to reach electric circuits sooner. The experiments begin very simply and grow in complexity and sophistication during the course. The introduction to the student book lists four goals, summarized as follows:

1. Abstract electrical concepts will be made real.

2. You will meet and become familiar with electrical technology.

3. You will get experience in solving real world "messy" experimental problems.

4. You will become designers, inventors, and doers.

THE AMBIANCE

The course begins with a distribution of kits to the students, which contain all the tools and parts needed for the 20 weeks of work, in a cardboard box about 30 x 40 x 16 cm. Figure 1 shows the contents laid out. The students buy the kit at approximately the cost of a textbook and after the course own a repertoire of tools, clip leads, and a multimeter for their ongoing use. An analog meter is used purposely, to pro-

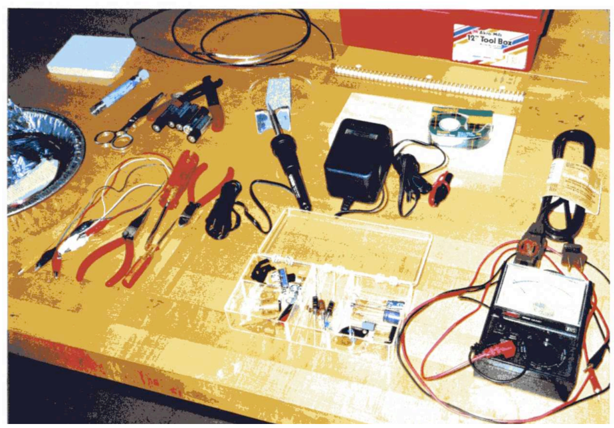


Figure 1. The kit.

vide experience with reading and interpolating from scales, and because it is an electro-mechanical application of physics that they study, and because it has circuitry they can understand. There is a complete set of tools and a soldering iron. The small parts, such as resistors, capacitors, LEDs, ICs, nuts and bolts, razor blades, etc. are in a plastic box. Power is supplied from a 12 volt a.c. plug-in transformer, an important feature for eliminating any shock hazard, and circuits are built on a perforated circuit board about 12 cm square. Other hardware, such as a sheet of styrofoam, a plywood baseboard, a pie pan, and so on, are also included. Connections are usually soldered, and the use of clip leads is minimized. A lab book, of 111 pages, leads the students through the experiments, but not in full detail. Component layout, measurement strategies, and trouble-shooting are left to them. They are encouraged to work in pairs, next to each other, each doing his or her experiment, but communicating to help each other and discuss what they are seeing. The lab book contains brief expositions of background theory when appropriate. Support for the students' experimentation comes from three sources in addition to the lab book:

1) They work independently but next to a partner, for discussion and for occasional help from extra hands.

2) There is a "help lab" each week in the evening before the student notebooks are collected for grading, staffed by faculty and grad students. Circuits that don't work are diagnosed and trouble-shot.

3) There is class time each week for preview comments and discussion of experimental results. In addition, since Caltech is a residential campus, there are upperclass students near at hand who have done the experiments and can provide advice. About half the freshmen do the labs, and the other half are in a different, more mathematical, course. Figure 2 below shows a student group at work in a dormitory room. There are three partners, which is not the usual rule.

Figure 2. Students at work

THE EXPERIMENTS

There are thirteen experiments, listed below:

Simple Circuit Elements
Advanced Circuit Elements
Diodes and Rectifiers
Variable Voltage Power Supply
Power Supply Performance
The Thermistor and the Bridge
The Capacitor
The Transistor Amplifier
A Current Balance
Electromagnetic Induction
High Voltage Supply, the Arc
Microwaves
Digital Logic

Here are the highlights: The first three get the students used to using the meter and they study the properties of ohmic and non-ohmic circuit elements (resistors, diodes and LEDs). Then they make a variable voltage power supply with an IC regulator and determine how well it regulates. They use a bridge to calibrate the temperature dependence of the resistance of a thermistor and then determine its heat capacity for the next experiment. They measure the stored energy in a capacitor by discharging it through the thermistor and measuring the temperature rise. The transistor amplifier experiment is a quiz to be done alone, to evaluate how well they can design a circuit and use it to determine the current gain of a junction transistor. They do well, and they almost all succeed in accurately determining the current gain. That is the end of the first half of the course.

The remaining experiments are allotted two weeks each to complete, and are more technically demanding. The current balance is the classic measure of the force between parallel currents done with two parallel multi-turn coils and a very sensitive balance they make out of simple parts. The picture below shows a schematic view of it. The torque generated by nuts on the left end of the support bar balances gravity plus the force between the coils. This adds a bit of mechanical engineering

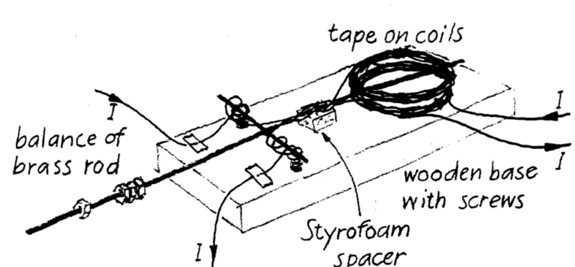
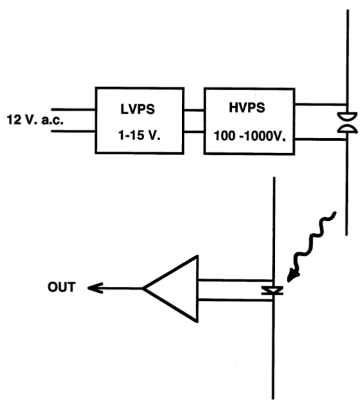


Fig. 3 A current balance.

to the work. They also are asked to analyze the net expected uncertainty in their force measurement, combined from multiple sources, and compare with the theoretical prediction. The induction experiment measures the a.c. coupling between the two coils used in the preceding experiment, and uses an opamp to amplify the induced voltage. They study the dependence on their spacing and the effect of an iron core in the center, and they need to make estimates of their expected results without their being a precise formula. They then build a high voltage power supply based on a 250 kHz r.f. oscillator, which produces more than 1000 volts at a safe high impedance. They study an arc between two closely spaced electrodes, and then use it to generate microwaves. The arc is coupled to a dipole antenna and the radiation is received by a matched antenna and detected with the help of a diode, opamp and meter. The sketch below shows this investigation diagrammatically, and following it is a picture of the apparatus, minus the pie plate reflector used behind the transmitting antenna.



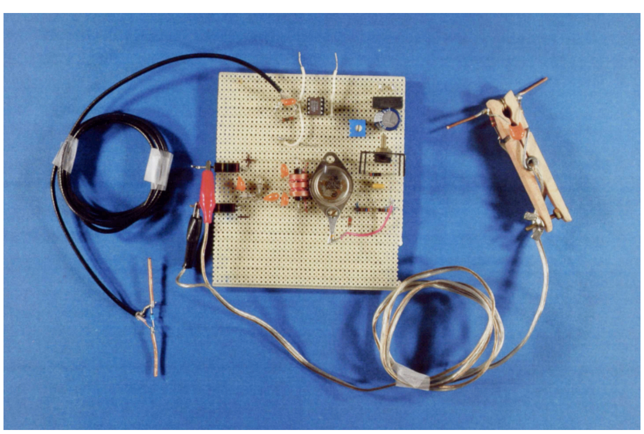


Fig. 4 The microwave experiment

Referring to the picture, many of the products of the twenty weeks of work are on the small circuit board. The variable d.c. power supply is in the upper right corner, and with a.c. input and fuse not shown. The big doorknob transistor powers the r.f. oscillator and its transformer, to the left, uses a few turns around a 5 mH inductor as the primary and the inductor windings as the secondary. There is a filter to generate d.c. from a voltage-doubler rectifier circuit. The high voltage is connected to two tacks between the jaws of a clothespin, which provides a micrometer adjustment of the transmitter arc length. The spark is pulsating because it is driven by an RC relaxation oscillation. The long black coax cable allows the receiving dipole to be moved around the transmitter to study the radiated field. A high frequency diode is across its arms. The rectified signal is amplified by an opamp circuit at the top center and read out on the multimeter. The students study the radiation pattern of the transmitting dipole in three dimensions. A final quiz experiment to be done alone follows, in which the students study CMOS transistor logic circuits. Like the other quiz, it is a new piece of learning and a test of their ability to design an experiment and interpret the results.

CONCLUSION

Is experimental experience needed for learning about electricity? Or anything else, for that matter. Clearly, the answer is yes. Is ZAP! better than conventional "canned" labs. Clearly, our assessment quizzes would be far beyond the abilities of the students from that sort of experience. But do our students learn more electrical concepts better? We have no controlled experiments. A truly controlled experiment is not a practical option. Like most higher education innovations, faculty opinion is what we have. Five successive Caltech faculty members have volunteered to run ZAP, over 15 years. It is not a simple task, so they believe in it. Others in engineering also do. Our students continue in later years on a campus rich in opportunities for work in labs, and they will obviously be better at the arts of trouble shooting, improvisation, and working with a partner. Though some students balk at the start, most finish ZAP! with satisfaction and a feeling of accomplishment. The large majority say they would recommend it to another student.

ZAP! is a unique combination of ambiance and curriculum, to our knowledge only replicated in one instance, at École des Mines in Nantes, where it has become a key part of the curriculum for all students. The faculty has adapted it to match their goals and their curriculum and they are enthusiastic about it. Like Caltech, the Nantes campus is residential, which has important advantages. It makes the help lab and working with a partner convenient for all and it provides opportunities for advice when needed from nearby upperclass students. Transporting ZAP! to a different kind of campus may not be easy.

We will be glad to consult with anyone who is interested in adapting the course. We can also supply kits and student books at the cost to the students (around $100, subsidized by the Caltech physics department). Please contact Jerry Pine at jpmail@capsi.caltech.edu