PittKit and the Breadboard Laboratory Interface Processor (BLIP): An Educational Apparatus Centered on the Individual Student.

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Abstract

We describe a kit of electronics tools, components, and equipment developed for the required one-semester instrumentation course in the Bioengineering Department at the University of Pittsburgh. The kit is owned by each student and includes a microprocessor-based apparatus that communicates to any standard computer (PC/Linux/Mac) without special software, acting as a variety of basic laboratory instruments that no longer must be purchased and maintained by the department. Fundamental electronics and bioengineering principals are taught using a hands-on approach that serves students in all branches of bioengineering. We report results after four years and more than 200 students, as we prepare to make the kits available to other universities.

Introduction

Electronics has traditionally been one of the cornerstones of biomedical engineering, with devices such as pacemakers representing milestones in the early application of engineering to medicine. In recent years, however, interest in electronics among biomedical engineering students has waned, as electronic devices have become increasingly complex, and miniaturized. Constructing custom electronics in the laboratory is far less common today than in decades past. At the same time, an explosion in imaging technologies and the incredible evolution of computers have usurped the interests of many students who might have once been electronics "gadgeteers." Nonetheless, the act of analyzing, constructing, and debugging relatively simple electronic circuits remains an effective way for students to learn about mathematics, physics, and the scientific method. Forty years ago a company named Heathkit[®] produced educational kits from which many enthusiasts learned the basic theory and practice of electronics. A surprising number of today's senior electrical engineers fondly recall building these satisfying and well-designed kits. Nothing comparable is available today.

Educational kits are still available, most notably from RadioShack[®], but these generally do not include much basic theory, being geared instead towards the hobbyist who wants to see something work without too much pedagogy. At the other end of the spectrum is National Instruments[®], which makes a wide array of well-supported equipment for university teaching and research laboratories. Such systems are generally too expensive for students to own individually and rely primarily on simulations of circuits for their educational value, although they do provide input and output for external systems. Recently they have introduced a new line of breadboard interfaces to address the need for more actual electronic components in laboratory courses.

A number of excellent books have been widely used that stress the practical aspect of electrical engineering. The Art of Electronics[1] was first published in the 1980 as the result of a course at Harvard taught by Paul Horowitz. A later edition was released in 1989 and is still a very useful book. More recently, another excellent book has been published, Practical Electronics for Inventors[2], which is used at MIT and elsewhere for laboratory oriented electronics courses.

These books are unusual in their comprehensive treatment of both the practical and theoretical aspects of electronics. Many other books are available to the hobbyist, notably a series by Forest Mims, including <u>Getting Started in Electronics</u>[3], which was sold for many years at RadioShack® and is still available online. Mims drew his pages by hand, and his smiling but accurate electrons have coaxed many young engineers over the years into the field.

In an attempt to make electronics in our biomedical engineering curriculum more hands-on, we have developed the PittKit[TM]. The PittKit a low-cost set of tools and components (less than $100) that each student owns through their standard laboratory fee. Included in the kit, in addition to electronic components for a series of educational projects, are a digital meter, a prototyping board, hand tools, a tool-box, and a custom microprocessor system that each students constructs on a printed circuit board. The system, known as the Breadboard Laboratory Instrumentation Processor (BLIP), is pre-programmed to implement the functions of a data acquisition system, signal generator, frequency counter, duration timer, and digital event logger. The BLIP eliminates the need for such equipment to be purchased, maintained, and upgraded by the department, and guarantees individual access by any student, any time. The BLIP communicates to a host computer via the Universal Serial Bus (USB), imitating a standard computer keyboard. No special software is required on the host computer, as the device transfers data by "typing" it, as if from a keyboard, allowing the data to be viewed and stored by any word processor or spreadsheet under any operating system. Powered from the USB port, the BLIP provides $+/-5V$, eliminating the need for bench-top power supplies, which are particularly prone to failure in the teaching laboratory.

Freed from laboratory equipment, students may complete some assignments in their dorm rooms, in addition to the laboratory. Currently in our fourth year and after use by more than 200 students, we can report excellent results, with many students stating satisfaction in constructing and owning their own mini-laboratory. After the current semester (Spring 2008), we plan to make PittKits and the accompanying on-line resources available to other schools, and we hope to enlist the broader community into its further development. We describe the PittKit, the BLIP, and our experiences with them in the following sections.

The PittKit Toolbox

Physically, the equipment we hand to each student consists of a toolbox and a set of components, including a printed circuit board and a microprocessor, which each student assembles. On the first day of laboratory, each student receives his or her toolbox (actually a fishing tackle-box) containing a digital multimeter, a prototyping board, various hand tools and components. A full listing of the parts in the PittKit is included in Appendix 1. The students' $75 laboratory fee covers the expense of the kit.
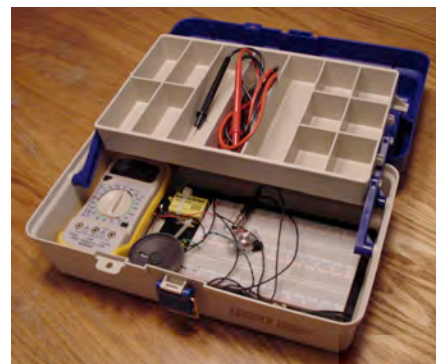

Fig. 1. PittKit Toolbox with digital meter, breadboard, etc.

The BLIP

During the first laboratory, each student also receives the parts with which to assemble a Breadboard Lab Interface Processor (BLIP). This is a simple and inexpensive system that provides basic laboratory functionality including a signal generator, event logger, frequency counter, duration timer, and data acquisition interface to any standard computer. The BLIP is constructed on a 3.5" x 2.75" epoxy printed circuit board with a solder mask to prevent unintentional bridging between pads (see Fig 2). Students follow clear step-by-step instructions for constructing the BLIP, with photographs at each step along the way (see Fig 3). Once constructed, the BLIP can be carried outside the teaching laboratory for homework involving hands-on experimentation, interfacing to the student's own computer (Macintosh®, Linux, or Windows®).

Fig. 2. A fully constructed BLIP.

The central component of the BLIP is the PIC16C765 microcontroller manufactured by Microchip Technology Inc. The processor features a built in Universal Serial Bus (USB 1.1) supported by the standard behavior of the PIC Microchip microcontroller series. Through the USB, the BLIP can be interfaced to virtually any modern computer. The BLIP takes advantage of the Human Interface Device (HID) class definitions for USB, which allow it to work without previously installed drivers on Macintosh OS X or later and Windows 98 SE or later. The attached computer sees the BLIP as a standard USB keyboard. This allows data from the BLIP to be acquired by any word processing or spreadsheet software application, just as if someone were typing the numbers on a standard USB keyboard.

Fig. 3. Picture from BLIP Construction Manual.

The BLIP has five primary modes, described below: (1) Data Acquisition, (2) Signal Generator, (3) Frequency counter, (4) Period Duration Timer, and (5) Event Logger. The desired mode is selected by setting onboard jumpers. The BLIP derives power from the USB bus, providing +5V at 500 mA and -5V at 40 mA to the experimenter, and the BLIP's digital and analog inputs and outputs are accessed via a 9-pin receptacle. These accommodate solderless connections using single-strand 22-gauge wire, the same as the standard breadboard included in the kit. A ¾ inch square prototyping area is provided on the BLIP for additional custom electronics, such as an audio amplifier.

Data Acquisition Mode

This mode allows recording of analog voltages and can be run at two different settings, high-speed and low-speed. When in high-speed data acquisition mode, the BLIP will continually sample and record an external voltage at a sampling rate of 7-50 kHz, adjustable by the onboard
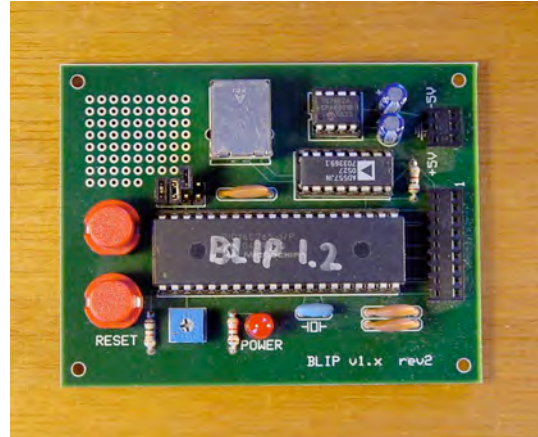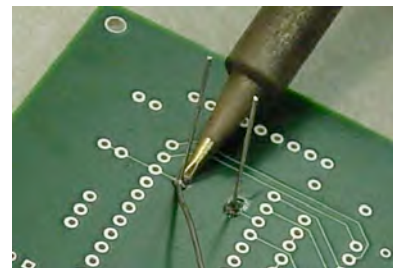
potentiometer. When the top button is pressed, the BLIP offloads the last 64 samples to the attached computer through the USB. The results sent to the computer are the digital conversions of the sampled voltage ranging from 0.00V to 5.00V, "typed" as decimal characters from 0-255 separated by carriage returns. For example, 2.5V is represented as "128" by the BLIP, and it is up to the student to do the conversion. When set to low-speed data acquisition mode, the BLIP continually sends voltage samples to the attached computer at a rate adjustable from 0.3 to 6 Hz by the onboard potentiometer.

Signal Generator Mode

When in signal generator mode, the BLIP sends a stream of bytes to an onboard D/A converter chip producing a 4V peak-to-peak analog waveform, selectable between square wave, sine wave, or triangle wave, (depending on the jumpers) with frequency set from 460 Hz to 6.8 KHz using the onboard potentiometer. The present frequency (in Hz) is reported to the computer through the USB port. A high-speed mode provides only square waves between 2 kHz and 80 kHz without reporting frequency to the computer.

Frequency Counter Mode

When in frequency counter mode, the BLIP counts the number of rising edges seen at the input each second. The BLIP types on the USB port in a hexadecimal format representing two bytes, comprising a single 16 bit binary number. The students must convert the high byte and the low byte to a decimal number themselves, which they do in our course using Excel®. We do not consider this to be an exceptional hardship, since it teaches a valuable lesson about the inner workings of binary mathematics. Frequencies from 1 Hz to 65 kHz can be directly measured, and higher frequencies can be measured using the "modulo" operator (subtracting off multiples of 2^{16}), since the counter rolls over at that number. This provides an example of sampling theory.

Period Duration Timer Mode

When in duration timer mode, the BLIP can be used to measure individual periods between digital impulses with surprising accuracy and precision. An external square wave clock must be provided for this mode, which determines the overall accuracy. The square wave continually increments an onboard 16-bit timer register, the current state of which is sent to the computer via the USB port as high byte and low byte,

152	217
242	087
034	183
…	

whenever a digital impulse occurs at the input. The precision is thus 1 part in 2^{16}, or 0.003%. The lesson is that *time* is usually the best way to get an accurate measurement. This mode is useful in monitoring signals with a variable period, such as a heartbeat detected using a speaker pressed against the carotid artery, as described below.

<u>Event Logger Mode</u>

In event logger mode, the BLIP continuously monitors 4 input pins for a digital signal, reporting their state via the USB bus whenever a trigger clock line experiences a falling edge. The four states are reported as a string of 1's and 0's separated by tabs and followed by a carriage return.

```
1       0       0       0
1       1       0       0
0       0       1       1
…
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This mode is particularly useful in monitoring human behavior with multiple switches or sensors.

Laboratory Topics

Using the BLIP and the PittKit, a series of topics form the basis for a weekly laboratory over the course of a semester. During this time students learn the fundamentals of analog and digital electronics. Whenever possible, the topics have themes from bioengineering. For example, we include a carotid pulse meter that uses a miniature speaker to produce pulsations of electrical current when pressed against the neck (see Fig. 4). These are converted by a simple current-to-voltage operational amplifier circuit, and the period between pulses is reported for each heartbeat by the BLIP. Alterations in heart rate are then generated by vagal stimulation ("bearing down") or by exercise.
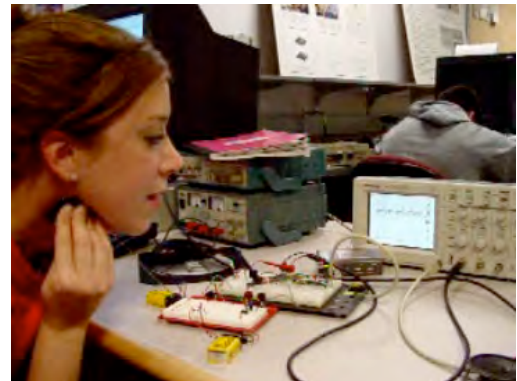
Fig. 4. Monitoring the carotid pulse with a miniature speaker.

Other topics for labs include the perception of pitch and tone using the Signal Generator Mode of the BLIP, relating these auditory features to the underlying Fourier components of the signals. We have conducted labs in which students each constructed a differential amplifier to detect the electrocardiogram, and explored monitoring of breathing using thermal dilution. Independent projects at the end of the semester have been the source of ideas that have been, or will be, incorporated into the regular labs, including the ever-popular lie detector using the Galvanic skin response, various robotic cars and cybergloves, and a particularly imaginative project called the *Grimace Guitar*, which changed the tone of a guitar upon detecting electrical activity from electrical sensors attached to a musician's face.

Nuts and Bolts of the PittKit Teaching Laboratory

As a result of the PittKit, our department no longer purchases and supports a power supply, waveform generator, frequency meter, and multimeter for each workbench in the laboratory (although a limited number of these are still available for special projects). Such equipment is expensive to purchase, prone to failure and theft, and needs continual upgrading. We do still

stock what amounts to a grocery store of parts, most of which are very inexpensive when bought in bulk. These include resistors, capacitors, LEDs, wire, solder, etc., which are cheap enough to leave out in cabinets for the students to use at will. The PittKits contain slightly more expensive components, such as a condenser microphone, speaker, thermistor, photoresistor, etc. that comes with each kit (see Appendix 1). We admittedly have camera surveillance in the lab, mainly to protect the computers and oscilloscopes. We believe there is still a need for a good basic oscilloscope in the electronics lab, and that every student should learn how to use one.

One interesting note about the USB interface: Since students can plug their BLIPs into their own computers, it raises the issue of liability if they damage their computers. The BLIP board itself offers no current limiting on the USB +5V power supply from the user's +5V bus, although the BLIP's voltage converter does protect the USB +5V supply from overdraws on the user's negative power bus. Most USB ports are immune to damage from short-circuit, and self-limiting to 500 mA. We have experienced only one case of damage to a computer's USB port, with an early model of the BLIP, before it was built on a printed circuit board. The power leads were reversed and the BLIP was powered externally. This is very unlikely with the current version of the BLIP, which is only powered by the computer, and solidly constructed on its printed circuit board. However, our official word is that we are not responsible if students use their BLIPs on their own computers. We have external USB hubs in the lab and recommend them elsewhere as well, just to be safe.

The BLIP-o-Scope

A recent new direction we are pursuing this semester is the *BLIP-o-Scope*, a Java applet that can be accessed by any standard browser from our website. When a BLIP is plugged into the computer and the website is accessed, the Java applet receives USB output from the BLIP as if being typed on a keyboard, and provides a graphical user interface simulating a standard oscilloscope for the Data Acquisition Mode (each of the other modes will soon have corresponding interfaces). Since the Java code is downloaded from our central server and interpreted locally, network bandwidth is not a problem. Thus we provide a graphical interface while still not requiring any special software on the individual computer. Figure 5 shows a sample screen from the BLIP-o-Scope demonstrating the voltage on a discharging capacitor, from one of our laboratory assignments. In addition to displaying the data, the BLIP-o-Scope can perform numerical and analytical functions, as well time-stamping each sample. The user can save the analyzed BLIP output, with time stamps and sampling intervals, to their local computer.
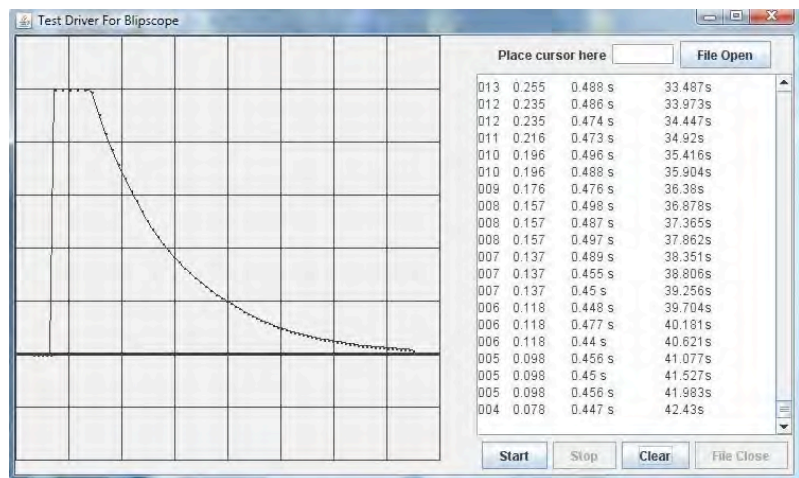

Fig. 5. Screenshot of the BLIP-o-Scope Java program, during the discharge of a capacitor.

The BLIP-o-Scope is implemented in Java to allow maximum client-side compatibility. Java is cross-platform, and requires only the Java Runtime Environment (JRE). The current JRE is automatically packaged with most browsers, and downloading or updating the JRE is very simple. Java also includes built-in security features that allow the user to determine what, if any, access internet applets have to their local system. Applets require

Fig. 6. Screenshot of the BLIP-o-Scope showing a sine wave produced by a second BLIP with aliasing.

digital signatures and explicit user permission to interact with the local system. The digital signature on the BLIP-o-Scope applet allows it to save the BLIP output to the local computer if the applet is considered "trusted" by the user.
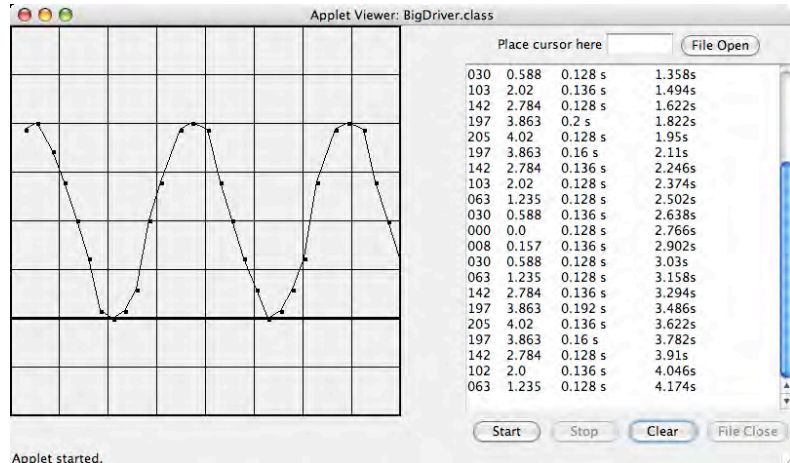
Fig. 6 shows another screen from the BLIP-o-Scope, with one BLIP acting as a sine wave generator at a frequency of 457 Hz, and a second BLIP in data acquisition mode connected to the browser. The online BLIP-o-Scope has a vertical scale of 1 volts/div, and the timescale is .5 seconds/div. Thus the apparent frequency is approximately 0.6 Hz, indicating that aliasing is taking place. This teaches the students about the dangers of aliasing, through which a sine wave that does not exist in the original signal may be seen and recorded.

Evaluation

The BLIP and PittKit were introduced in 2005 and are now in their fourth year. Standard teaching evaluations are given at the University of Pittsburgh, and Table 1 summarizes relevant results from those evaluations from 2005-2007, with 101 students responding.

Table 1. Course evaluation results 2005-2007 (mean); 101 students (58%) responding.

Instructor's overall teaching effectiveness (1 - poor / 5 - excellent)	4.13
75th percentile for Engineering School	4.11
This course has improved my ability to:	
Use math concepts to solve engineering problems	3.50
Design an experiment to obtain measurements or gain additional knowledge about a process	3.38
Design a device or process to meet a stated need	3.51
Use laboratory procedures and equipment	4.04

(1 - not at all, 2 - very little, 3 - some, 4 - a lot, 5 - a great deal)

The standard university evaluations had not yet occured for 2008 at the time of this writing, but we did conduct the following specific survey about the BLIP, six weeks into the Spring 2008 semester, with 50 students responding. Scores were on a scale of 1-5. Table 2 summarizes the results.

Table 2. BLIP survey Feb. 2008, 50 students (93%) responding.

question	mean
1. Prior to this course, my experience with electronics was:	3.96
Extensive=1 to *Minimal=5*	
2. Constructing and testing the BLIP proceeded without undue frustration.	1.78
Strongly Agree=1 to *Strongly Disagree=5*	
3. Using the BLIP has been a valuable educational experience	1.91
Strongly Agree=1 to *Strongly Disagree=5*	
5. I enjoyed the hands-on nature of the work involved in constructing the BLIP.	1.37
Strongly Agree=1 to *Strongly Disagree=5*	
6. I think it is likely that I will use my BLIP outside the instrumentation course.	3.43
Strongly Agree=1 to *Strongly Disagree=5*	

The results show that although most students had little or no experience with electronics (mean=3.96), they nonetheless experienced little frustration constructing and testing the BLIP (mean=1.78), and thought it had been a valuable education experience (mean=1.91). In particular, they enjoyed the hands-on nature of the work (mean=1.37). Put another way, although 72% of students had little prior experience (4 or 5 in question 1), 83% had little or no frustration building it (1 or 2 in question 2) and 91% enjoyed building it (1 or 2 in question 5). It is interesting, however, that question 6 yielded a mean of 3.43, with approximately half of the students thinking it unlikely that they would ever use the BLIP outside the course.

We have been very pleased (and somewhat surprised) at the success rate of BLIP construction. Although the majority of students had never soldered before, virtually every BLIP has functioned upon completion within the first two weeks of the course. A significant number of students have volunteered each year to come back the following year and to act as undergraduate teaching assistants, in addition to our usual graduate TA's. This has provided valuable continuity. We hope the tradition will grow into a kind of clubhouse mentality, with students interested in the art of electronic design and prototyping naturally congregating to share their experience and excitement. Such a facility would be valuable not only educationally but also in providing a source of inexpensive, customized equipment for the local research community.
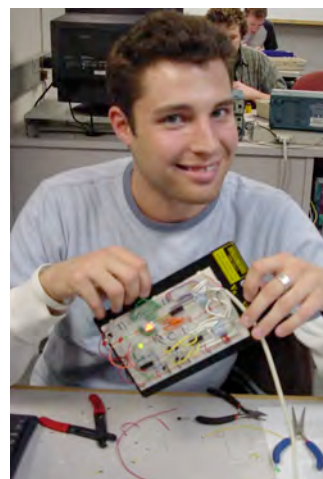
Conclusions and Ongoing Work

As we conduct our fourth semester using the PittKit and the BLIP, we have for the first time what we believe is a fully debugged hardware platform. By the end of the semester we expect to have a set of projects and supporting material ready to go online to distribute to other universities. Our website is www.pittkit.org and the BLIP is available for sale through the University of Pittsburgh bookstore (please see our website for details).

The educational value of practical electronics goes beyond that which benefits only students interested in electronics. Nowhere else in the curriculum can such complex linear and non-linear systems be embodied into measurable machines, and differential equations and logic be so clearly seen in physical operation. Debugging a circuit with a multimeter and an oscilloscope is an effective way to teach both electronics and the scientific method. One learns to "think like the circuit" and in the process, keep an accurate schematic. These are basic skills that translate to all forms of science and engineering.

Acknowledgements

Appendix 1: Listing of Parts for the current PittKit

Tackle box	Dual Banana Plug
Dual Breadboard	Red and Black Test Clips
3½ Digit Multimeter	USB cable
diagonal cutting pliers	2 pushbuttons
needle nose pliers	1.5" Speaker
wire strippers	Cadmium Sulfide Photocell
screw driver	Thermistor (10K @25 deg C)
9V battery	Condenser Microphone
battery clip	BLIP printed circuit board and components

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2. Paul Scherz, *Practical Electronics for Inventors*, second edition, McGraw-Hill, 2007.
3. Forest Mims, *Getting Started in Electronics*, published by Radio Shack.