A low-cost system for introducing students to circuits and electrical properties

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The authors have developed a simple and inexpensive hands-on computerized tutorial aimed at introducing beginning students to basic circuits and electrical properties. The system is capable of a wide variety of electrical measurements, including $V(I)$ and $I(V)$ characteristics, voltage step function response (*e.g.*, charging and discharging capacitors), and time-dependent behavior using a low-frequency oscilloscope. The hardware is based on an inexpensive USB-data acquisition device. Freely-available custom software developed by the authors provides numerous experiment modules, and is designed to be highly extensible. The project can be implemented for $< \$200$ per seat, and has recently been successfully utilized in an introductory general physics course at the University of Alabama.

I. INTRODUCTION AND MOTIVATION

Electronic devices have become ubiquitous in modern society. No matter how complex these devices, the electrical properties of their component materials and the basic principles behind them remain the same. It is becoming increasingly crucial that students have a detailed, hands-on understanding of the basic principles of electric circuits and the electronic properties of materials. More importantly, the proper training of the next generation of scientists and engineers compels us, as instructors, to introduce these concepts in a manner commensurate with what they will encounter in advanced laboratory courses and research settings. This represents a significant challenge in terms of overall cost and flexibility to address changing needs. In this article, we present an example system we believe meets these criteria at a minimum of cost, the details of which we make freely available.[1]

Within many disciplines, students are exposed to the basic concepts of electronic devices and electrical properties of materials. However, providing students with a modern, hands-on approach to basic circuits and electrical property measurements *resembling what they would find in a research laboratory* is often lacking. We believe this is due in no small part to the depth and breadth of knowledge required and the significant cost involved in equipping a teaching laboratory with modern data-acquisition-based software and hardware. Not only is this a major gap in students' education, it is a serious impediment in many cases to their introduction to laboratory or industrial research. Far too often, teaching labs seem hopelessly out of date for those of us working daily in related fields. Prior to this project, this was often the case for the authors, but cost alone prohibited a commercial solution to the problem. Our goal with the present system is to give students at least a glimpse of how electrical property measurements are performed in a modern research lab, at the minimum of cost.

Many physics courses do currently employ a computerized hands-on approach to electronics and electronic properties. Unfortunately, the cost can be prohibitive.

Comparable systems to what we present here can costs thousands of dollars per seat. Further, proprietary commercial systems are rarely sufficiently open to extend or repair as instructional needs change – hardware is proprietary, software is closed-source, and electronic devices change rapidly. Finally, many commercial systems are not sufficiently transparent for students to grasp the inner-workings of the underlying software and hardware – in the end, closed systems are in danger of being 'black boxes' to the students, hiding many of the fundamental aspects of electrical property measurement. The present project aims to provide a completely open and low-cost solution for students to perform experiments *similarly to how they are actually performed in research laboratories*, and alleviate one barrier for promising students to begin research.

In the hopes of addressing some of the issues outlined above, the authors have developed a simple and inexpensive hands-on computerized tutorial aimed at introducing students to basic circuits and electrical properties of materials.[1] Keeping hardware cost at a minimum, and freely distributing software[2] will allow, we hope, rapid uptake of the system by others. The project provides a complete hands-on system for modern data-aquisition-based electrical transport measurements, for $<\$200$/seat. The software to run the data acquisition hardware, laboratory procedures, complete hardware schematics, assembly instructions – everything needed to build the hardware and install the software – is freely available online. The hardware itself is based on the LabJack U3 data acquisition device[3] ($90 with educational discount), augmented only by a few passive components and a single op-amp.[4]

The software allows control over sourcing and measuring current and voltage, time-dependent behavior of RC circuits, and a simple oscilloscope. $I(V)$, $V(I)$, and $V(t)$ curves can be measured and saved to simple ASCII files for post-analysis. The hardware is designed to be as inexpensive as possible, transparent, and easily assembled; the software, easily installed and rapidly parsed. Currently, the prototype system is complete, and has been classroom tested (20 units for 48 students) in Spring 2007

in an introductory physics course.[5]

In the spirit of keeping the system as simple as transparent as possible, as well as working within the hardware limitations inherent with our desire for minimal cost, we initially created a list of working assumptions to guide the effort. **First**, for an introductory laboratory class, we accept an accuracy of $5-10\,\%$ for teaching fundamental concepts. **Second**, components can be pre-selected to avoid hardware and software limitations – components available to the students will not fall outside the measurable range. **Third**, the system must be portable, simple, and easily reproducible by colleagues without access to technical support. **Fourth**, minimal cost and maximal simplicity override minor performance and accuracy gains. **Finally**, the system must be as far as possible 'student-proof' – so long as no external hardware is interfaced, the system must not be capable of destroying itself!

II. HARDWARE

LabJack U3: The heart of the system is the LabJack U3 USB-based data acquisition and control device.[3] The U3 provides 16 software-configurable "flexible I/O" (FIO) terminals, which can be configured as digital input, digital output, and analog input, along with two timers, two counters, and four additional digital I/O connections. When configured as analog inputs, the FIOs provide 12-bit resolution ($0-2.4$V single-ended, ±2.4 V differential). Analog input reads typically take 0.6–4.0 msec. One dedicated 8-bit analog output (DAC0, $0-5$ V) is available, with a second analog output (DAC1) available depending on the software configuration. The U3 is USB driven and powered, requiring no external supply connection. The primary advantages of the U3 from our point of view are extremely low cost[6] ($90, with educational discount; volume discounts available), flexibility, and an fairly open driver interface. The U3 has several limitations which must be taken into consideration, however, which are relatively minor and easily worked around.

One primary limitation of the LabJack U3 is that the analog inputs are pseudo-bipolar – essentially, one can only measure positive voltages. The 12-bit FIOs yield only ~1 mV voltage resolution, limiting accuracy on voltage and current measurements. The FIOs also have a rather low input impedance ($20\,\text{k}\Omega$), making meter loading a potential problem. The refresh rate (20 msec) and output frequency cutoff (3 dB at 16 Hz), to an extent restrict time-dependent measurements. Output voltages are essentially limited to 3.6 V, and the fact that the U3 is USB-powered severely limits overall current draw.

Given these limitations, we employed a number of 'workarounds.' In particular, the low refresh rate, low input impedance, and output frequency cutoff require forethought in designing experiments, particularly where circuit time constants play a role. The simplest and most effective is carefully choosing the components for each
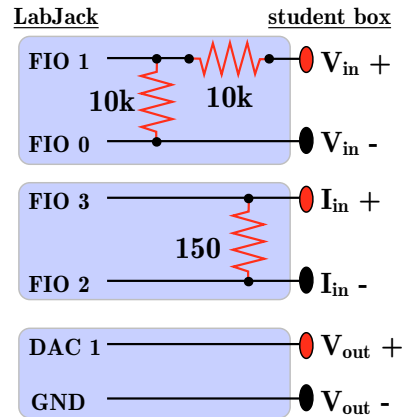

FIG. 1: Schematics of the voltage input, voltage output, and current input connections between the LabJack U3 and the laboratory system. A 2:1 voltage divider increases the voltage input range of the LabJack, current measurements are performed with a resistive shunt. Voltage is sourced directly from the DAC.

laboratory ahead of time, such that the students will not immediately be aware of many limitations. When limitations are discovered, they can be used as an important pedagogical tool for further instruction. We have found that students readily understand and accept hardware limitations, so long they can be explained.

Other limitations are also not so serious on further reflection. The lack of true bipolar I/O requires manually reversing polarity and performing 'positive' and 'negative' measurements, which in some cases can provide an instructional advantage. For example, measuring the forward $I(V)$ characteristic for a diode requires the student to carefully observe polarity, rather than being able to rely on simply changing the software parameters. The input voltage limitation is circumvented by the simple addition of a 2:1 voltage divider on voltage measuring inputs (see below), giving us a measurement range sufficient for most experiments.

The first four FIOs are configured (in software) as differential analog inputs, which are used for current and voltage measurements. The first analog output (DAC0) is used to drive a simple voltage-current converter for current sourcing, and the second analog output (DAC1) provides voltage sourcing. Figure 1 shows the interfacing between the U3 and the I/O connections on the student boxes.

Measuring Voltage: Input voltage is measured between the FIO1 and FIO0 terminals (Fig. 1). This gives a rather limited input voltage range ($0-3.6$ V), and we therefore connected the voltage input terminals "$\pm V_{in}$" on the student box through a simple 2:1 voltage divider to extend the measurement range.

Measuring Current: Naturally the U3 measures only *voltages*, necessitating the need for a current to voltage converter. A simple resistive shunt is sufficient for

this purpose, and current measurements are performed with a shunt ($150\,\Omega$) between FIO3 and FIO2 analog inputs. So far as the students are concerned, this acts like a classic ammeter - it must be in series with the load. Nominally, this gives us a maximum measurable current of $24\,$mA (due to the maximum FIO input voltage), and a minimum resolvable current change of $6\,\mu$A (due to the FIO resolution). The *output* current of the student boxes is limited to $\sim 10\,$mA, and the output voltage to $\sim 5\,$V, thus for judicious choice of loads, the $0-24\,$mA input current limit does not present a serious obstacle. As mentioned above, we design laboratory procedures with limitation in mind, and limit the selection of loads the students may use to work within the hardware limitations.

Naturally, due to the rather large value of the shunt resistor, its non-negligible voltage drop must be taken into account when doing, *e.g.* $I(V)$ characteristics. We take this as an opportunity to introduce the students to a true four-point measurement (see Fig. 5) and working around non-ideal meters and sources. By recognizing the hardware limitations and making them explicit, the students quickly learn to work within them and understand proper four-point measurements.

Sourcing Voltage:The voltage output simply uses the built-in analog output DAC1 referenced to ground (the first output, DAC0, is used for current output, see below). This limits the voltage range to $3.6\,$V, which again is adequate with careful component choice.

Sourcing Current:: Sourcing current represented the most difficult challenge within the constraints decided upon. The U3, unfortunately, is not capable on its own of driving sufficient currents, necessitating an additional power supply. The primary factor above all others is minimum cost, which eliminates a great many far more elegant solutions. Portability was another prime issue in addition to cost and simplicity. Ideally, the system should not be tethered to a wall outlet, which precludes the use of separate ac supplies to drive active elements.

For this reason, the programmable current output is a very simple battery-powered voltage-to-current converter, driven by batteries, as shown in Fig. 2. The voltage-current converter essentially consists of one general-purpose op-amp[4], and one programming resistor. The op-amp itself is supplied with two $9\,$V batteries. We added a DPST switch to open-circuit the batteries when not in use, and battery test points on the outside of the project box. Anecdotally, we did not replace a single battery in the 20 units over the course of a semester.

The desired current level is programmed with the DAC0 output ($0-3.6\,$V when using both analog outputs) on the U3, referenced to ground. The single programming resistor governs the ratio between input voltage and output current. In our case, $R_{\mathrm{prog}} = 310\,\Omega$ yields $3.2\,$mA/V in, for a maximum of about $10\,$mA output. This circuit allows only unipolar output, but as the LabJack itself is only pseudobipolar this is not an additional limitation.
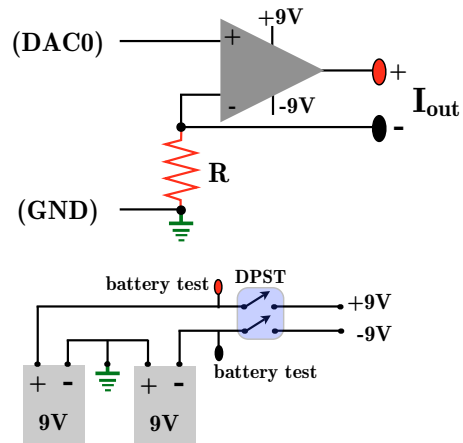

FIG. 2: Voltage-current converter circuit. The resistor R selects the ratio between the input voltage and the output current. For portability, the op-amp is powered from 2-9 V batteries.
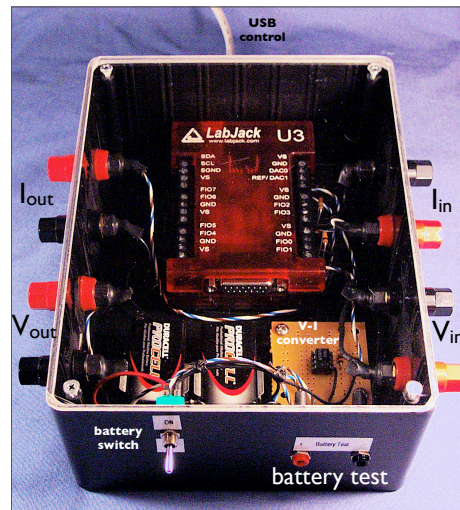

FIG. 3: A finished student laboratory box.

Finished Product: Figure 3 shows a completed system, housed in a 8x6x3 in project box.[7] The total estimated cost per completed box was \$160. We added transparent plexiglass covers for the boxes (not included in cost estimate), in order to make the simplicity of the underlying hardware as transparent as possible to the students. The U3 is (upper center) is held in place with Velcro[8] to allow for rapid replacement. More curious students can easily recognize the voltage divider and current-measuring shunt resistor. Standard female 'banana' plugs[9] are used for current and voltage input/output, while two female mini-banana plugs serve as battery test points.[10] The USB control cable and battery switch are also visible in the Fig. 3.

III. SOFTWARE

The software was developed entirely by one of the authors (P.L.), using the LabWindows/CVI development package[11] from National Instruments. All of the software for this project, excepting the LabJack driver and its interface, has been made freely available online[1] under the GNU General Public License.[2] An emphasis has been made on simplicity of the user interface, and consistency across the modules as much as possible. For example, all measurement modules present identical parameter input fields and graphing capabilities as far as possible, and additional help is available through 'tooltips' at any time by right-clicking on elements within windows. A simple ASCII configuration file or a GUI interface within the software ("Settings" menu) allows field-tuning of hardware and software behavior by instructors (*e.g.,* calibration factors, altering I/O settings). Most students appeared to find the software intuitive, with few questions regarding usage. A usability study is underway to fine-tune the user interface, as is a comparative study with more traditional approaches to the same laboratory procedures.

The simplicity and modularity is reflected in the underlying code as well – the infrastructure allows new or modified experimental modules to be coded and implemented in a minimum amount of time. Thus, as new ideas develop they can be quickly realized. Extensive feedback was solicited from students at all levels, faculty, and a software usability expert. In order to facilitate uptake of the system, a "demo mode" is automatically entered when no hardware is present. Potential users can download the software, and explore the functionality of the system free of cost. All software functionality is present to 'test-drive' the system, with actual measurements replaced by randomly-generated numbers.

Multimeter: Different tutorial modules can be selected from the "main" applicaiton window, Fig. 4. The first software module the students typically encounter is a 'multimeter' panel, Fig. 4, chosen from the 'dc circuits' menu. From this panel, the student can source current or voltage, and simultaneously measure current or voltage, in any combination. Currents from $0-10$ mA can be sourced, and measured from $0-20$ mA, while voltages can be sourced from $0-3.5$ V, and measured from $0-7$ V.

The multimeter panel is not meant to mimic the behavior of a hand-held multimeter precisely. Rather, its goal is to familiarize students with the basic practices of sourcing and measuring currents and voltages. When the multimeter module is selected from the "dc circuits" menu (Fig. 4), the source and measurement regions of the module are blank until the user selects a source and measurement function. The two text areas at the bottom of the window give various instructions, which change as the user interacts with the module. Initially, they prompt the user to select a source and measurement function. Once functionality has been chosen, the uppermost text area relates to the chosen source (*e.g.,* reminding the user that
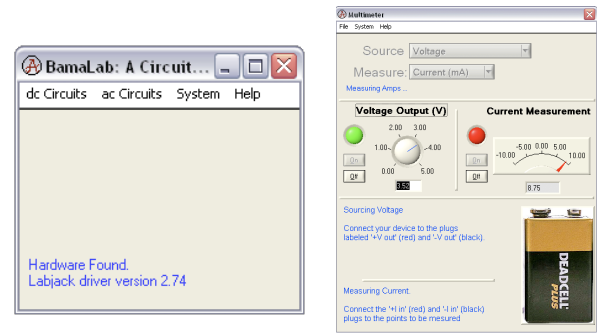

FIG. 4: Left: A screenshot of the main application window. Right: A screenshot of the software, showing the 'multimeter' panel. Current or voltage can be sourced or measured in any combination, both source and measurement are updated in real time. Active text areas at the bottom of the panel give the user instructions for the selected source and measurement.

the current source also has a switch), the lowermost to the chosen measurement. In the case shown in Fig. 4, the user selected to source voltage, and measure current.

Selecting voltage sourcing activates a dial, on/off button, indicator LED, and numerical readout (middle left). The user can either dial in the current or type a number in the text box, and turn the source on or off with the labeled buttons. The 'LED' turns green when the source is active, red when it is off. The current can be changed in real-time (all sourcing and measuring is real-time, with ~ 50 msec update time).

Selecting current measurement activates a needle gauge, on/off button, indicator LED, and numerical readout (middle right). The on/off button starts and stops the readout, the status of which is also indicated by an 'LED.' Both the numerical readout and needle gauge read the current in real-time while active. Though strictly speaking only unipolar measurements are performed, the readout is bipolar to help the student troubleshoot incorrect wiring (polarity reversal). Further, this panel allows a quick 'field calibration' – *e.g.,* by connecting the current input to the current output and electing to source and measure current. Similar behavior occurs when the user, *e.g.*, sources voltage and measures current - the contents of the window reflect the chosen source and measurement.

Usually this panel is used for the very first dc circuits experiment, which simply has the students attempt to source and measure current and voltage for three types of components: resistors, diodes, and capacitors. This short activity gives the students an introduction to key electrical components and basic wiring concepts as well as an overview of the software they will utilize in later lab sessions. Subsequently, the multimeter panel can be used to measure the equivalent resistance for series and parallel resistors, and directly verify that the current and voltage, respectively, are the same for both resistors.

Current vs. Voltage: The next level of complexity for the students is to perform current *vs.* voltage sweeps, $I(V)$, or voltage *vs.* current sweeps, $V(I)$. Both
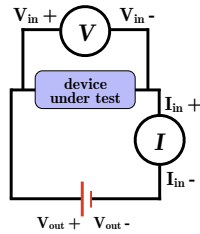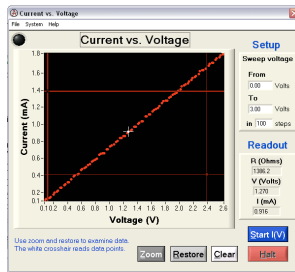
FIG. 5: Left: A screenshot of the software, showing a measurement of a $1350\,\Omega$ resistor using the current *vs.* voltage module. The maximum on the voltage axis does not correspond to the maximum sweep voltage, due to the finite resistance of the 'ammeter.' Right: Schematic of a four-terminal $I(V)$ measurement.

FIG. 6: A module for observing voltage step responses. Applying stepped voltages (*i.e.,* either suddenly turning a voltage on or off) allows real-time observation of charging and discharging behavior. Two successive measurements are shown on screen, one measuring the response of a series RC circuit, and one measuring the stepped output alone for comparison.

sweeps are supported, and the software functionality is essentially identical. Both types of sweeps are provided for two reasons: first, for non-linear components (*e.g.,* diodes) the characteristics appear different to students at first sight, and secondly, a true four-terminal measurement is qualitatively different in each case. We limit our discussion to the $I(V)$ functionality below.

The $I(V)$ function is selected from the "dc circuits" menu on the main window (Fig. 4). A screenshot of this panel is shown in Fig. 5. The "Control" region of the window (upper right) asks the user to specify the start and end voltages, and how many steps to take in between. The output is unipolar, and limited from $0-3.5\,\mathrm{V}$ as discussed above (the user will be coerced if values outside this range are specified). Sweeps can run "up" or "down" as desired.

Once the desired values are chosen, clicking the blue "Start I(V)" button performs the measurement and updates the graph in real time. The 'LED' in the upper right corner when the measurement is active. At any time, the red "Halt" button can be pressed to immediately stop the measurement. After taking data, the two red crosshairs can be used to select a region of data, and the "zoom" button will rescale the plot to show only that region. "Restore" will auto-scale the plot to its original state. Data will remain on the plot (and in memory) until the "Clear" button is pressed. The small white crosshair is a plot read-out, and when dragged to a data point, the "Data display" in the lower right will indicate the current, voltage, and resistance $(R = \frac{V}{I})$ at that data point. A text field in the lower left gives interactive status and instructions, and, as in any panel, 'tooltips' are available by right-clicking on objects within the panel.

Measuring $I(V)$ characteristics quickly introduces the students to proper four-terminal measurements and the effects of, *e.g.,* finite wire and ammeter resistances. In order to perform a four-terminal measurement (Fig. 5) the student must connect the current measurement in series with the load. Further, they must simultaneously measure the actual voltage drop on the device under test,
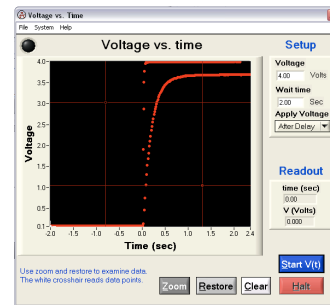
as a non-negligible voltage drop occurs across the $150\,\Omega$ shunt resistor in our 'ammeter.'

In any of the measurement panels (excepting the multimeter panel), any data currently on screen can be saved through the "File" menu. If multiple curves are taken without clearing the plot, all data currently on-screen is saved to the data file, not just the most recent data. The data itself is saved in a tab-delimited ASCII file, with a one-line text header for column labels, readily imported by *e.g.,* Excel or OriginLab.

In one example, students performed $V(I)$ measurements for series and parallel resistor combinations, and performed linear regression to find the effective resistance. Once simple resistor circuits have been mastered, students can be introduced to non-linear elements (such as diodes). In particular, light-emitting diodes are an excellent. Not only is non-linear behavior observed (and thus $I(V)$ and $V(I)$ on first sight appear to be different), students can clearly see the device light up only for a single voltage polarity. This also allows a brief introduction to semiconductor physics and non-linear regression. For example, comparing the threshold voltage for light-emitting diodes of various colors to the output wavelength (as measured with a diffraction grating), students were able to estimate Planck's constant to within $\sim 10\,\%$.[12]

Step Response: The next level of complexity is mastering RC circuits and time-dependent phenomena. Figure 6 shows a module which allows characterization of step function responses. In one case, the student observes the response of a circuit to a downward voltage step (from V to 0), in the other case, the response to an upward step is observed (from 0 to V). This lets students monitor in real-time the charging and discharging of a parallel RC circuit, for example.

Measuring the discharge curve of an RC circuit, for example, a user-selected constant voltage is applied for a specified wait time, and subsequently (at $t = 0$ on the plot) the voltage is reduced to zero. This functionality is selected by choosing "initially" from the "Apply Voltage"
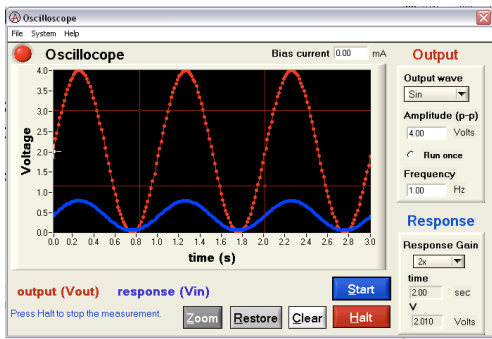
FIG. 7: A module for learning the time-dependent behavior of circuits. Students can apply a low-frequency waveform to a circuit (sine, square, triangle, or sawtooth), and observe the amplitude and phase behavior of the response. The driving sinusoid and the response are measured simultaneously.
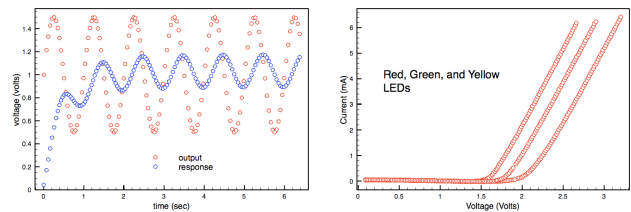

FIG. 8: Left: Measurement of the voltage on a $2200\,\mu$F capacitor in parallel with a $200\,\Omega$ resistor driven with a sinusoid. Right: Current-voltage characteristics for red, green, and yellow LEDs. Students compared the threshold voltage with measured output wavelengths to estimate Planck's constant.

drop-down menu. The actual voltage on the resistor or capacitor can be monitored during this time, and the RC time constant directly observed. Again, data can be easily exported for subsequent analysis, a good introduction to exponential and logarithmic behavior.

The charging curve can be just as easily measured by selecting "After Delay" from the pull-down menu. In this case, the measurement proceeds for the specified time with zero voltage, and at $t = 0$ the specified voltage is applied. This allows one to observe the corresponding charging curve for an RC circuit, which is shown in Fig. 6. Also shown is the step response itself, measured by simply connecting voltage output to input. Given the $20\,$kΩ input impedance of the LabJack FIOs, and the time resolution of $\sim 10\,$msec, components giving a fairly large time constant ($\gtrsim 0.1\,$sec) should be selected.

Oscilloscope: The last module completed at the moment mimics the behavior of an oscilloscope and function generator. A variety of waveforms can be applied and plotted in real time, and the response of a circuit element plotted at the same time. The waveforms are generated in software, and limited by the refresh rate of the U3 DAC and its output filters. A dc offset voltage is necessary to keep the output voltage at or above ground at all times, due to the pseudobipolar nature of the LabJack U3. This offset is automatically included without user intervention. Square, triangle, sawtooth, and sinusoidal waveforms are currently supported and generated in software. In principle, arbitrarily complex waveforms can be added in software as needed. Figure 7 shows the result of applying a sinusoidal voltage to a resistive circuit, and Fig. 8 to a parallel RC circuit. This allows direct observation of the phase-shifted response of a capacitor in an RC circuit, and an introduction to the frequency-domain description of ac circuits. In more advanced classes, one can use, *e.g.,* triangular or square waveforms to illustrate integrating and differentiating RC circuits, or the effects of 'stray capacitance.'

Peak to peak amplitude can be specified, up to 4 V, and a 'Response Gain' can be used to magnify the on-screen

signal for easier comparison (only 'raw' data is saved). Triggering is done in software after a specified number of cycles – the default is to trigger every 3 cycles, but this value is user configurable in the 'Settings' menu. Output frequency is limited primarily by the output filters on the LabJack DAC outputs (3 dB at 16 Hz), in practice $\lesssim 5\,$Hz provides reasonable waveforms. Once again, by careful choice of components, this rather low frequency limitation need not be a problem. Induced voltages due to time-varying magnetic fields, and RLC resonant behavior are rather inaccessible given the available frequency range, however.

Example measurements: Figure 8 shows two additional measurements performed with the present system. In the first case, the initial response to a sinusoidal excitation on a $2200\,\mu$F capacitor in parallel with a $200\,\Omega$ resistor was measured. Clearly observable are the initial charging behavior of the capacitor, and its phase-shifted response. In the second case, the $I(V)$ characteristic for red, green, and yellow LEDs were measured, and the threshold voltages (V_{th}) extrapolated. Students measured the output wavelengths (λ) of the LEDs using a diffraction grating, and estimated Planck's constant using the averaged values of $\frac{hc}{\lambda} = eV_{th}$ for each LED. Though this is certainly a 'rough' experiment, $\sim 10\,\%$ accuracy was obtained in most cases.

IV. OUTLOOK

In the inaugural semester, seven roughly hour-long laboratory procedures were developed by P.L. for a non-calculus-based introductory physics course: a 'components' lab, introducing students to voltage and current sourcing with resistors, capacitors, and diodes; a 'resistors' lab involving the measurement of $I(V)$ characteristics for series and parallel resistors to find equivalent resistances; a 'sourcing' lab comparing true four-terminal resistance measurements with voltage and current sourcing ($I(V)$ and $V(I)$ characteristics of resistors and diodes); an 'rc circuits' lab, measuring the charging/discharging characteristics of RC circuits to find time constants; an 'ac circuits' lab, measuring the phase-

shifted response of a capacitor in real-time; and a procedure to measure Planck's constant using LEDs of various colors (described above[12]).

Future modules in development include magnetic field mapping using a simple and inexpensive Giant Magnetoresistive field sensor[13] powered and measured with the existing hardware, basic optoelectronics using photocells and light-emitting diodes, and temperature-dependent resistivity using liquid nitrogen and a thermocouple temperature sensor. We believe that the flexibility of the hardware and modularity of the software will allow a wide variety of additional modules to be developed.

We do not envision that the present apparatus will completely replace traditional experiments using, *e.g.,* function generators and oscilloscopes – these are instruments with which students must be familiarized. In particular, higher frequency phenomena and resonance behavior are essentially inaccessible with the current hardware, as are most induction phenomena. We envision the present system as a way to augment existing courses and add flexibility, particularly in introductory electricity and magnetism courses where simple transparent experiments are often lacking. In particular, we hope this system can be a viable alternative where laboratory budgets are severely limited, or where funds could be better spent on other laboratory endeavors. Further, we have made every effort to make the system as open as possible, such that even more industrious students could reproduce the hardware and software if they desire. The authors are happy to assist anyone interested in implementing the system outlined here.

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* Electronic address: `pleclair@ua.edu`; Project homepage: `http://code.google.com/p/bamalab`

[1] The project software, hardware schematics, installation instructions, sample laboratory procedures utilizing the system, and many other details can be found at the project home-page, listed above. Binary downloads of the software package are also available.

[2] The GNU public license is available at `http://www.gnu.org/copyleft/gpl.html`.

[3] See `http://www.labjack.com` for information including pricing, software and documentation. The LabJack U3 is currently listed at $99, or $90 after educational discount.

[4] We used the NTE976 which we had in stock, $8.93 from `http://www.mouser.com`. Many cheaper substitutes are available.

[5] Details regarding this course can be found at `http://ph102.blogspot.com`.

[6] A PASCO Xplorer GLX configured with voltage/current sensor is another low-cost equivalent. It provides a portion of the functionality of the current system at ∼$400 per seat. The proprietary software and hardware represents, in our view, a lack of flexibility however. The National Instruments USB-6008 device compares quite favorably to the LabJack U3, and could be readily substituted. It does have a slightly higher cost (∼$60 more).

[7] Radio Shack, 8x6x3in ABS project enclosure, $6.99.

[8] Adhesive-backed velcro is usually available at any local fabric store, *e.g.,* `http://www.hancockfabrics.com/`.

[9] See, for example, McMaster-Carr p/n 7124K42, $12.14 per package of 10.

[10] The smaller size prevents students from plugging sensitive test loads directly into 18 V from the batteries.

[11] See `http://www.ni.com/lwcvi/` for details. Academic site-licenses available. An effort is underway to make the software build-able with a free cross-platform development environment.

[12] A separate article on this experiment is in preparation. A sample procedure is available at `http://code.google.com/p/bamalab/`.

[13] Non-Volatile Electronics (NVE) offers a number of low magnetic field sensors under $10. See `http://www.nve.com/analogSensors.php`.