Requirements for the Effective Application of Personal Instrumentation in ECE Undergraduate Courses

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Dr. Yacob Astatke completed both his Doctor of Engineering and B.S.E.E. degrees from Morgan State University (MSU) and his M.S.E.E. from Johns Hopkins University. He is currently Assistant Vice President for International Affairs at MSU. Dr. Astatke was a full-time faculty member in the School of Engineering for over 20 years, where he rose to the position of Associate Dean for Undergraduate Education. He has more than 20 years experience in the development and delivery of synchronous and asynchronous web-based course supplements for electrical engineering courses. He also runs several exciting summer camps geared towards middle school, high school, and community college students to expose and increase their interest in pursuing Science Technology Engineering and Mathematics (STEM) fields. For over a decade now, Dr. Astatke has facilitated the donation of 250+ Electrical and Computer Engineering (ECE) portable laboratory instrumentation boards and has conducted capacity-building training workshops for five universities in Ethiopia. This work has improved the education of thousands of ECE students in Ethiopia annually. He has expanded his services to other African countries such as Nigeria, South Africa, and Cameroon. Dr. Astatke is recipient of several awards, including the 2016 Global Engineering Deans Council (GEDC)-Airbus Diversity Award, 2016 Black Engineer of the Year (BEYA) for College Level Promotion of Education, and the 2013 American Society for Engineering Education (ASEE) National Outstanding Teaching Award.

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Demetris L. Geddis is an associate professor and Chair of Electrical and Computer Engineering at Hampton University. He has extensive research experience in the areas of Integrated optoelectronics, Optics, Microelectronics, and Electromagnetics. He has worked as a Research and Design Engineer at Motorola and Bell laboratories. Also, he worked at NASA Langley Research Center as a NASA faculty fellow for the Nondestructive Evaluation Sciences Branch where he performed research in the area of optical fiber sensing for real time health monitoring of aerospace vehicles. Current research interests and publications are in the areas of Photonics, Optoelectronics, Microelectronics, Heterogeneous thin film integration, single-fiber bi-directional communications, optical sensing, and ring lasers. From 2008 to 2011, he was a Research Engineer at the Georgia Tech Research Institute where he fabricated scalable multiplexed ion traps for quantum computing applications. Before joining Hampton University in 2017, Prof. Geddis was a faculty member at Norfolk State University for 12 years.

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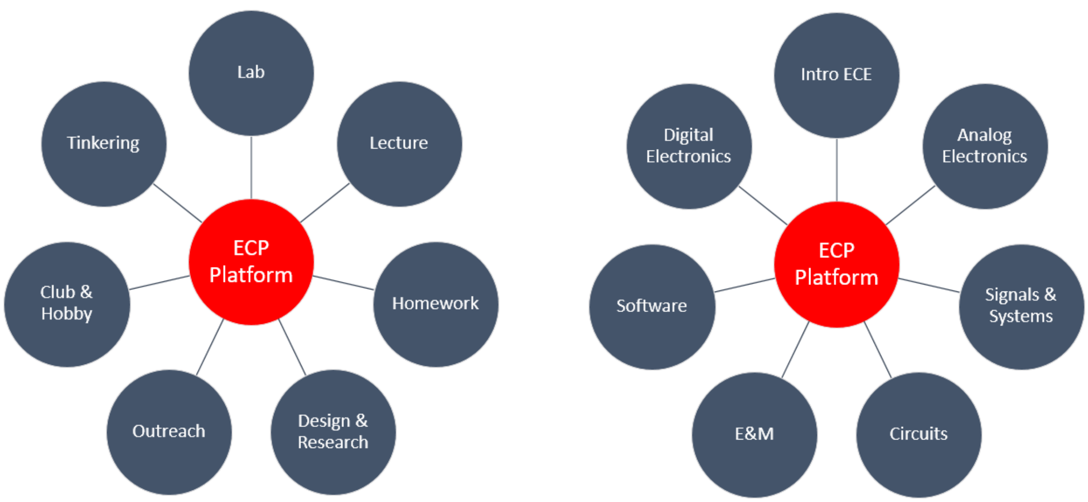
Shujun Yang received PhD in electrical engineering from Old Dominion University, Norfolk, Virginia, in 2006. From 2006 to 2008, he was an engineer at Applied Materials Inc., Sunnyvale, California. From 2008 to 2009, he was an engineer at Continental AG (former Siemens VDO), Huntsville, Alabama. Since 2009, he has been teaching at Department of Electrical Engineering, Alabama A&M University, Huntsville, Alabama. He is a member of IEEE, and a member of Microwave Theory and Techniques Society.

Abstract

Over the last few years, ECE education has been undergoing some dramatic changes made possible by the availability of low cost personal instrumentation such as Mobile Studio (RPI), myDAQ (National Instruments), Analog Discovery (Digilent/NI) and others. All of these devices were designed to free ECE undergrads from the constraints of fixed space, equipment and course scheduling so they can conduct experiments whenever and wherever they wish. Instructors are now also able to design the learning environment for their students that focuses on student doing and learning rather than on whether a lab meeting can be scheduled as part of their course. Experimental activities can be incorporated in lecture classes and be included in homework assignments. The freedom for both students and instructors to do what is right rather than what has historically been possible is what has positively impacted student learning. In addition, there are many other areas of application including high schools, outreach/recruitment activities, etc. that are only realistic if the unit price is much less (e.g. less than $50). Clearly, a much lower price requires reducing performance in some way. The question addressed in this paper is then whether the reduced capabilities that come with a lower price are sufficient for student learning. The specific low cost device addressed is the most readily available product priced under $40, Analog Devices ADALM1000 (aka M1K). Its performance and use will be compared with both the Analog Discovery and a commonly used benchtop scope.



A Personal Instrumentation Platform Should Support
All Types of Student Activities and All Aspects of EE Curriculum
Figure 1

Introduction

There is a rapidly growing literature on hands-on education with personal instrumentation. In ASEE Annual Conference alone, there have been 62 papers mentioning myDAQ, 47 Mobile Studio, and 45 Analog Discovery from 2010-2017. Essentially all of these papers report learning gains through the use of these powerful and generally inexpensive platforms. A sampling of the best of these papers is found in the references [1-18, 21]. One of the most elegant studies has been reported in a series of papers by Ferri et al [7] from Georgia Tech where they added hands-on modules using myDAQs in a variety of courses that previously had no experimental component. Student performance was compared between the topics addressed this way and those done more traditionally without experiments. Students consistently did better on topics in which experimentation played a key role. This is the approach that has come to be called Experiment Centric Pedagogy (ECP). Assessment of hands-on pedagogy in general shows that the approach has very positive impact on the depth of understanding of complex concepts. This has particularly been the case in the early years of a university program and for underrepresented and minority students. Hands-on learning is also helping to recruit and retain college engineering students and enhancing their future employment opportunities. Experimenting and solving problems in a hands-on environment can provide a solid grounding in engineering principles and hands-on learning, in general, just plain more fun for faculty as well as students. At present, hands-on learning is made possible largely through the use of benchtop instrumentation with new, small and mobile active learning platforms making large inroads in the ECE student's learning environment.

Figure 1 shows most of the most obvious areas for application of a broadly useful ECP Platform. To be effective learning tools in all of these areas, it is necessary that entire system that is the ECP Platform, work well. The ECP Platform specifically consists of a small hardware package (a circuit board loaded with components in a protective package), connected via USB to a computer and the software on that computer that controls and collects data from the board. The hardware/software system has the functionality of a wide variety of traditional benchtop instruments including oscilloscope, arbitrary waveform generator, DC power supply, network analyzer, spectrum analyzer, logic analyzer, digital I/O ports, and sometimes DC meters. Both the hardware and software must function well, be easy to connect to circuits and be packaged robustly to survive living in a student backpack. The circuitry must also be designed so that it is well protected from over voltages, shorts connected to voltage sources, etc. Fortunately, myDAQ, Analog Discovery and (in the past) Mobile Studio all easily meet these requirements, as shown by the many excellent papers published on their use. They also come with a wide variety of support materials including tutorials, datasheets, contents for many types of courses, etc. The available online learning infrastructure is well developed and generally very impressive. The remaining critical system characteristics are cost and performance (i.e. frequency response, dynamic range, etc.). Since everything else is basically equal, comparisons of ECP Platforms must focus on these two characteristics.

In a series of online practitioners workshops run over the last two summers, faculty actively using ECP Platforms and other small, mobile, electronic learning platforms (e.g. Arduino, Raspberry Pi, PSoC, ARMmbed, LaunchPad) enthusiastically shared what they have been doing, identified best practices and also addressed barriers and other problem areas. The findings of these workshops were shared with NSF and equipment vendors, many of whom also participated as observers in the workshops. Very high on the list of feedback to vendors was the lone issue that significantly slows the spread of technology enabled pedagogy – cost. Specifically, they concluded that "equipment prices tend to still be too high and are not sufficiently stable to enable effective planning, especially with respect to how costs are split between universities and their students [12]." There was a discussion of possible business models that could enable students to purchase and keep their own personal kits. While the cost of these active learning platforms is quite low (usually less than or comparable to the price of a typical new ECE textbook), many schools (especially Minority Serving Institutions or MSIs) find it a major challenge to ask their students to purchase or even rent the existing device options. Some purchase a collection of personal instruments and then loan them to their students. However, limited resources make it difficult or impossible to provide the full access needed to realize the real potential of the ECP enabled by these excellent modules. Even at institutions where students can easily afford their own devices and parts kits, students outside of ECE often do not use them in more than one class and, thus, tend to sell them to classmates. This defeats the purpose of empowering students to learn and apply electronics in new ways throughout their studies and careers.

Using a device whose price is under $50 makes most of the application problems go away, if the device can be shown to work. Thus, in this paper, we address the general question of what performance criteria must be met in each of the application areas. Because the Analog Discovery and myDAQ platforms have already been shown to provide a solid learning environment, the usefulness of other platforms can be assessed by performing a typical set of experiments that have already been done with these devices with a lower cost alternative. When these experiments are performed, it is necessary then to determine the dynamic range, frequency response, ADC resolution, power levels, software, instructional support, etc. that are necessary for student learning to progress in activities and courses typical in an undergrad ECE program. For example, what course content can be addressed with only frequencies through the audio range? How important is MATLAB or LabVIEW connectivity? What cross platform tools need to be supported (Windows, Linux, OS-X, etc)? Does this provide the pedagogical scaffolding to prepare students for using more advanced/capable instruments in future years? What is the price point that makes personal instrumentation affordable to a student? Is there well-developed, reliable, highly functional software similar to, for example, Digilent's Waveforms that allows for simple access to and control of all system functionality, especially including data collection?

Methodology

The personal instrumentation marketplace is growing and changing rapidly. (Note that in this paper, we consider only highly portable and, therefore, small devices about the size of an external hard drive or a cell phone. There are many other devices that are book size or larger and, thus, too large to be easily mobile.) One of the earliest successful products – Mobile Studio – is no longer available. It was designed by and manufactured for a university with no intention of spinning off a commercial enterprise, at least on its own. When other products became available, production ended and it was replaced in the classroom, mostly by Digilent's Analog Discovery. Available for about the same amount of time as Mobile Studio are the CircuitGear devices from SysComp. Their CircuitGear Mark II has a bandwidth of about 10MHz (40MS/s and 10bits) and costs $189. Their new CircuitGear Mini has a bandwidth of about 200kHz and a price of $85. SysComp does a good job of supporting their products with educational materials. The most generally useful device is Digilent's Analog Discovery which has a bandwidth of about 30MHz (100MS/s and 14 bits) and lists for $279 (version 2). Academic prices are about $100 less. New players are entering this space every couple of months. For example, the EspoTek Labrador with a bandwidth of about 100kHz (750kS/s and 8 bits) was funded through Crowd Supply and is available for $29. Even Digilent has their OpenScope (funded through Kickstarter) with a bandwidth of about 2MHz (6.25MS/s and 12 bits) and costs $89. What is consistently the case with these and other crowd funded projects is that they are highly over-subscribed because there is so much interest in affordable, portable personal instruments to enhance the educational experiences of ECE and other engineering and science students. They also, typically, do not have the simple to use software platform available with the more expensive options. The presently most popular devices also have an extensive set of activities, modules, design projects, etc. available through their company websites.

While the overall performance of the available products varies, they tend to be generally similar. There is one notable exception, so that is the product addressed as a case study in this paper. The circumstances outlined above have motivated Analog Devices to bring some new products into the marketplace. The first is their ADALM1000 active learning module (aka M1K), which does much of what the more expensive boards can do at about a fifth the cost. It has a bandwidth of about 30kHz (100kS/s and 16 bits) and is available for under $40 from Digi-key. While ADI is not known for building educational hardware, they are not new to the development of personal instrumentation. They played critical roles in the design, implementation and verification of both the Mobile Studio and Analog Discovery by providing a variety of engineering design support, component selection, prototype verification, manufacturing and test assistance. This paper addresses whether the M1K can be utilized in undergraduate courses based on evaluation by instructors participating in the HBCU Experiment Centric Pedagogy (ECP) project [1, 2]. In this project, faculty from the 13 HBCUs with ECE programs have been implementing ECP in their first year, circuits, electronics and design courses for the last three years using Analog Discovery. Thus, they know what works for their students.

Reiterating the methodology used in this study, a representative set of electronic activities were done with the M1K and Analog Discovery, with the latter providing the standard for performance and usability because it has been applied in ECE courses so widely. For one activating involving higher frequencies, measurements were also made using a popular benchtop oscilloscope. The goal is to test the hypothesis that the overall performance of the M1K makes it a useful alternative to Analog Discovery for application in undergraduate ECE courses.

ADALM1000 (M1K) Background

In this section, the background on the specifications for the M1K board is discussed, including details on what the specs are and how they were arrived at. First, the specifications:

USB powered, 2 analog channels and 4 digital channels
Measure and source current (- 200mA to +200 mA) and voltage (0 to +5V) simultaneously
Source and sink current (2-quadrant operation)
Oscilloscope (100 kS/s), function generator (100 kS/s)
16-bit (0.05%) basic measure accuracy with ~ 100 µV resolution
1 MΩ input resistance in Hi-Z input mode. Capacitance is 390pF.
Fixed +2.5 V and +5.0 V power supplies (source and sink up to 200 mA each).
4 - 3.3 V digital input and output pins
Fixed 3.3 V digital power supply (limited current)
Open source software runs on Windows, OS X, Linux (including Raspberry Pi)

It remains a challenge to develop USB-based hardware that is useful in a wide array of teaching laboratory conditions while maintaining a satisfactory level of performance at low cost. The solution arrived at with the ADALM1000 achieves higher precision, supplies higher power, and lower noise than many comparable devices. Analog electrical systems can be viewed to interact in the voltage and/or current measurement domains. The typical instrumentation tools used by electrical and computer engineering students generally operate in the voltage domain, and trade current and power for performance to an extent which makes it challenging to interact with most basic real-world systems.

Bench function generators are invaluable tools for generating test signals to stimulate systems. They typically include an output in series with a 50Ω resistor and might require external components to buffer their output signal to a point where it is of use for driving physical systems requiring significant current to be supplied (e.g. DC motors, LEDs or incandescent bulbs). Bench oscilloscopes can display high speed signals possibly into the GHz, but can require thousands of dollars of add-ons in order to measure current and, in turn, the power flowing into or out of an electrical system.

One of the main uses for the differential voltage inputs of the RPI Mobile Studio and Analog Discovery was to measure current by measuring the voltage across a shunt resistor. This functionality was brought on board in the ADALM1000 design as part of the overall SMU concept. (See Figure 2) A source measure unit (SMU) is a type of test equipment that is capable of both sourcing and measuring at the same time. This removes one of the major reasons to implement differential inputs and provides much of the same capabilities at reduced hardware cost.

Introductory laboratory exercises might require six or more electrical connections to be made perfectly before measurements can be made, and literally dozens of knobs and buttons to be dialed in specifically for the system at hand. These same introductory engineering exercises often require significant amounts of time spent building up external supporting circuitry to afford functionality similar to that of the ADALM1000 integrated source and measurement hardware. The ability to measure the voltage across and the current through a single connection at a reasonable speed allows for basic explorations to be made with as little as two connections. Even sophisticated explorations require at most a half-dozen connections.

Design Tradeoffs

What were the design tradeoffs that allowed the board to achieve a useful set of properties while keeping under the target price point? The design of the ADALM1000 requires making tradeoffs in voltage, current, power, and speed. With the intent of building an affordable tool for introductory exploration of complicated electrical and mixed electrical/physical systems, the tradeoffs were balanced to offer high dynamic range, the ability to source waveforms at frequencies higher than the human ear can hear, and with enough electrical power to allow the direct interface with just about anything that runs on batteries. Offering this functionality via USB makes a wide array of exploration immediately achievable without requiring power from a 120VAC wall adapter be supplied to the board.

Deciding to forgo including negative input and output voltage ranges and negative power supplies greatly simplified the design and lowered the overall cost of the bill of materials to fit within the cost target that was set. Providing a fixed +2.5 V power supply in addition to the fixed +5V power supply allows the equivalent of -2.5 to +2.5 signal range by using the +2.5 V supply as the common reference node. By combining both channels differentially the equivalent of -5 V to +5 V swing is possible.

Output Power

Analog systems encountered in early engineering labs typically range from milliwatts to tens of watts of electrical power. It is not possible to supply power for a large motor with the amount of voltage and current available through a USB port, but it seems sufficient to support experiments spanning up to one watt of electrical power (5 V times 200 mA), in comparison to the relatively low power handling capabilities of many USB instruments such as the ~100mW max for Analog Discovery. One watt per channel allows a two channel device to fall within the 2.5 W power budget of USB without difficulty.

Dynamic Range

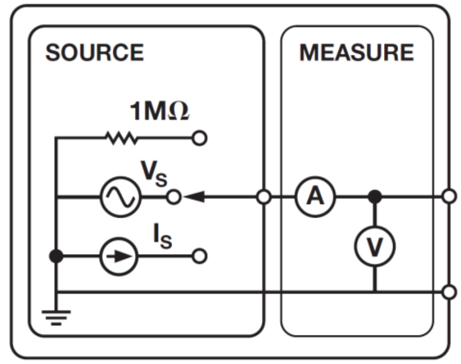
To attempt to accommodate the wide array of explorations one might want to carry out, the ADALM1000 was designed with sixteen bit data converters, capable of representing up to 65536 different values (2^{16}) between the minimum, 0 volts and -200mA, and maximum +5 volts and 200mA range of the device. The use of wide dynamic range analog-to-digital and digital-to-analog converters greatly simplifies the amount of hardware in the analog signal chain to the extent that programmable gain is not required.

Sample Rate

Sample rate is also one of the hardware design parameters to consider. Human senses are typically substantially slower than the equipment used for electrical test and measurement, but most early exploration can occur with signal frequencies within the realm of human hearing (audio). Slower signals are impacted less by the small parasitic (inadvertent "bonus") resistors, capacitors, and inductors which are present in all electrical circuits. Working with slower signals also offers pedagogical benefits. It can, for example, be tremendously enriching to gain an understanding of filter circuits by listening to the waveform at various nodes in the filter.

To learn circuit concepts at audio frequencies sets a minimum sample rate of 44 kilohertz, a sampling rate often used in digital audio. With the desire to simultaneously measure both voltage and current on two channels (a total of 4 16-bit values), an upper limit of approximately a million samples per second was determined by the desire to offer continuous data streaming at the maximum rate over the high-speed USB 2.0 interface. Budget, interface, and availability made the AD5663R two-channel 16-bit digital-to-analog converter and the AD7682 four-channel 16-bit analog-to-digital converter, good fits for the data conversion aspect of the design, each offering a peak sample rate of a 250 KSamples per second. Such a rate offers the end user the ability to work with signals with higher sample rates than most traditional PC sound cards.

What is unique about the board?



Source Measurement Unit
Figure 2

As noted above, the two analog channels are configured as Source Measure Units. (Figure 2) This is a significant departure from what most students will encounter in an undergraduate circuits or electronics lab, and, thus, can lead to confusion on the part of the instructors making the transition to using the ADALM1000. An SMU is an instrument that combines a sourcing function and a measurement function on the same pin or connector. It can source voltage or current and simultaneously measure voltage and/or current. It integrates the capabilities of a power supply or function generator, a digital multi-meter (DMM) or oscilloscope, a current source, and an electronic load into a single, tightly synchronized instrument. Most SMUs are “DC” instruments, however with the bandwidth and 100 KS/s speed of the ADALM1000, it can be considered as more of an “AC” SMU allowing the measurement of complex impedances.

Because the generator source and measurement system are tightly synchronized the ADALM1000 hardware supports what is called the repeated sweep (discontinuous) mode. In the discontinuous mode the output goes into a Hi-Z state between sweeps and when the software is stopped. At the start of each sweep the source outputs are restarted at the same point in the waveforms so no "triggering" is required. Everything is automatically synced which reduces the complexity of setting up many measurements.

Even though the ADALM1000 is at its heart an SMU, it can also be viewed as a conventional oscilloscope and arbitrary waveform generator. However, because the output function (source) and input function (measure) share a common pin, when considered as separate instruments only one function can be used at a time. This can be confusing to some users who are maybe not so familiar with an SMU. The added benefit of being able to simultaneously measure the current being supplied by the sourcing function (or measure the voltage when sourcing current) can be a useful adjunct to reinforce the voltage, current and resistance relationships of Ohm’s Law.

Software Support

Personal instrumentation requires three general components that do an excellent job of spanning much of what ECE grads will encounter on the job. First, there is the mixed signal hardware (both analog and digital) including its associated power supplies and conditioning. Second is the firmware resident in processor that runs the hardware. The combination of hardware and firmware is the physical device. The third is the software resident on a personal computer that interfaces with the hardware and enables control of the hardware. This software provides the functionality of arbitrary waveform generators, oscilloscopes, power supplies, network and spectrum analyzers, voltmeters, ohmmeters, data loggers, etc. As with other personal instruments, there are several choices of software used to interface with a student’s laptop:

Pixelpulse2, ALICE, Matlab, Python and C++. The software provided for use with the ADALM1000 is open source and can be modified or tailored to the specific needs of a given pedagogy.

Pixelpulse2 provides a simple entry level interface which is intended to ease the learning curve for first time students (e.g. K-12) with little prior exposure to standard bench top instruments. An intuitive click-and-drag interface makes exploring system behaviors across a wide range of signal amplitudes, frequencies, or phases a simple exercise and speeds early learning of basic concepts. The capabilities of the software is limited by design to the simple types of measurements most often encountered in early exploration of circuits.

For more advanced labs, the ALICE desktop package provides more extensive measurement functionality and a more conventional interface that looks and feels more like benchtop instruments. It supports the following functions: 1) Two Channel Oscilloscope for time domain display and analysis of voltage and current waveforms; 2) Controls for the two channel Arbitrary Waveform Generator (AWG); 3) X-Y display for plotting captured voltage and current vs voltage and current data as well as voltage waveform histograms; 4) Two Channel Spectrum Analyzer for frequency domain display and analysis of voltage waveforms; 5) Bode Plotter and network analyzer with built-in sweep generator; 6) Impedance Analyzer for analyzing complex RLC networks and as a RLC meter and Vector Voltmeter. Board Self-Calibration is provided.

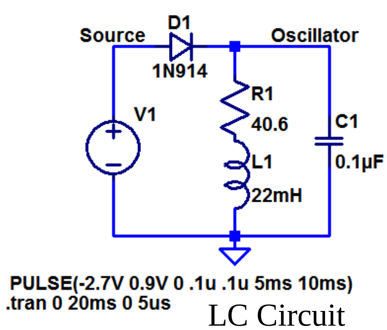
Interfaces to programming environments like Matlab, Python, and C++ provide the opportunity for instructors to include content in their courses that address programing, data analysis, signal processing, and control systems in addition to circuits and electronics. These capabilities have been implemented in undergraduate courses, summer high school programs, middle school courses and after school activities and general middle and high school outreach events, with K-12 activities mostly using Python because it is simple to use and free.

Applications

Three typical applications have been addressed to assess whether or not the M1K can provide the level of performance necessary for general applications. The first is an LC Oscillator, which is an experiment used in a 1st year Physics course. The second is a Thevenin/Norton equivalent experiment found in nearly all undergrad ECE programs. The third is a Joule Thief experiment, not generally used in any program, but a popular project for electronics tinkering.

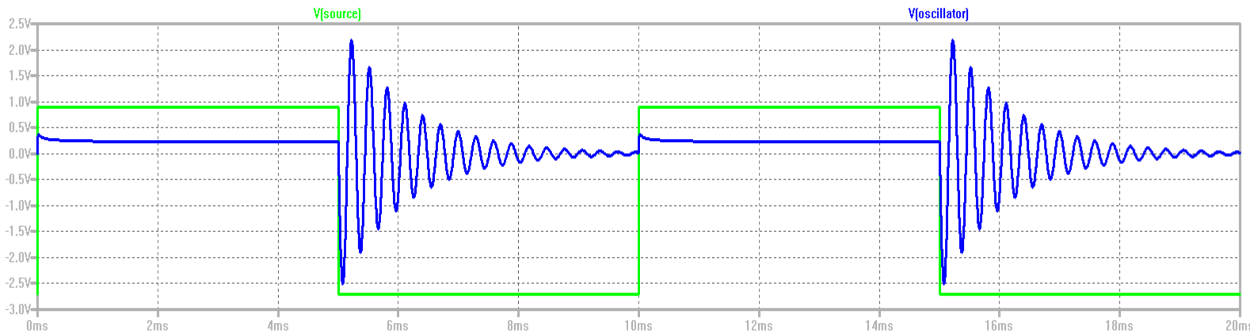
Application – LC Oscillator

Figure 3 shows a simple and fairly universal application that can demonstrate some of the trade-offs when instructors compare the possible use of personal instruments in their courses: a circuit primarily consisting of an inductor in parallel with a capacitor. The circuit model for the real inductor includes an ideal inductor and resistor instead of just an inductor. The signal generator produces a 3.6V peak-to-



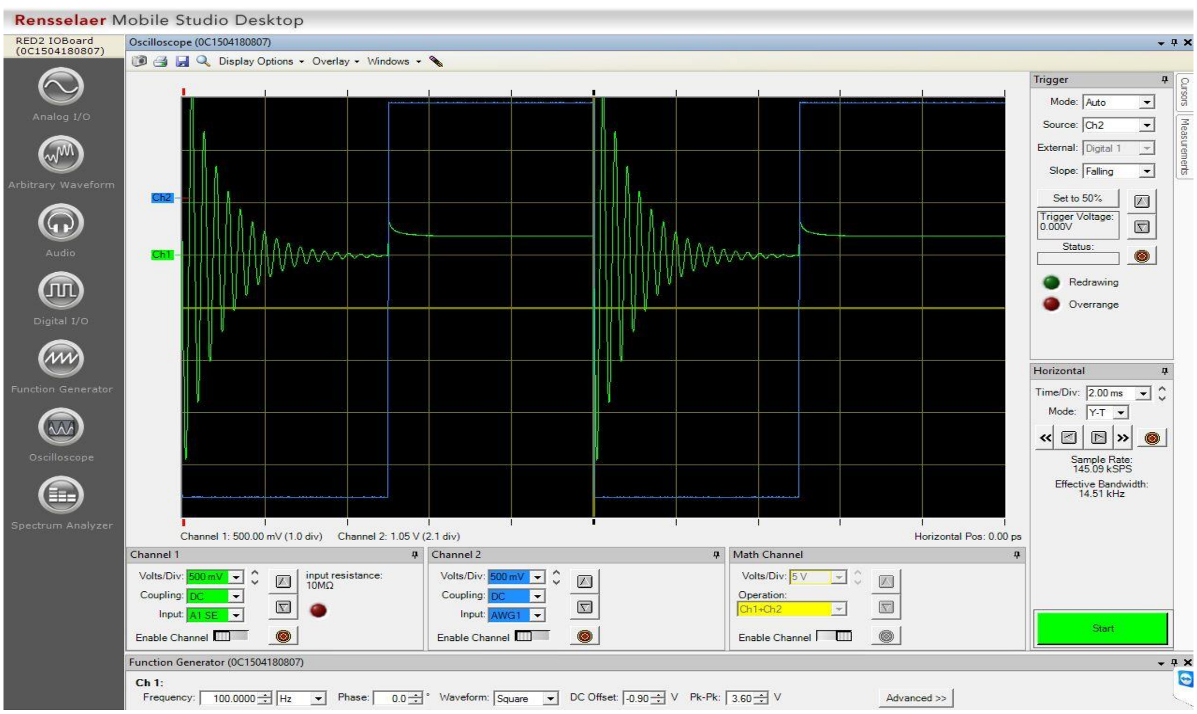
LC Circuit
Figure 3

peak square wave with a 0.9V offset. When simulated, the voltage at the source and across the parallel LC combo is as shown in Figure 4.



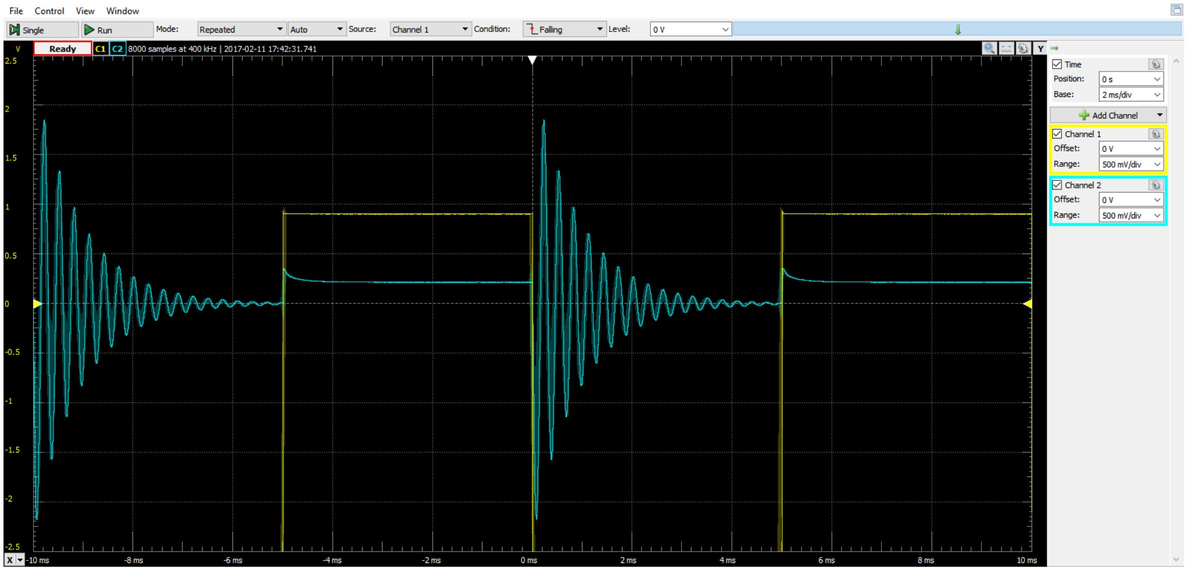
Simulated Input (Green) and Output (Blue) Voltages for LC Circuit
Figure 4

The circuit was built with the components as modeled and a Mobile Studio was used to drive the circuit and measure the resulting voltages. Note that the vertical voltage display for the Mobile Studio has a small offset and the trigger is set to sync with the falling input pulse. Otherwise the two signals are indeed identical. (See Figure 5)



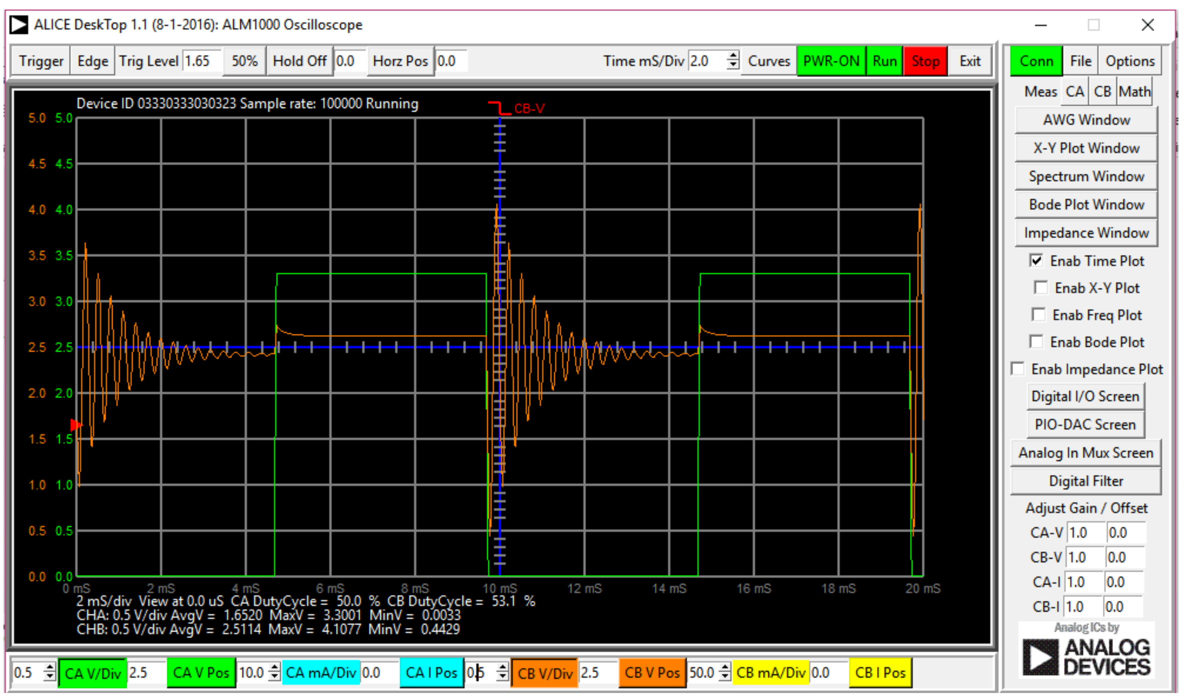
Input (Blue) and Output (Green) Signals Measured with Mobile Studio
Figure 5

Next an Analog Discovery was used for the same purpose. As seen in Figures 5 and 6, both of these devices and their controlling software produce plots that look like standalone scopes with periodic voltages oscillating plus and minus around a finite offset. Voltages are both positive and negative. Horizontal scales and vertical scales for both input channels are included in the plots.



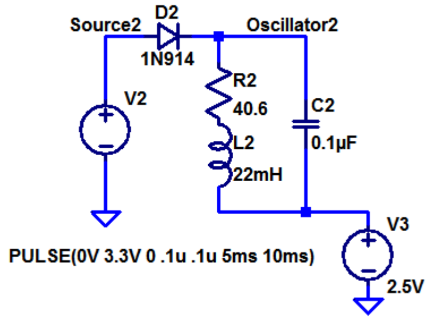
Input (Yellow) and Output (Blue) Measured with Analog Discovery
Figure 6

Finally the M1K was used to demonstrate one of the primary differences in this device, even when the ALICE software is used and the output appears conventional. The resulting screenshot again looks like a scope, but the voltages are only positive, as shown in Figure 7.

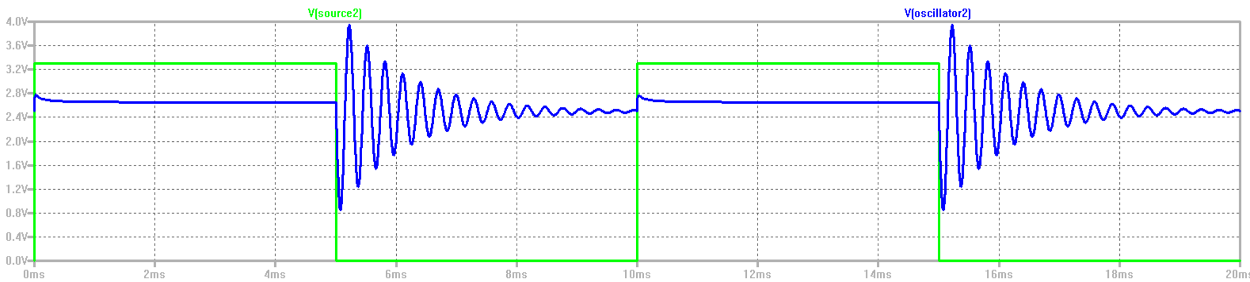


Input (Green) and Output (Orange) Measured with ADALM1000
Figure 7

There are two major differences in how the circuit is configured for M1K measurements. (See Figure 8) First the bottom of the parallel LC combination is connected to 2.5V rather than grounded. Second, the signal generator outputs a square wave that oscillates between 0V and 3.3V. The overall range of voltage change was chosen to be slightly smaller in this case to keep the LC oscillation on the screen. This works slightly better and shows another tradeoff that is often necessary with M1K because it has a range of only 5V rather than the 10V range of the other devices. Once these changes are made, the signal looks very much like what is observed with the other two and agrees completely with the simulation, with the latter shown in Figure 9.

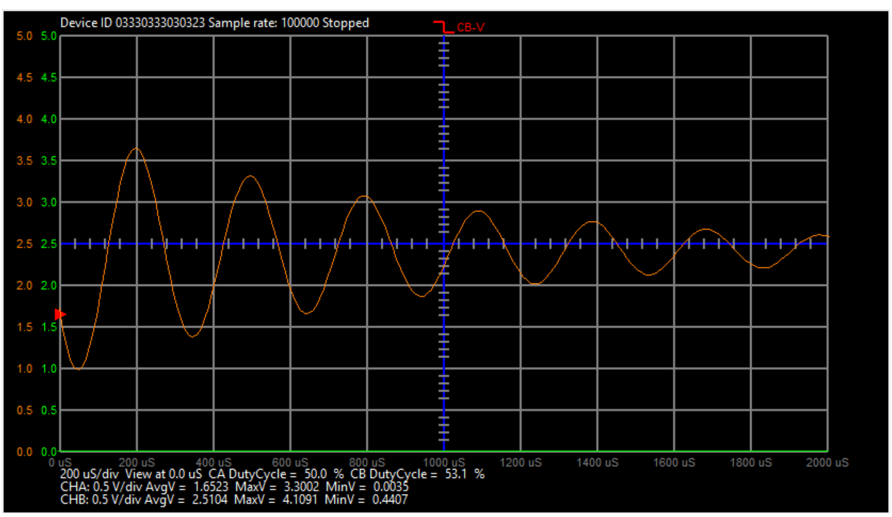


LC Circuit for ADALM1000
Figure 8



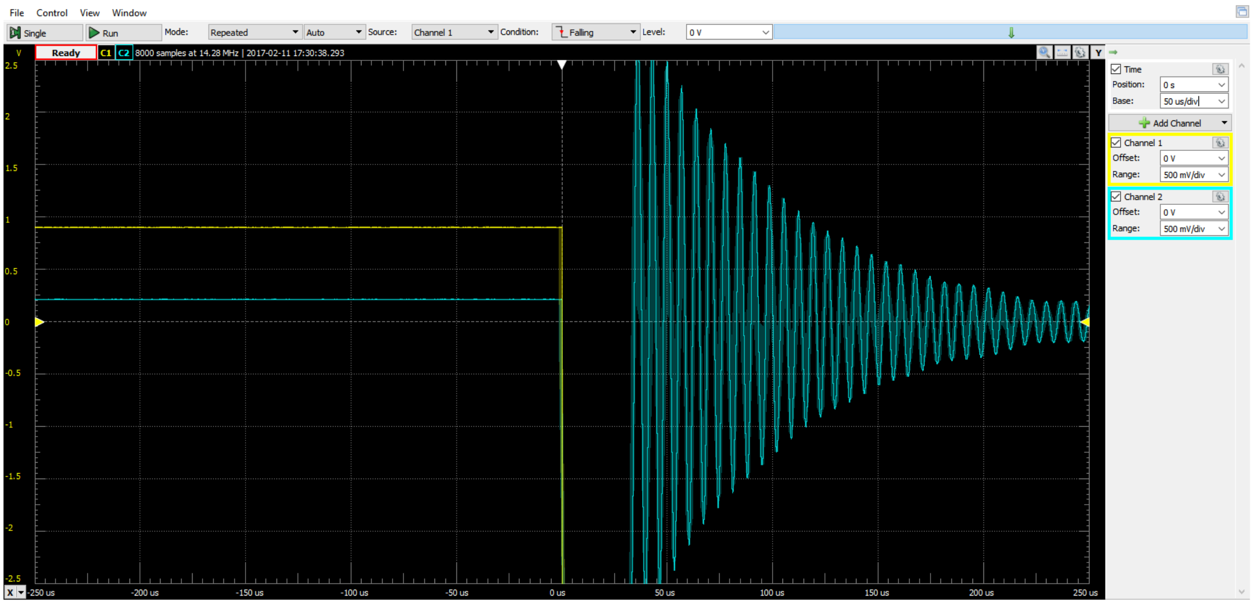
Simulated Input (Green) and Output (Blue) for ADALM1000 LC Circuit
Figure 9

If desired, the time scale can be expanded to see smaller details in the signals. Shown in Figure 10 is the same signal as in Figure 7, with only the time scale changed. This plot makes accurate determination of the natural oscillating frequency easier to determine. This can be done using cursors which are provided with all three boards and their supporting software.



Input (Green) and Output (Orange) Signals Measured with ADALM1000 – Expanded Scale
Figure 10

The frequency limitations of M1K make it problematic to perform a logical next step in this experiment. If the 0.1µF capacitor is removed, the signal will still oscillate but at a much higher frequency determined by the parallel combination of the input capacitance of the analog measurement channels and the parasitic capacitance of the inductor. Since the output signal is qualitatively the same as observed previously, students are led to the conclusion that there must be some hidden capacitances in the circuit. Nominal values for these capacitances can be found from the datasheets for the measurement device and the inductor used. Both datasheets are provided for students in the classes that study this experiment. Doing this experiment requires the student to work at the higher three levels of Bloom's Taxonomy, and, thus, they are better prepared to think like an engineer [5, 19, 20].



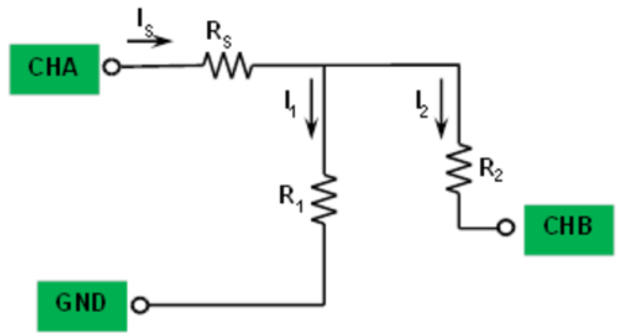
Input (Yellow) and Output (Blue) for LC Circuit Measured with Analog Discovery
The Capacitor in this Case is the Parasitic Capacitance of the Inductor
Figure 11

Of the three personal instrumentation devices, this can, in fact, only be directly observed using Analog Discovery. The exponential decay of the damped oscillation can be observed by all three, but the oscillation frequency cannot. Typical self-resonant frequencies for inductors run from 100kHz to more than 100MHz, with the inductor used here having a self-resonant frequency near 300kHz. The lower frequency observed above (160kHz) is due to the addition of the input capacitance of the Analog Discovery analog input. Thus, this experiment helps to demonstrate the impact of both the parasitic capacitance and the input capacitance because the circuit behavior is the same as for a much larger discrete capacitor. Using concepts from Signals & Systems, it is possible to expand the frequency response of the M1K, as discussed in the section below on the Joule Thief Experiment, but not to frequencies this high because the frequency response of the components used in M1K is too limited. It does provide a great opportunity to investigate inherent limitations in measurement devices by comparing and contrasting the signals from all available measurement choices, which also encourages upper level Bloom's thinking.

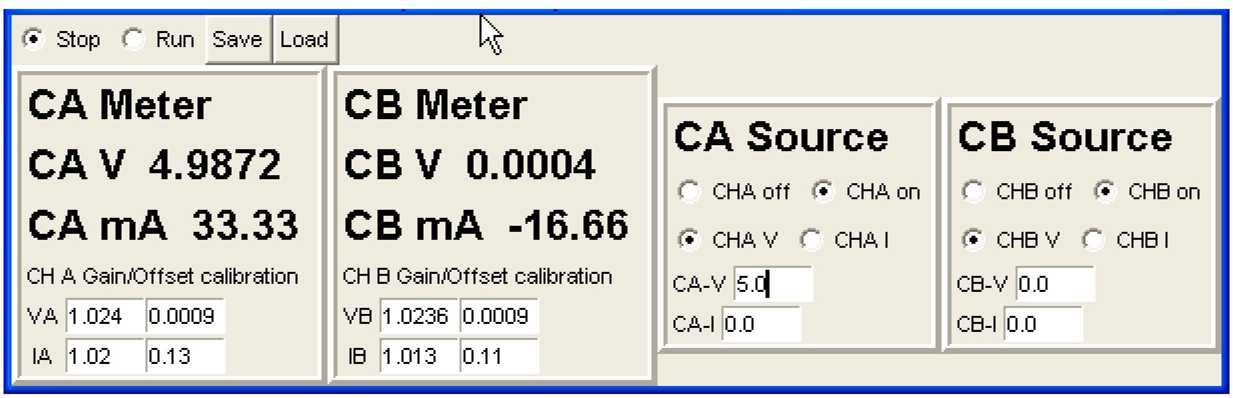
Application – Thevenin and Norton Equivalent Circuits

Two of the most common experiments found at essentially all of the HBCU engineering schools participating in the ECP project involve Voltage Division and Thevenin/Norton Equivalents [3]. An experiment that addresses Norton sources shows how the unique capabilities of the M1K can be used to produce a very elegant and simple procedure. Assume that the circuit in Figure 12 consisting of three resistors is powered by a DC voltage source connected between CHA and GND. This requires CHA to be configured as a voltage source.

Assume the voltage is 5V. If CHB is also configured as a voltage source with 0V, it is a short circuit so the current measured by CHB will be the short circuit current, which is needed for the Norton source representation. The ALICE software has an option called the Meter-Source combination which has the window shown in Figure 13. On the right CHA is set to be a 5V source and CHB set to 0V. An experiment where all three resistors are 100Ω results in the voltages and currents shown.



Thevenin/Norton Circuit
Figure 12

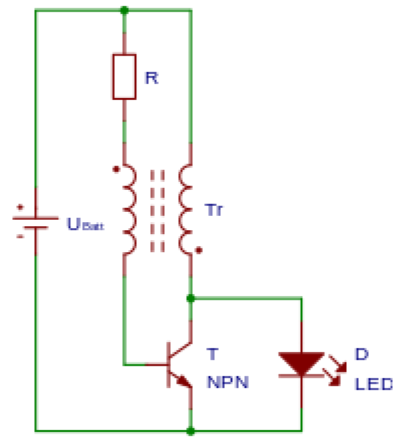


ADALM1000 DC Meter Measurements of Thevenin/Norton Circuit
Figure 13

To obtain the Norton (also Thevenin) resistance, CHA can be shorted out and the net resistance across an open circuited CHB measured with a conventional multi-meter or using the ALICE Ohmmeter option. The ALICE meter requires that the resistor combination be one of the resistors in a divider where the other resistor is known. Doing the same experiment with either the Mobile Studio or Analog Discovery requires that the voltage be measured for a known load and the net resistance calculated from the measured voltage. This is done automatically by ALICE. The Ohmmeter resistance measurement is a bit less elegant than the current measurement.

Application – Joule Thief

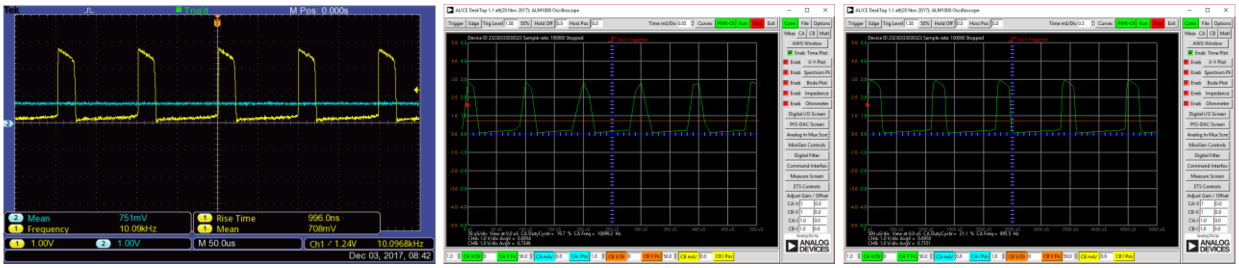
A very clever circuit that both students and instructors enjoy working with is the Joule Thief, a very simple circuit that makes it possible to power a white LED with an old AA cell battery, even after its voltage has decayed to nearly 0.5V. (The reader is encouraged to do a web search for the Joule Thief to see the very large number of information sources available for this little project.) Components necessary for this experiment are shown in Figure 14: battery and battery holder or connector, 1kΩ resistor, 2N2222 BJT or similar, white LED, jumper wires and protoboard. A coupled inductor is also necessary which can be hand-wound on a ferrite core or a commercial coupled inductor like the one included in the ADAP2000 parts kit sold with the M1K. A Joule Thief is a free-running boost converter, whose operation depends on the transistor operating point moving throughout a very wide range of conditions. Thus, learning activities can be built around it for nearly all core EE courses, including Circuits, Electronics, E&M (inductor theory) and more advanced courses like Power Electronics.



Generic Joule Thief Circuit
By Rowland - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31765405
Figure 14

Surprisingly, one of the most interesting Joule Thief activities can allow students to explore the basic concepts in sampling theory and also show the power of hardware/software co-design. The sampling done by most scopes used by students is Real-Time Sampling. However, it is possible to achieve higher frequency response at much lower cost using Equivalent Time Sampling. This feature was recently added to the ALICE software suite so that students can tinker with it.

A typical Joule Thief signal, showing the voltage across both the battery and the LED is shown in Figure 15. The signal in Figure 15a was obtained using a Tektronix TBS 1072B, a 70MHz Digital Oscilloscope that sells for well under $1000. The frequency is not exceptionally high, but it has short rise and fall times. Even so, the frequencies in the signal are well under the maximum sampling rate of the scope of 1Gs/s. Thus, Real-Time sampling provides a smooth, accurate representation of the Joule Thief pulses. As shown in Figure 15b, this is not the case with the M1K, because of its much lower sampling rate of 100ks/s. The M1K only produces about 10 samples per cycle and they are located at quite different points in each cycle. Thus, the pulses are not smooth and change from cycle to cycle. The signal displayed also shows a lot a jitter because the triggering time moves from pulse to pulse. By using Equivalent Time Sampling, it is possible to combine measurements from many cycles and superimpose them which results in the smooth signal that follows. (See Figure 15c)

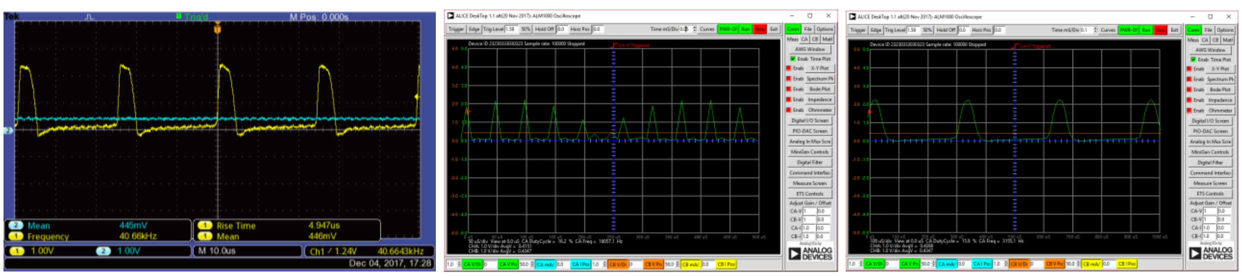


(a) (b) (c)

Joule Thief Oscillating at ~10kHz with Measurement Obtained Simultaneously Using (a) a Tektronix TBS 1072B and an ADLM1000, (b) with and (c) without Equivalent Time Sampling (ETS)

Figure 15

Students are able to try a variety of sampling configurations that can result in many more points per cycle or even a reversed signal. This provides a great opportunity for students to tinker with sampling to see what happens. For example, the next set of signals shown in Figure 16 is for pulses around 40kHz where the poor Real Time Sampling of the M1K is more apparent. Note that for both of these sets of measurements, the pulse frequency was changed to obtain the best possible signal because the sampling frequency is fixed. A potentiometer was added in series with the 1kΩ resistor, which allows the frequency to be changed by at least an order of magnitude.



(a) (b) (c)

Joule Thief Oscillating at About 40kHz with Measurement Obtained Simultaneously Using (a) a Tektronix TBS 1072B and an ADLM1000, (b) with and (c) without Equivalent Time Sampling (ETS)

Figure 16

Discussion

This paper explores the question: What are the necessary capabilities for a personal instrumentation platform to be sufficient for student learning? The authors have made extensive use of Analog Discovery in essentially all of their courses with substantive circuits and electronics content, so that is the device that is used as the established standard, along with traditional benchtop instruments. The ADALM1000, which lists for less than 25% of an Analog Discovery was designed with significantly different capabilities to achieve its much lower price point. By using the ADALM1000, the study reported on here shows that it is possible to provide inexpensive, mobile, hands-on pedagogy that addresses most ECE educational needs by effectively trading off dynamic range, frequency response, ADC resolution, power levels, software, instructional support, etc. to produce a product most students can afford to own. The minority of activities that cannot be fully addressed can be handled by simulation and the occasional use of or access to data from benchtop instruments or more expensive personal instruments.

An intriguing use of M1K is in a Signals and Systems course, which is often taught with no labs. In addition to the study of transfer functions using various filters and op-amp configurations, it is possible to also address sampling. The ALICE open source suite of Python applications, which includes the ETS capabilities, is a great example of what can be done with M1K or any of the other personal instrumentation devices because they can be fully controlled using freely available software like Python. Thus, it is also possible to include software-based activities in any undergrad ECE course or even use any of the hardware platforms to teach introductory programming. A simple Python-based nightlight project is included as part of the Intro to ECSE course at Rensselaer. This is also used in outreach activities, so essentially all of the courses and activities in Figure 1 can be addressed using this simple, inexpensive device, especially if more powerful instruments are also available for occasional use.

Shown in the table below is a sample of the devices mentioned in this paper. Two are available at this time and three are in development. The ADALM2000 (M2K), not mentioned previously in the paper, similar to the Digilent OpenScope in performance and price point, except that it will achieve 10X the bandwidth with two fewer bits of converter resolution. Both devices are produced by experienced companies. The Labrador is developed to push the price point down even below that of the ADALM1000 (M1K). It is not clear if it will perform as planned because the company is a start-up run by recent graduates. Their basic design looks good though.

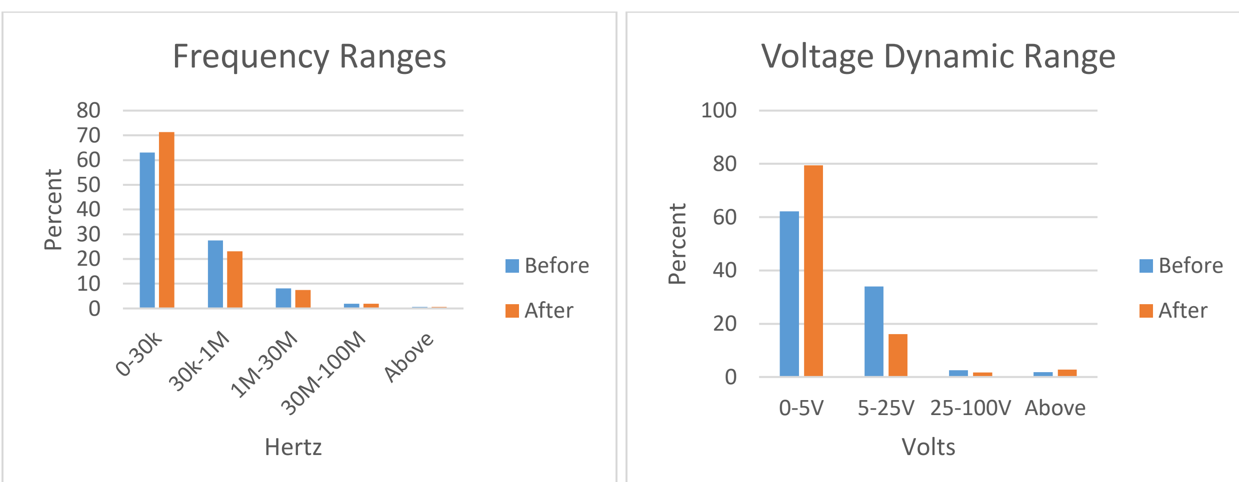
Table 1
Personal Instrumentation Products

Present Products		In Development			Spec
AD2	M1K	OpenScope	Labrador	M2K	Name
$179	$40	$89	$29	$100	Price[+]
30MHz	20kHz	2MHz	100kHz	20MHz	Freq
100Ms/s	100ks/s	6.25Ms/s	750ks/s	100Ms/s	Sample
14 bits	16 bits	12 bits	8, 12 bits	12 bits	Dig Res
-25V to 25V	0 to 5V		-20V to 20V	-20V to 20V	V Meas
0 to 50mA[*]	0 to 200mA	0 to 50mA	0 to 10mA	0 to 50mA	I Source
-5V to 5V, 3.3V	5V, 3.3V, 2.5V, 0V	-4V to 4V	3.3V, 5V, 12V	-5V to 5V, 3.3V	V Source
2	2	2	2	2	Anal I/O
16	4	10	2	16	Dig I/O

[*] AD2 current range can be increased more than 10X with external supply
[+] Estimated academic prices

Another way to look at the broad question addressed here is implied by the diagrams in Figure 1 and mentioned in the abstract. Can the device chosen be used by students in all activities and all core classes? Even with the frequency and dynamic range limitations of the M1K, it will have sufficient use in each context to make it a worthwhile addition to a typical student's learning toolbox. It or similar devices, in a parameter range accessible to the M1K, have even been used in Controls and Communication activities [7]. so it is useful beyond the core courses listed. Of course both of these areas really require substantial increases in dynamic range and/or frequency response to be generally useful. At minimum, the less capable device can be used by students as they try ideas out, both inside and outside of class, even if they cannot provide sufficient power to drive robot motors or reach frequencies of interest for some communication system.

In a survey conducted by the authors of active users of personal instrumentation from more than a dozen universities (see Figure 17), it was found that over 70% of circuits and electronics experiments can be done within the specs of the M1K (where the limiting factor was more the dynamic range than frequency response) and over 80% within the specs of the AD2 (where the limiting factor was also the dynamic range). Essentially all practitioners said that the voltage dynamic range limitation could be taken care of by occasionally using 9V batteries. Thus, which device is selected will be determined by the price point and the availability of more capable benchtop instruments. The AD2 can do nearly everything required of instrumentation, but, as noted above, at least occasionally using standard instruments is beneficial for student learning. If the new products achieve close to their planned specs, they are likely to prove as useful as AD2. If standard instruments are available, then the M1K can put the measurement tools in student hands at a much more accessible price point. Thus, all of these devices are indeed useful, but context and overall educational goals matter. Finally, anyone considering the use of personal instrumentation should also be open to adopting other inexpensive platforms like the Arduino, Launchpad, Raspberry Pi, etc. The choice of other platforms will also impact the requirements for personal instruments.



Instructors from 12+ universities surveyed on the required specs **Before** and **After** they began using Analog Discovery in circuits and electronics intensive courses. Numbers are the percentages of their experiments falling in each range.

Figure 17

Active users of Analog Discovery boards were also asked if they could give an example of an experiment they would like to do, but could not do it with Analog Discovery. For voltage dynamic range, the only response was to provide a power supply that can operate at ±12-15V for more flexible op-amp experiments. For frequency response, no obvious examples were provided, but none of the faculty surveyed use either the Joule Thief or the LC Oscillator configured with only the inductor and its corresponding parasitic capacitance. Neither of those experiments can be done at all interesting frequencies with the M1K. As for desirable capabilities that are not presently available, the ability to source, sink and measure current were mentioned, especially for Thevenin/Norton source studies. Those capabilities are available with M1K, although overall accuracy was not as good in earlier versions of the board, but is significantly improved in the most recent version (Version E).

Finally, the general question addressed in this paper was broken down into several more specific questions, in the context defined by the commercial products listed in the table, to provide some additional guidance for instructors considering the use of any personal instrument.

1) What course content can be addressed with only frequencies through the audio range? Most basic circuits and electronics concepts can be addressed using frequencies only through the audio range. At Rensselaer Polytechnic Institute, essentially equivalent experiments for intro to circuits and electronics have been written for Analog Discovery, Mobile Studio Red 1 and Red 2 and benchtop instruments and the bandwidth for Red 1 did not go beyond audio. Things become more difficult when addressing inherently higher frequency phenomena. For example, the document from Texas Instruments on Signal Integrity (http://www.techni-tool.com/Tektronix-Fundamentals-of-Signal-Integrity) addresses analog measurement deviations caused by phenomena such as ringing and signal reflection from loads and sources. The former can easily be replicated at low frequencies, but the latter generally cannot. However, students can address all such phenomena using simulation and apply experiments to clearly identify effects that can be shown at low frequencies. What is left will be the high frequency phenomena. They could also be provided with some access to benchtop instruments or to data sets obtained with benchtop instruments. The latter is the better choice because it provides opportunities to enhance the overall measurement skills of students. More on this topic in item 5 below.
2) What limitations do dynamic range/resolution/power levels present? Resolution is generally the least important because very few physical phenomena need to be measured to better than 5% accuracy to observe and identify. Most devices presently available utilize 14 or 16 bit converters, but, even with noise, 12 bits should be sufficient for nearly all applications. Power level and dynamic range can be very limiting. They can, for example, completely eliminate the possibility of using standard, magnetic coil relays in an experimental circuit because the power supply built into a personal instrumentation platform is insufficient to drive them. Basic principles can be addressed using a reed relay or other device requiring low power. Thus, the basic ideas in a circuit can be addressed by anything, but not always actual practical designs. There are exceptions. M1K can handle most of the interesting dynamic range required by small magnetic relays, DC motors and incandescent lights. So while not high power it is higher power than the standard AD2 and heading in the right direction to cover experiments that need

slightly more than 1W. The AD2 has an optional external power supply that increases the available current range more than ten times. More generally, this issue can be addressed by making sure that some benchtop instruments and power supplies are available for more demanding applications. Another option is to build additional plug-in modules that add dynamic range or power. Some devices offer a more robust power supply as an add-on. Thus, it is not necessary to have expensive benchtop components available, but giving students some opportunities to use them is very important for their overall education.

3) How important is MATLAB or LabVIEW connectivity? Working engineers use MATLAB and/or LabVIEW so students should do likewise. They should also be able to program their devices in standard languages like Python, C++, etc. Having these capabilities make it possible for their learning experience to be much more like the working experience of practicing engineers. Everyone needs some experience moving between the analog, digital, hardware and software worlds. The additional current available with M1K or with the optional AD2 power supply permit the investigation of programming for loads that are much larger than with Arduinos and similar devices.
4) What cross platform tools need to be supported (Windows, Linux, OS-X, etc)? Most recent personal instrumentation products have expanded from just working with Windows to other standard platforms, including those used on phones. The value of this expansion is most evident in developing countries where students nearly all have phones but very few have computers. If the goal is to get the platform in the hands of the students, limiting to Windows makes little sense.
5) Does this provide the pedagogical scaffolding to prepare students for using more advanced/capable instruments in future years? As reported previously [4], use of personal instruments as oscilloscopes, function generators, etc. generally makes it easier for students to learn to use traditional benchtop instruments. Students have the time to get very used to their personal device and, because often it is necessary to take care in setting up experiments (as discussed in the question where scaling is addressed) they develop a deeper understanding of how to make a good measurement. That does not, of course, keep students from erroneously concluding that they only know how to make measurements with devices like Mobile Studio and Analog Discovery, so instructors have to provide the context that shows the similarities and differences between types of instruments and students must be given the opportunity to use different types from time-to-time. A very good option to consider is to supply each student with the least expensive board that does what is necessary for their personal needs and then have a few of the more expensive and capable boards available for students to check out. Then they can simultaneously make measurements with more than one device and identify similarities and differences. This option requires a relatively small investment.
6) What is the price point that makes personal instrumentation affordable to a student? This is a difficult question to address quantitatively. However, there is a lot of anecdotal evidence in the US and elsewhere that prices over $100 seem to present a barrier to student ownership in developed countries and about half that or less in developing countries. Prices have moved a bit upward once the market has been established because the value proposition of the small, portable learning platform is well understood. The power of the $100 barrier is such that nearly all new products are priced there or below.

Conclusions

The ADALM1000 (M1K) has been shown to provide solid, easily used data for three reasonably typical experimental configurations. Thus, it is expected that it can provide the kind of hands-on exploration that is too often missing in engineering education at a much lower price point than has typically been the case. Sheppard et al [22] have described the direction that engineering education must take in the book *Educating Engineers: Designing for the Future of the Field.*

1. *In the engineering science and technology courses, the tradition of putting theory before practice and the effort to cover technical knowledge comprehensively allow little opportunity for students to have the kind of deep learning experiences that mirror professional practice and problem solving.*
2. *Laboratory and design experiences are generally treated as applications or adjuncts that follow the learning of theory in engineering science and technology courses. The lab is a missed opportunity: it can be more effectively used in the curriculum to support integration and synthesis of knowledge, development of persistence, skills in formulating and solving problems, and skills of collaboration.*

The M1K permits the integration of the lab experience in the student learning environment, as do the other options, at increased frequency response, but with similar functionality. No option enables everything that we would like to do, but, with the addition of some higher performance, usually benchtop, instruments, a fully authentic learning experience can result.

The general emphasis of this paper has been on the use of ECP Platforms in undergraduate engineering courses. However, a significant fraction of the experienced instructors presently using Analog Discovery teach courses for 1st year students, the content from which can also generally be used in high schools. This is particularly true for courses based on the Electrical Engineering Practicum [21], because it provides a simple, one-credit-equivalent, hands-on path to exploring electronics. Some of the authors of this paper have also used similar materials in activities involving middle school technology students and teachers, with the latter receiving their training through summer RET programs. The middle school and high school activities have been offered using every personal instrumentation option discussed in this paper. The same equipment has been used in general outreach events involving students as young as second grade. Thus, all ECP Platform options discussed can be used with all communities, again with the primary driving force being the program budget.

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Appendix

Lab # 7: Verification of Thevenin's and Norton's theorem

Objective: To verify Thevenin's and Norton's theorem for linear circuits.

Equipments: Electronic Power Supply, Digital Multi Meter (DMM), Resistors and Connecting Wires.

Procedure:

(a). Thevenin's Theorem

Resistor	Color code value (Ω)	DMM value (Ω)
R1		
R2		
R3		
R4		

1. Measure the values of the 4 resistors given to you, using the DMM
2. Construct the circuit as shown in Fig: 1.
3. Adjust the power supply voltage to 15V and measure the load voltage V_0

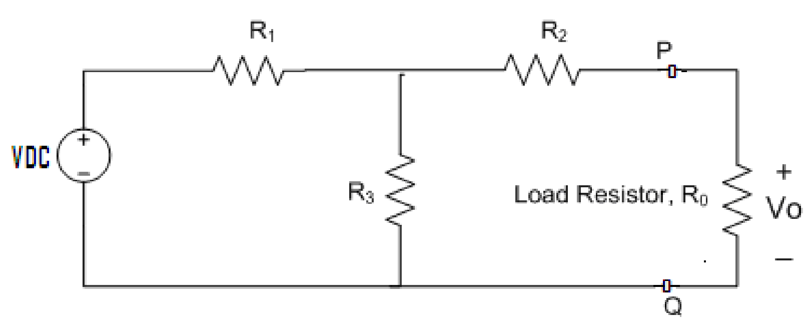


Fig. 1

4. Remove the load resistor, R_0. Measure the Thevenin voltage / open circuit voltage at terminals P-Q.

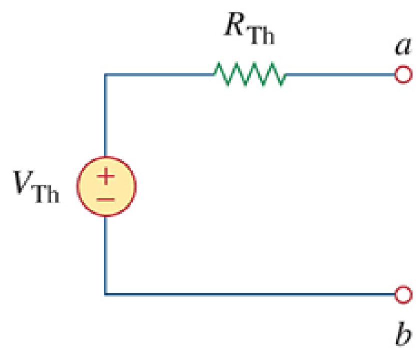
5. Calculate the Thevenin voltage

6. Kill the independent voltage source and measure the Thevenin equivalent resistance R_{Th}

7. Calculate the Thevenin equivalent resistance R_{Th}

V_0	V_{oc} / V_{Th} (measured)	V_{oc} / V_{Th} (calculated)	R_{Th} (measured)	R_{Th} (calculated)	V_0 (Thevenin circuit)	V_0 (calculated)

8. Construct the Thevenin equivalent circuit.



9. Add the load resistor R_0 to this circuit and measure the load voltage V_0.

10. Calculate the load voltage V_0

11. Is Thevenin's theorem verified?

(b). Norton's Theorem

1. Construct the circuit as shown in Fig: 1.

2. Adjust power supply voltage to 18V and measure the load voltage V_0

V_0	I_{sc} / I_N(measured)	I_{sc} / I_N (calculated)	R_N (measured)	R_N(calculated)	V_0 (Thevenin circuit)	V_0 (calculated)

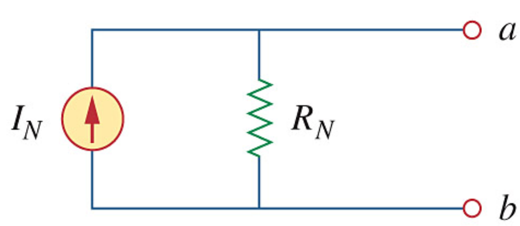
3. Replace the load resistance R_0 by a short circuit and measure the short circuit current I_{SC}.

4. Calculate the short circuit current I_{SC}

5. Kill the independent voltage source and measure the Norton equivalent resistance R_N

6. Calculate the Norton equivalent resistance R_N.

7. Draw the Norton's equivalent circuit.



8. Add the load resistor R_0 to the equivalent circuit and calculate the load voltage V_0.

9. Use sources transformation to replace the Norton equivalent circuit by a voltage in series with R_N

10. Add the load resistor R_0 to the transformed circuit and measure the load voltage V_0.

11. Is Norton's theorem verified?