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The Homemade Alternative: Teaching Human Neurophysiology with Instrumentation Made (Almost) from Scratch

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Recording human neurophysiological data in the teaching laboratory generally requires expensive instrumentation. From our experience in developing inexpensive equipment used in teaching neurophysiology laboratory exercises, we offer a strategy for the development of affordable and safe recording of human neurophysiological parameters. There are many resources available to guide the design and construction of electronic equipment that will record human biopotentials. An important consideration is subject safety, and the electrical characteristics of any equipment must meet strict galvanic isolation standards. Wireless data gathering offers the most complete isolation from 120VAC current. As an example, we present a homemade electrocardiogram recording circuit using only inexpensive and readily available components. We outline the feasibility of constructing equipment that meets the needs of the student laboratory for good data collection, and we consider the obstacles likely to be encountered in these projects. If students actively participate in the equipment design and construction, the process can also be a teaching tool. Students may gain a deeper understanding of the human neurobiology by making the electronic data acquisition and its presentation more transparent.

Key words: human neurophysiology; electrocardiogram; teaching laboratories, laboratory equipment

INTRODUCTION

Those of us fortunate enough to have sufficient resources at our disposal to purchase laboratory instrumentation and data acquisition and analysis software for undergraduate neuroscience laboratories sometimes forget that this is not the case for most college and high school instructors. One of us (S.H.) is reminded of our good fortune each summer when teaching a Howard Hughes Medical Institute (HHMI) sponsored outreach program designed for Maine high school biology teachers and students. These teachers often have budgets of less than $1000 for all their courses for a full year. Instructors at many public universities and community colleges also face financial squeezes that can restrict the experience of students in the physiology teaching laboratory.

We are actively working to make college laboratory neuroscience more affordable. We and our colleagues have developed laboratory exercises using inexpensive invertebrate preparations, and even a plant, to demonstrate basic principles of cellular and systems neuroscience (Wyttenbach et al., 2002; Johnson et al., 2002a, 2002b). In addition, we have designed inexpensive instrumentation to gather data from these preparations (Land et al., 2001, 2004; Johnson et al., 2007), and software to capture and analyze these data (Lott et al., 2009).

We have recently applied our efforts to the development of student laboratory exercises in human neurophysiology, and inexpensive ways to accomplish these exercises. Students at Bowdoin College and Cornell University often show interest in many different types of exercises that focus on human neurophysiological and psychological parameters. For example, laboratory exercises in human neurophysiology are among the most popular in the following courses at Bowdoin. In our Comparative Physiology course the human cardiovascular unit, in which students design an experiment around some variable that they believe will alter human cardiovascular function, is always greeted and executed with enthusiasm, and this exercise scores highly on student course evaluations. In our introductory neurobiology course, the unit on visual psychophysics, in which students design an experiment around one of the visual illusions on the Psy-Cog CD-ROM (Wyttenbach, 2006; Wyttenbach, 2012, this volume) using classmates as their subjects, is also popular. This exercise serves as an introduction not only to visual perception, but also to the use of statistics to analyze data based on larger subject sample sizes. We have recently introduced a "Lie Detector" laboratory exercise, used in both the HHMI outreach workshop and in the Bowdoin introductory neurobiology course which measures electrodermal responses to emotional changes with galvanic skin response amplifiers. We also use variants of the *Gymnema* gustatory experiment (Shroeder and Flannery-Scroeder, 2005) as an introduction to the senses in our introductory biology and our core Neurobiology courses.

To record human neurophysiological parameters like the galvanic skin responses (GSRs), electrocardiograms (ECGs), electromyograms (EMGs), electro-oculograms (EOGs), and electroencephalograms (EEGs), expensive data acquisition systems are often required, in addition to transducers, amplifiers, and computers (Colgan, 2012, this volume). Presently, this is an expensive proposition, and the cost can discourage faculty from offering any human neurophysiological recording in their undergraduate lab courses. In community colleges this may be even more of a problem. For example, in our experience the physiology in Human Anatomy and Physiology courses in community

colleges that prepare medical professionals (e.g., nurses and medical technicians) is often given far less emphasis than the anatomy in the laboratory sections. Again, this is at least in part due to the expense of neurophysiological data collection and analysis.

Our teaching development efforts have not previously extended to human physiology for a number of reasons. First, we are instructors who have primarily used invertebrate preparations for laboratory teaching. We tell our students that these model systems with "simpler" nervous systems allow an understanding of basic nervous system properties like cell excitability and neuronal communication in all animals, including humans. That has been our focus in neuroscience laboratory teaching. Second, in addition to the expense of human recording equipment, we have been intimidated by the rigorous safety protection that must be seriously considered when designing data collection tools to be used on human subjects.

Student interest in human neurobiology and our experience (S.H. has an extensive background in human biology and has taught non-majors courses in human physiology) encourages us to develop human laboratory exercises and the means to accomplish them. Relatively recent developments in technology such as the proliferation of inexpensive microcontrollers like the Arduino microcontroller board (http://www.arduino.cc;

http://en.wikipedia.org/wiki/List_of_Arduino_compatibles contains descriptions of most of the Arduino-compatible microprocessor boards currently available) has made data collection from sensors of all types affordable. Their use in biological teaching applications has been limited so far (but see Otto et al., 2011), but is technically possible. Combined with the available resources for homemade transducers, amplifiers, and other instrumentation, microprocessors as analog/digital interfaces can make the recording of many human physiological parameters financially feasible. Simultaneously, wireless technology has become widely available and affordable so that the human electrical safety problem is solved.   By using wireless connections between instrumentation and computers, human subjects can be completely isolated from 120VAC power lines.

FROM CRICKETS TO ELECTROCARDIOGRAMS: THE PATH

We have been working on several strategies to bring human neurophysiological recordings to our classes. One is to adapt techniques developed primarily for invertebrate neurophysiology exercises for human use. For example, our gPrime software (Lott et al., 2009), developed for data acquisition and analysis from *Crawdad* preparations (Wyttenbach et al., 1999) uses the sound card of Windows
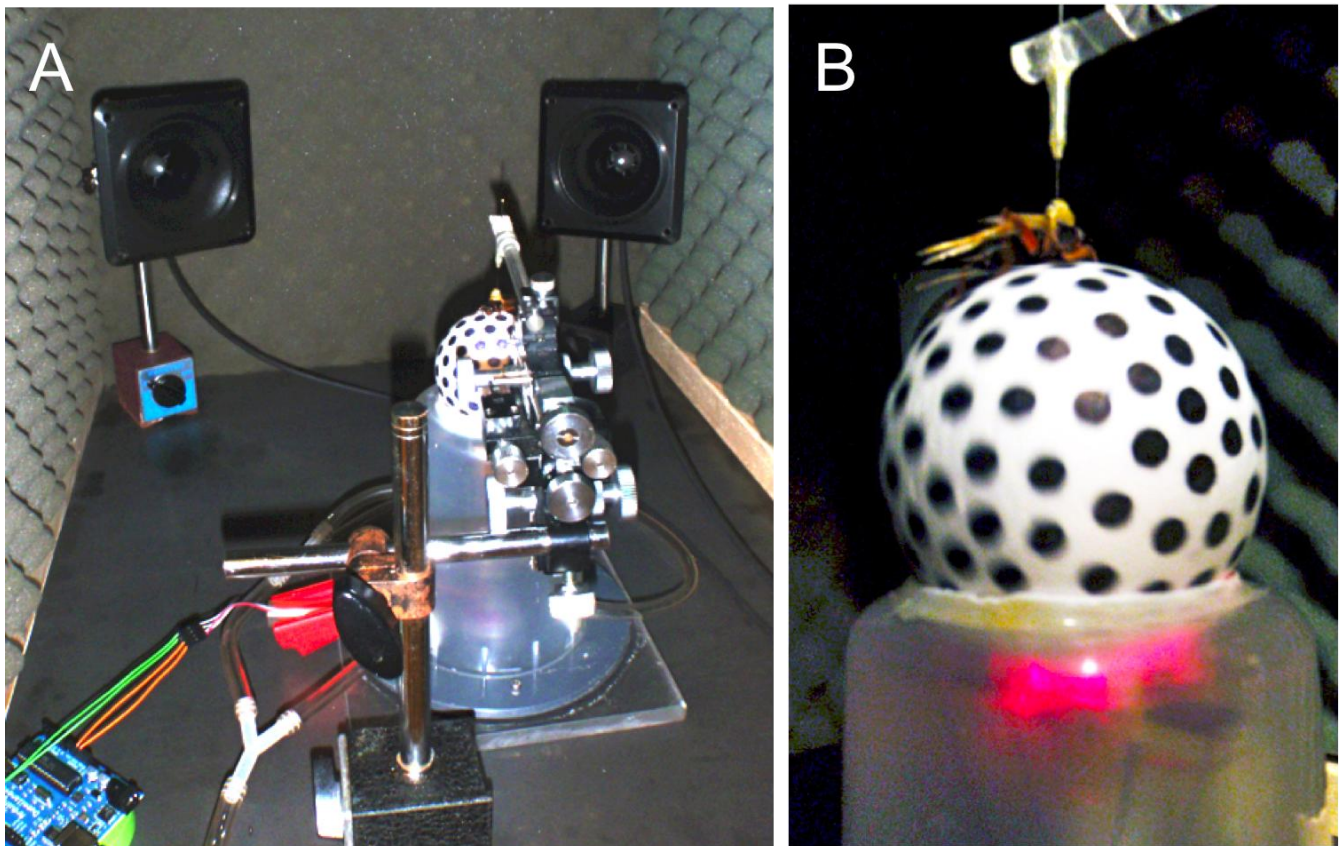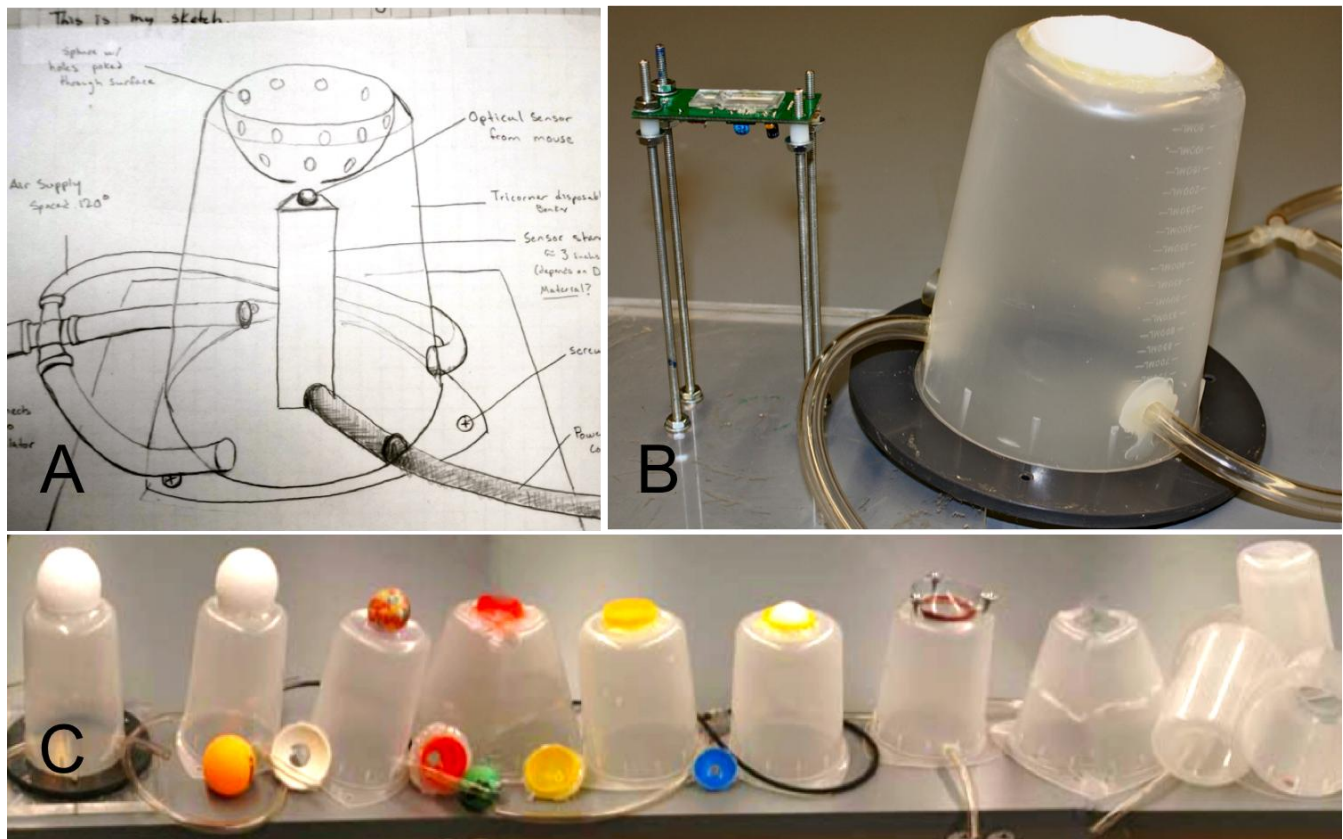

Figure 1. The completed cricket locomotion tracker chamber. *A.* The interior. *B.* A cricket running on the suspended ball.

Figure 2. Development of the motion sensor platform for a cricket locomotion tracker. *A.* Katie Du Bois's initial design sketch. *B.* The completed platform, showing the motion sensor board supported on threaded rods, and the cover constructed from a tri-corner disposable beaker. *C.* A series of platform prototypes.

computers as an A/D converter to record extracellular record human EMGs and ECGs since these have electrical characteristics similar to extracellular nerve recordings.

There are limitations though. The computer sound card is designed to operate in the range of human hearing, from 20Hz to 20kHz. Thus EEG waves, some frequency components of an ECG, like the T wave, and the EOG may be of too low frequency to be accurately reproduced by the computer sound card. There are also safety issues with the transmission of data from powered devices that we will discuss later.
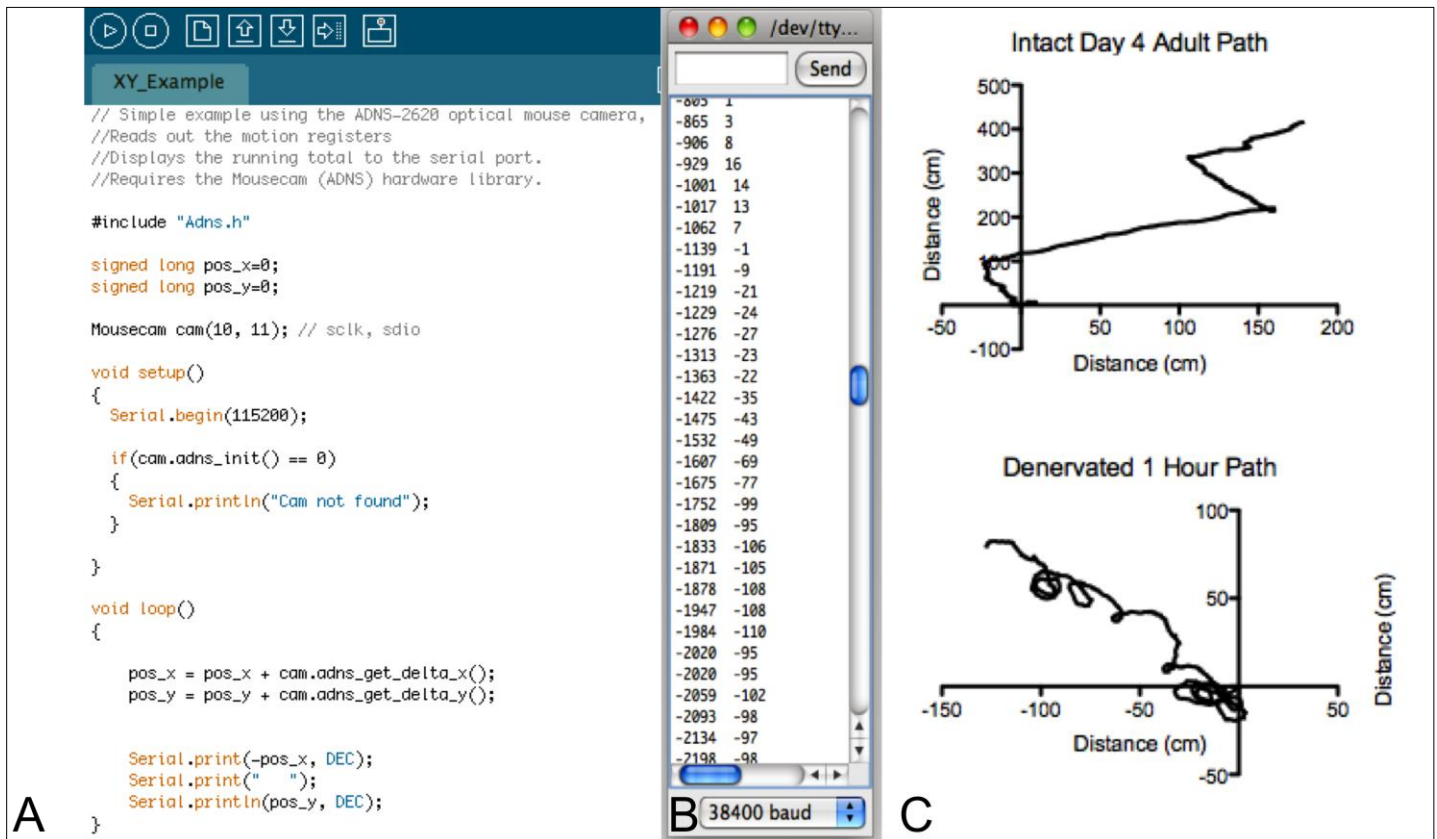
Another approach is to explore widely available resources to build the equipment yourself and develop software from scratch. We (S.H. and K.D.) started our path to developing human neuro equipment in a fairly unlikely way. K.D.'s undergraduate honors research at Bowdoin College required the design and construction of a locomotion tracker (Fig. 1) to record phontactic responses of crickets. We used nothing but inexpensive and widely available parts from hardware and general merchandise stores, and based our tracker around a motion sensor designed for a computer mouse and an Arduino microcontroller.

When we began the process, we looked at a number of published papers with guidelines for building a cricket locomotion tracker. Katie was working on an eight-week summer fellowship and we did not have the time or budget

to build any of these systems. Some provided a degree of precision that was not necessary for Katie's work. Necessity became the mother of invention, and we started looking at the individual components required, and tried to come up with alternatives that could be constructed quickly and cheaply. Many solutions came easily (see the finished project in Fig. 1), but the actual platform housing the motion sensor and the cricket ball itself required more ingenuity.

Starting from her rough design sketch (Fig. 2A) Katie was particularly inventive in the design of the motion sensor and cricket ball assembly. We ended up using a tri-cornered disposable 1000ml beaker as the platform, with half of a plastic baseball (with a large hole cut into it for the passage of air) holding the Styrofoam ball itself (obtained from a fabric store). The ball was modified with black marker polka dots that could be tracked by the motion sensor. We obtained the motion sensor board as a kit (Mouse Eye: www.rachelselectronics.com), and we soldered it all together in less than an hour. The building's compressed air supply served as our air source, and Tygon tubing delivered the air at the base of the platform. We used threaded rods (from a hardware store) tapped into plexiglass as the adjustable platform for the motion sensor board itself.

By adjusting the height of the motion sensor board on the threaded rods (see Fig 2B), we were able to place the

Figure 3. The cricket locomotion tracker display and graphs. *A.* The Arduino sketch for data acquisition and display. *B.* The serial port readout. *C.* Movement graphs created from the distance data.

sensor the required 2mm from the spinning ball to produce accurate distance measurements. There was a lot of trial and error required to find the proper size cup that would hold the ball at the correct distance from the motion sensor, and the size and shape of the hole that allowed the exact amount and flow of the air that suspended the ball (Fig 2C).   An inexpensive Arduino microcontroller and previously written software routines for signal acquisition and graphing were used for data acquisition and presentation (Fig. 3). We obtained very precise data with this homemade unit that took about a week to construct and cost less than $100. Some parts, like the magnetic stands that supported the speakers and the micromanipulator that adjusted the position of the cricket on the ball, were scavenged from the lab. They would cost more if purchased, although inexpensive alternatives are possible for these components as well.

Our design and construction of the locomotion tracker is an example of our approach to inexpensive human physiology data acquisition.   Many of the tracker's components could be modified or replaced for human neurophysiology data recording. For example, the motion sensor could be replaced by human physiology sensors and an amplifier.   The Arduino board's direct serial connection to the computer could be replaced with a wireless Bluetooth connection.   Bluetooth components designed for the Arduino IDE are inexpensive and widely available, as they are used in robotics applications. The

Arduino data acquisition and display software can be modified for human physiological data collection and analysis.   The cricket software tracks XY coordinates in space (Fig. 3C). These X and Y inputs could be replaced by time and voltage, turning the distance and direction display into a simple oscilloscope.

Both in print and online, there are many plans for transducers, amplifiers, and microcontroller circuits that are suitable for human neurophysiological recording. There are also simplified software languages, such as "Processing," the language most Arduino software relies on, that allow non-programmers to use a more intuitive syntax and plug-in libraries to create sophisticated applications.   The technical aspects may seem daunting at first; but, as we discovered in the process of building the cricket motion tracker, the necessary skills are often easily learned and many solutions become apparent when the project is broken down into smaller functional modules.

For those preferring not to start from scratch, there are a limited number of inexpensive kits designed for recording specific human physiological parameters. For example, shields which include a digital amplifier and software routines for data analysis and display come ready to be snapped onto an Arduino board for recording data like electrocardiograms (see http://www.olimex.com/dev/shield-ekg-emg.html).   They require only transducers and a Bluetooth connection for successful recordings. There are also ready-to-use oscilloscope programs for both personal
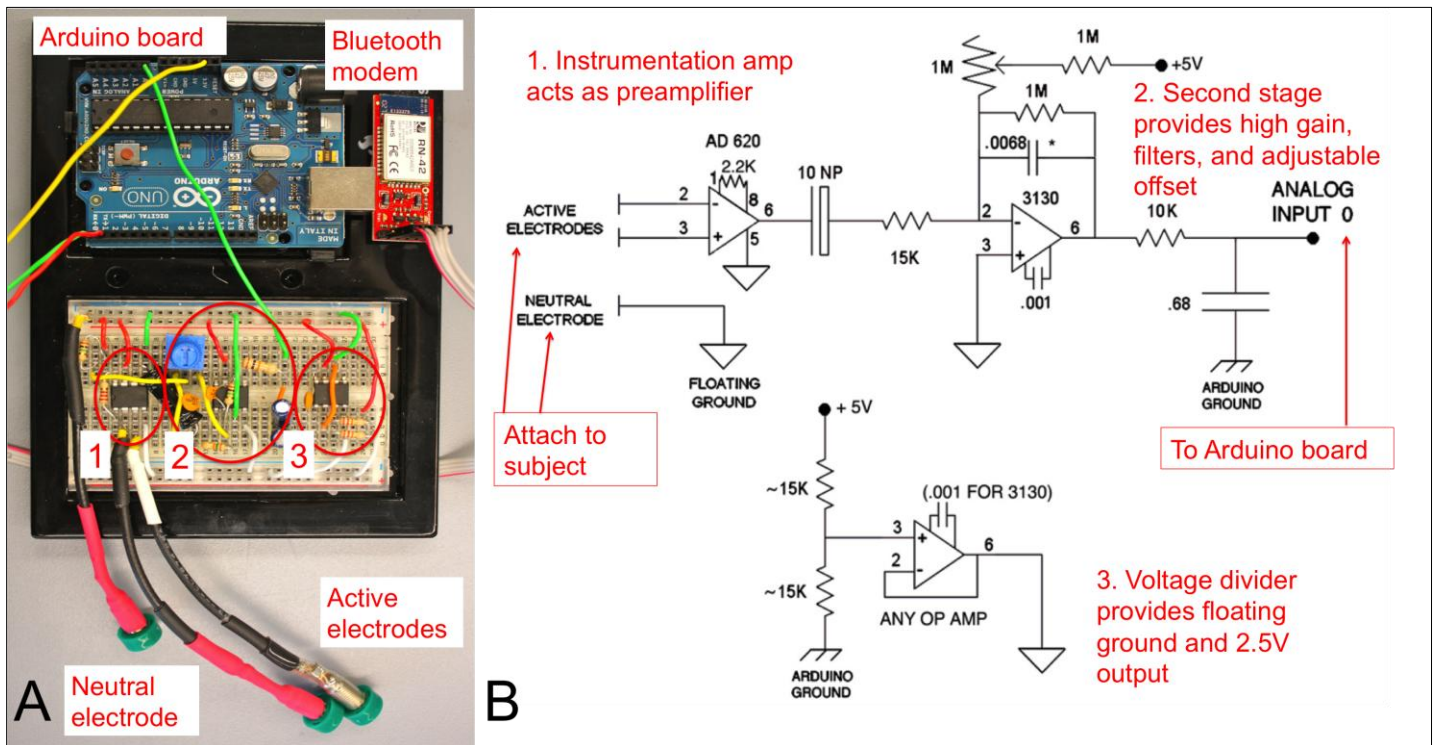
Figure 4. A. Example of an electrocardiogram circuit wired to an Arduino microprocessor board and Bluetooth transmitter (numbers correspond to the labeled modules on the schematic). B. The original schematic the ECG circuit was based on, with red annotations describing the functions of the three amplifier stages. Power source is not shown. The amplifier may be powered by the computer's USB connection (if using a battery-powered laptop) or by 4.5-6VDC batteries (wireless connection). The original schematic can be found at https://sites.google.com/site/chipstein/.

computers and mobile devices (see example below).

It is often simplest to use commercially prepared transducer cables because they are the most inexpensive components. However, they are also fairly easily reproduced; they consist of nothing more than a connector to the amplifier, shielded cable, and connectors (often metal snaps) to the transducers themselves. The cables and connectors can be constructed from components purchased from electronics suppliers (e.g., Mouser, DigiKey, or even Radio Shack), and the appropriate disposable electrodes are available inexpensively from medical equipment suppliers.

THE BUILDING BLOCKS
The skills required to design and construct the instrumentation and develop the software for human recordings can be daunting. However, there are good resources available to help anyone choose the hardware components, put them together and start recording. Using a basic electrocardiogram recording as an example, we outline the development of an inexpensive piece of recording equipment for human neurophysiology.

The Electrocardiogram Circuit
We based the design of our ECG amplifier on a simple circuit found online (see https://sites.google.com/site/chipstein/ for the EEG circuit that was used as inspiration for the ECG circuit described). Nearly all

electronic circuits begin on a breadboard, and breadboarding is an essential skill for anyone interested in designing circuits. Breadboarding tutorials can be found in books for electronics hobbyists, and there are many guides available online.

By taking a modular approach to reading schematic diagrams, what seems to be a complex instrument can be broken down into functional units, each of which can be built and tested simply, and the modules then wired together. The parts for any ECG circuit include a preamplifier (based around an instrumentation amp IC, appropriate filters that pass the desired signal while restricting unwanted electrical noise and interference, and an adjustable voltage offset circuit to convert the signal to the required voltage input of the A/D converter. There is often a second amplification stage as well. As originally designed, the amplifier was powered by the Arduino board itself (from the computer's USB connection), but batteries can power it as easily if a wireless connection to the computer is used for human safety. The fact that this amplifier was only modified slightly from the EEG circuit in the original source (a smaller gain was configured on the instrumentation amp) illustrates that the amplifiers necessary to record various human biopotential parameters are very similar electronically. Apart from the more traditional print sources, there are many amplifier circuits available online, some documented more helpfully than others, some quite complex and others surprisingly

simple. Specific circuits are widely available for GSR, EMG, EOG, and EEG amplifiers. A search engine with a phrase like "electrocardiogram circuits" returns many pages of text and image results. The constraints of a specific design will limit the choices. For example, the Arduino board must receive a signal between 0 and 5 volts, and it is important to choose or modify a design so that it accommodates this requirement.

Once the breadboard ECG circuit is completed (Fig. 4), it can be tested by using a battery-powered (for safety) hardware oscilloscope. An oscilloscope would display any human biopotential without the need for an A/D converter to test the amplifier circuit before completing the other components. The functional circuit can be transferred to a prototyping shield that fits directly onto an Arduino board or a faster microcontroller board. Breadboard prototypes that test well can be made permanent using printed circuit boards (PCBs) manufactured by services that will design PCBs based on breadboard schematics. Circuits on PCBs can be housed in readily available enclosures that can be fitted with the necessary connectors for transducers. There are even enclosures sold specifically for an Arduino board and an accompanying shield (see http://www.sparkfun.com/products/10088 for an example).

The Microcontroller

Once the amplifier circuit is functional, A/D conversion is needed for signal display, analysis and storage. The choice of the microcontroller board to do this is practically as wide open as the choice of amplifier circuits. In our ECG example, a basic Arduino board was used (Fig 4). The Arduino family of boards is diverse and has by far the most comprehensive documentation. Descriptions and tutorials are available at www.arduino.cc, and the hardware is sold by a variety of retailers referenced at the Arduino site. Since the Arduino platform is Open Source, there are also clones and modifications of the original boards. The sampling rate of the 16MHz 8-bit Arduino board is slower than most commercial A/D converters, and is not suitable for the fast signals seen in extracellular nerve recording, but it is fast enough for recording most human neurophysiological parameters. Newer 32-bit Arduino-compatible microprocessors (as examples, see http://www.digilentinc.com/Products/Detail.cfm?Prod=CHIP KIT-MAX32 and http://leaflabs.com/devices/maple) increase the sampling rate and can be substituted for the original Arduino board.

Galvanic Isolation from 120VAC

It is important to remember that it is absolutely essential that human subjects are completely isolated from 120VAC power. Even well isolated AC grounds can malfunction, resulting in a potentially lethal electric shock, especially when recording ECGs across the heart. The amplifier and the recording computer should not receive power from the AC mains. Commercial recording devices use medical grade isolation circuits. Opto-isolation is conceptually quite simple, and isolation circuits can be easily designed and constructed. Though these circuits can provide safe isolation, when amateurs are constructing the equipment, there is always the chance of tragic error.

There are two acceptable options for isolation when constructing equipment for human recordings. One is to have all parts of the recording and display components use battery power. DC adapters are not acceptable. While not dangerous like a building's AC supply, a computer battery could conceivably (though very unlikely) deliver a non-dangerous but uncomfortable shock.

If using the sound card option to record data, the all-battery solution is the only isolation option. This is unfortunate because sound editing programs like Audacity can act as effective displays of biological signals. All that is necessary is to get the signal into the sound card of a computer, as we have done at Cornell with extracellular nerve recordings, and either dedicated software like gPrime or Spikehound (an updated modification of gPrime; see http://spikehound.sourceforge.net/), or a sound program like the free Audacity. Sound editing software can display the signal and offer both time and amplitude analysis solutions. It is important for the life of the sound card to make sure that the signal voltage is not greater than the card can handle. There are inexpensive USB audio converters that could be used instead to deliver the signal to the software (for example, the Behringer UCA202), ensuring that the computer receives an appropriate voltage. An advantage to using the computer's sound card as the A/D converter is that it eliminates the need for an external microprocessor like the Arduino board.

Wireless solutions for data gathering and transmission avoid even the chance of a low current DC shock from a battery-powered laptop. There are currently no practical ways to effectively deliver a wireless ECG signal to the computer's sound card. However, there are both radio frequency (RF) and Bluetooth options for wireless delivery of signals from the Arduino board to the computer (see http://arduino.cc/en/Guide/ArduinoBT for an example of an Arduino board adapted for Bluetooth communication). In our ECG example, the Bluesmirf transmitter (manufactured and sold by Sparkfun Electronics; see http://www.sparkfun.com/products/10269 for a description) was used. Configuring Bluetooth connections adds a complicating aspect to a successful recording solution. Setting up a Bluetooth connection can be challenging, but the software routines and tutorials available online from the Arduino community make this substantially simpler. Once the recording software can find the Bluetooth transmitter and receive data, Bluetooth offers a wireless solution free of the interference that can plague radio frequency transmission. Getting to that point can be tricky because the procedure is quite specific to the computing platform, its operating system version, the specific microcontroller, and the display software. However, the configuration of all Bluetooth connections follows the same functional steps. A transmitter that can be used with the specific microcontroller is wired to the correct ports on the microcontroller board (these instructions should come with the Bluetooth modem). With the Bluetooth modem powered on, the computer is then configured to find and pair with the device using a designated pairing code. The

transmitter is assigned a port and the ECG display software configured to look for the transmitter on that specific serial port. There are instructions available for all computer platforms, and specific modems and microcontrollers. As examples, Bluesmirf guides can be found for Windows 7 at http://www.otherrobots.com/Tutorials/BluetoothModemBlueSMiRFSetup/tabid/60/Default.aspx, and a Macintosh OSX guide for the Bluesmirf can be found at http://www.whizzosoftware.com/forums/blog/1/entry-48-bluesmirf-silver-bluetooth-modem-and-mac-os-x/.

Note that in either of these isolation solutions (sound card or Bluetooth), the subject is not isolated from the current used to power the ECG amplifier itself. The voltage supply for the amplifier consists of household batteries (somewhere between 4.5V and 9V depending on the design), and the current the subject is potentially exposed to is negligible.

Computer Display and Analysis
The Arduino IDE uses a Processing-based language for the board itself; display and analysis routines can be written in Processing, C++, Python, Matlab, or LabView. A simple starting point for displaying human data, and doing some basic data analysis is to use existing oscilloscope programs. We used a software oscilloscope designed for the Macintosh platform (Fig 5) called Macduinoscope (see https://sites.google.com/site/davidbuzz/macduinoscope for a history of the development of this scope, as well as download links) on the Macintosh, and a LabView based (but standalone) oscilloscope program called SimpleGraph for the Windows platform. Macduinoscope samples data very quickly, but is specific to certain Arduino boards and software versions. SimpleGraph is sponsored by Angstrom Designs, and there are very detailed instructions for the application at the company website (http://www.angstromdesigns.com/software/faq/58-labview-arduino-driver-larva). It works with several versions of Windows, and recognizes many Arduino boards. As executed, the program receives data fairly slowly (but quickly enough for an ECG), and the analysis procedures are limited. LabView users can modify the program for enhanced capabilities. SimpleGraph could be developed into a program that would run on a Macintosh or Linux computer. An appealing aspect of using this program is that it is not necessary to do any software coding at all because the microcontroller instructions are uploaded as scopes allow time and amplitude measurements. There firmware to the microcontroller board during the installation process. Figure 5 displays triggered samples of the wireless signal from the ECG amplifier we constructed, displayed on the Macduinoscope and SimpleGraph. While the analysis is rudimentary on both, even these simple are some dedicated ECG display and analysis programs often requiring additional software like Matlab or LabView, and individuals proficient in these platforms may be able to design their own biopotential recording software. However, these programs are quite expensive. One free software option specifically designed to record human biopotentials is Electric Guru (http://www.realization.org/page/topics/electric_guru.htm), which operates only on the Windows platform. There are more free Open Source programs designed specifically for recording EEGs (see http://openeeg.sourceforge.net/doc/sw/ for some examples collected by the OpenEEG project).
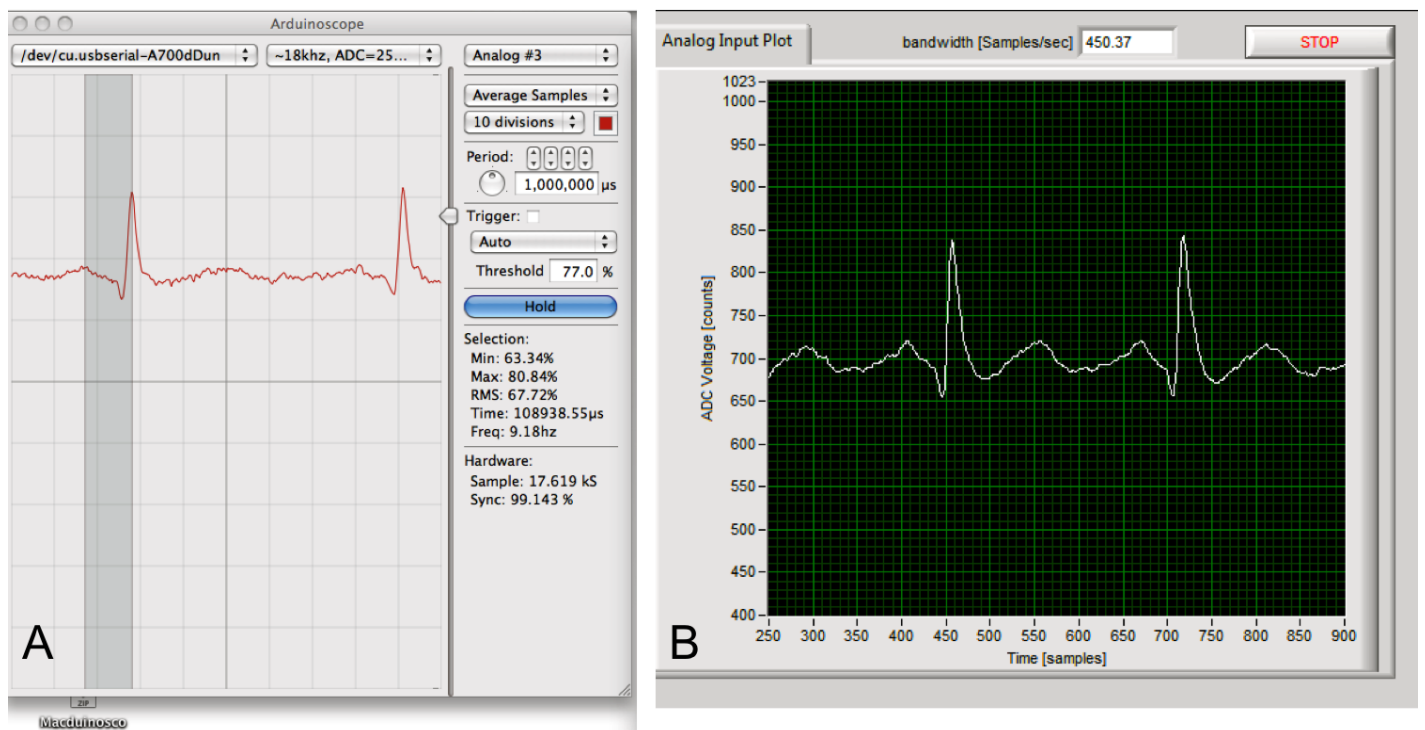

Figure 5. Human ECG samples obtained by wireless Blutooth connection displayed on two software oscilloscopes. *A.* Macduinoscope display for the Macintosh. *B.* SimpleGraph display in Windows Vista.

CONCLUSION

None of our solutions have all the capabilities of a commercial data acquisition system. Faculty also may need to have departmental or institutional permission to carry our human neurophysiology exercises. Instructors deciding to build their own equipment do need a certain technical comfort level. The journey from rough devices and computer applications to hardware and software that can be used in a teaching lab can be challenging and quite rewarding.

The goal doesn't necessarily have to be a lab full of devices that can be used in traditional lab exercises. The design and construction process itself can be the pedagogical focus. A course could be designed around the construction of physiological recording systems, with students using the finished project for actual recordings. Courses such as these are offered as part of many engineering programs, and biology students might get a deeper appreciation of the biological processes by understanding more about the instrumentation used to record them.

Print and online resources for all of the individual building blocks are plentiful. A more complete annotated list of resources is available at http://www.bowdoin.edu/~shauptma/resources/humanneurophysiology/.

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