Work-in-Progress: A modular course on sensors, instrumentation and measurement: Supporting a diversity of learners' agency of self-direction

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Linda Vanasupa has been a professor of materials engineering at the California Polytechnic State University since 1991. She is currently a visiting professor of materials engineering at Olin College. Her life's work is focused on creating ways of learning, living and being that are alternatives to the industrial era solutions–alternatives that nourish ourselves, one another and the places in which we live. Her Ph.D. and M.S. degrees are in materials science and engineering from Stanford University and her B.S. degree in metallurgical engineering from the Michigan Technological University.

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Abstract

Introductory courses in circuits can be challenging for some because it requires the learner to connect the concept of invisible electron motion to voltage measurements. This 10-module course was designed to be a fun way of learning about authentic, relatable circuit applications. It uses the voltage divider as a basic instrumentation circuit for sensors and advances to filtering, feedback, and amplification circuits using operational and instrumentation amplifiers. During the course, students use breadboards and circuit components to design, build and test circuits that measure: temperature, weight, relative humidity, their heartbeat, their blood pressure, and distance by ultrasonic echo-location. By the end of the course, students are able to: apply Kirchhoff's laws and Ohm's law to the design of amplifiers, low-pass, high-pass, and band-pass filters/amplifiers; measure the frequency response of a filtering circuit using a Bode plot; create a calibration curve (or transfer function) for a sensing circuit; use computational tools to analyze data and transform measured data; and troubleshoot an instrumentation circuit. A feature of the course is that it is designed to support self-directed learning for a diversity of learners, with an aim to strengthen their sense of mastery and agency. The design elements include: Textbook; video lectures; instructions that incorporate recommended current practices for neuro-diversity, instructional design, and visual navigation. The materials have been piloted and refined over a period of 7 years with approximately 500 students. Course materials can be downloaded at no cost; future development includes low-cost, supporting hardware. The course was rated a positive experience (39/74) approximately twice as frequently than it was rated either negative (3/74) or not rated (14/74) by first year students in the Fall 2019 offering of the course (85 students) at a small residential engineering college. There was no statistically significant difference in the responses by groups of female (40/74), male (29/74) or transgender/non-identified (5/74) student groups. This paper describes the design elements of the course and modules and a data set that illustrates the design supports students' use of multiple learning resources.

Introduction

A course on electronic circuits is common in engineering programs. It is often a challenging one for novices because it relies on the abstract ideas of electron motion, charge build-up reflected in voltage, and time-dependent responses. While sensing, instrumentation, and measurement are common activities in engineering, introductory circuits courses often focus on concepts and analytical approaches to circuit function. For example, the edX course on electrical circuits lists as learning objectives: designing and analyzing circuits; lumped circuit models and abstraction; construction of simple digital gates; and measurement of circuit variables [1]. This paper is about a course designed to enable the novice learner to begin using foundational understanding to design simple instrumentation circuits that can sense and measure physical phenomena that are concrete to the novice learner, such as angle, weight, temperature, relative humidity, distance, and one's own heartbeat, pulse, and blood pressure. After completing the modules, students are given an opportunity to design a final project involving sensing, measurement, and instrumentation. As a first-semester, first-year college course, we have also incorporated a number of design elements that foster success for novices of a diversity of learning styles and for those who are in the process of adjusting to all the newness of college life. We first explain the course design and then describe the data on student responses to the course in Fall 2019.

Module Design

The 10 modules were designed by Brian Storey and Bradley Minch, each as a two-part activity for first-year engineering students: 1. A problem set (p-set), where students primarily compute results to learn the concepts; 2. A laboratory (lab), where students build a measurement circuit and collect performance data. The overall course learning outcome is to demonstrate the ability to design, build, and test sensing and measurement instrumentation circuits that use resistors, capacitors, op-amps, and sensors.

Specifically, by the end of the course, the student will be able to:

- Use a voltage divider to create a sensing circuit;
- Produce a Bode plot and explain the frequency response of a circuit;
- Design low-pass, high-pass, and band-pass filters/amplifiers;
- Analyze data and transform measured data;
- Troubleshoot a circuit.

The equipment needed to conduct that labs and some of the p-sets include a computer, an Analog Discovery 2 (Digilent, https://store.digilentinc.com/), and 5V power supply circuit board, powered by a USB port of students' laptop computers. The power supply was designed by Bradley Minch (plans and materials list found at https://pages.olin.edu/isim). Students learn to use an oscilloscope, a function generator, and a network analyzer using the Analog Discovery software. The modules are presented in approximate order of increasing complexity. Over the course of the semester, students develop the understanding, skills and knowledge to achieve the course learning outcomes. Table 1 below lists the topics of the modules and the associated learning goals.

Table 1. A list of the module topics and their learning goals.

Module	Topics	Learning goal(s)
1	A simple pendulum (lab)	Measure the change in pendulum angle with time using a potentiometer as a position sensor; solder components onto a printed circuit board that serves as a 5V and 2.5 V power supply.
	Resistors in series and parallel (p-set)	Use a breadboard and resistors to measure how the resistance changes when resistors are connected in series and in parallel
2	Monitoring temperature (lab)	Use a thermistor to monitor the changes in temperature in a cooling liquid.
	Resistors in series and parallel 2 (p-set)	Learn how the total resistance changes when resistors are wired in series and in parallel.
3	Measuring mass using a strain gauge	Measure mass using a special voltage divider (*Wheatstone bridge*), an instrumentation amplifier and a strain gauge
	Capacitors and RC circuits (p-set)	Observe how capacitors respond to direct current voltage inputs and an alternating current voltage square wave input

4	Using capacitors to measure humidity	Build a circuit to sense and compute relative humidity by measuring capacitance.
	RC Circuits as filters – FFTs and the Bode plot (p-set)	Build and characterize filtering behavior of two different filtering circuits at a range of frequencies.
5	Electrocardiograph	Use filters and amplifiers to build a circuit that will sense and measure a heartbeat
	Filters in cascade (p-set)	See how filters work when cascaded and behave at their limits; learn how to design the filters to that they function independent of one another
6	Blood Pressure	Design and test a band-pass filter that can isolate a blood pressure signal
	Op Amps (p-set)	Experience how the operational amplifier functions and how it can be used to get more accurate voltage measurements.
7	Controlling current with op amps	Configure an op amp as a buffer; Use negative feedback around an op amp to create a current source.
	Foundational op-amp circuits (p-set)	Learn how op amps can be used to perform mathematical operations on their inputs.
8	Pulse measurement with light oximeter	Design a (pseudo) pulse oximeter using a photodiode, filters and op amps.
	Complex numbers (p-set)	Become familiar with mathematical operations with complex numbers; see how complex numbers can be used to show the frequency response of an RC circuit.
9	Ballistocardiograph	Build and test a ballistocardiograph from strain gauges, op amps and second-order roll-off filters.
	Analysis of filters with complex impedance (p-set)	Use impedance to derive the form of op-amp circuits that function as amplifiers and filters
10	Ultrasonic range finder	Design, build and test an ultrasonic range finder.

Course Context and Design

This course is delivered at the Franklin W. Olin College of Engineering ("Olin") to ~80-100 incoming engineering students in their first semester by a team of four instructors. It is one of four courses that each student takes in their first semester. Olin is an undergraduate residential college with 100% of traditionally-aged students (18-24) living in on-campus dorms. The college community identifies as a learning community, "bound by a vibrant culture of innovation and a vision to change engineering education to make it a fun, engaging, meaningful and powerful experience." [2] A typical demographic for Olin is roughly half who identify as female and half as male (about 5-10% of Olin students identify as transgender or gender non-conforming). Students are assigned to one of four sections of 25 or fewer students and two instructors. The course is designed with a "learn-by-doing" approach, emphasizing experiential learning. The weekly face-to-face times are two, 100-minute sessions. These sessions begin with a brief demonstration (~5-10 minutes) followed by largely unstructured time to allow students to complete the modules at their own pace. Faculty create a culture of collaborative learning, encouraging students to work together, yet asking them to each build their own circuits, and turn in their own work in the form of p-set responses and laboratory reports. The course is offered for Credit or No Record. Credit is earned by completing most p-sets and laboratories. The quality of the submissions is allowed to vary from "developing" in the initial weeks to what is deemed as "proficient" in the later weeks of the semester.

Course resources that are provided to the students at no additional cost are: A textbook (Storey); The laboratory instructions; Instructional videos (Storey and Minch); two faculty per section and peer coaches -, Analog Discovery 2, MATLAB® software, breadboards and all circuit elements and sensors needed for the course. The instructional materials can be accessed at Storey's course website: http://isim.olin.edu/index.shtml. The facility consists of a room with laboratory tables sufficient so that each student can have their own work area, Figure 1, below. However, the p-sets were conducted in a classroom that had shared tables (accommodating up to eight students per table).

Figure 1. The laboratory classroom contains workbenches for each student, but students are encouraged to collaborate. From left to right, Walter, Linda (corresponding author) and Ivonne.

Instructional Materials Design

As mentioned, there are three types of instructional materials that we provide: textbook, videos, and instructions. Below is a brief description of each.

The textbook (Storey) is a succinct description of the concepts covered in the modules, focused on the concepts in order of their occurrence in the course.

The video content, available on YouTube® (links at), contains a guide on soldering the power supply designed by Minch and a series of lectures to accompany the textbook by Storey.

The instructions, co-authored by Storey and Vanasupa, are designed to reach students of different learning styles and facilitate self-directed agency in learning. The design elements and effectiveness of these instructions is analyzed are discussed elsewhere [3]. In short, each contains a visual overview, a statement of goals and objectives, and references to something meaningful or concrete. These elements were included to aid a neurodiversity of learners [4, 5]. The instructions also contained step-by-step instructions interspersed with points of reflection to aid students' development in a sociocultural setting of peer-to-peer learning [7].

Student Response to Course – Fall 2019

Vanasupa conducted a study to understand the use of course materials by students. After receiving Institutional Review Board approval, a survey was distributed to the Fall 2019 cohort of students in the sensing, instrumentation and measurements course after they completed the tenth module. This demographic (74 respondents of 85 enrolled) consisted of 40 individuals who self-identified as female, 29 as male and 5 as transgender/non-binary or non-identified. The proportions who indicated their pre-college circuit experience are shown in Figure 2. Sixty one of the respondents received their pre-college education in the United States, five were educated in multiple countries. A chi-squared test of proportions reveals that there was no statistically-significant difference in the self-reported pre-college circuit experience between the three groups who self-identified as female (37), male (22) or non-binary/transgender or non-identified (5). (p=0.496). The data excludes 7 females and 7 males who did not respond to this question.

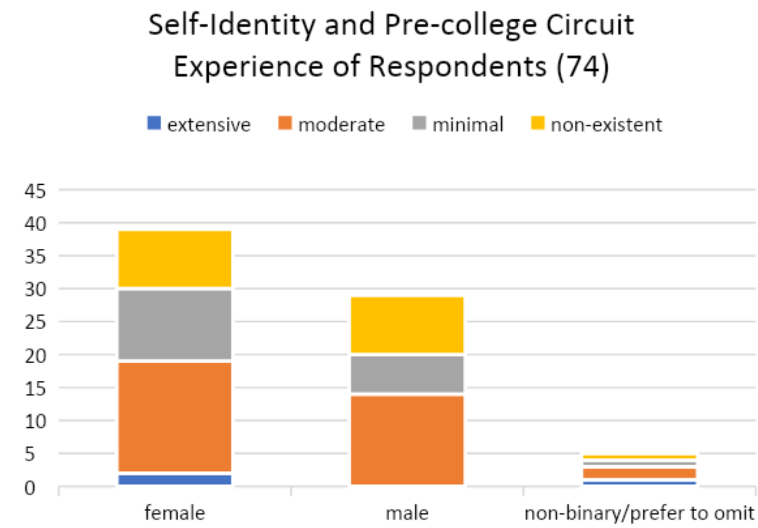

Figure 2. Self-identity and self-reported pre-college circuit experience.

Table 4. Self-reported experience with the course.

I consider my learning experience in labs and problem sets, overall:

	female	male	grouped	
Left blank	7	7	1	15
Really rough, would not wish it on anyone	0	0	0	0
Overall, less than good	1	2	1	4
Okay, not necessarily bad or good	9	4	0	13
More good than bad	19	12	2	33
Really good	4	4	1	9
	40	29	5	74

Students' self-reported experience of the course labs and problems sets was biased toward a positive experience, with 39/74 respondents indicating "More good than bad/Really good" and 13/74 indicating "Okay, not necessarily bad or good" and 17/74 indicating either "Overall, less than good/left blank". We assumed that leaving this question blank was more likely to be associated with a negative experience, but admittedly, we don't know; assuming it is negative represents the worst-case scenario. Using chi-squared test of proportions, the responses were statistically equivalent by groups (p=0.541, excluding “Really rough, would not wish it on anyone,”). The proportion of blank responses was also not statistically significant across the groups (p=0.833).

When asked what their top three resources were for their learning, students indicated the highest value of peers in the course (54/74 respondents); peer coaches (46/74); lab instructions (43/74); faculty (39/74); the textbook (28/74); course videos (16/74) and personal research (12/74). Figure 3 illustrates the proportions that were identified within the top three resources for the 74 respondents.

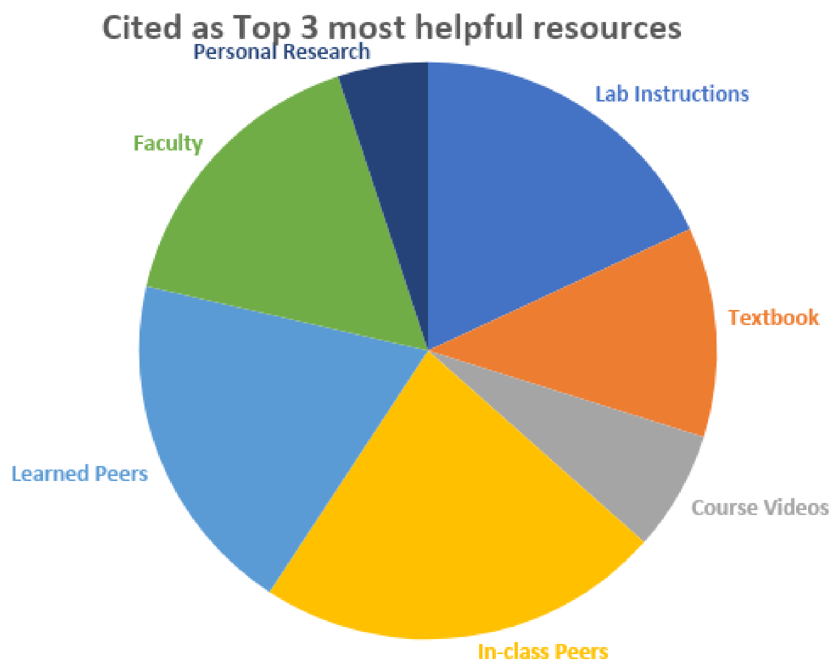

Figure 3. Citations of the top three most useful resources.

As shown, the resources that were considered within the top three were distributed across the six resources that were provided and students own research. Using a chi-squared test of proportions, the groups—female, male, and non-binary/non-identified—were deemed statistically equivalent (p=0.82) in terms of the resources they identified as most important to their learning.

Discussion

We feel that the structure of the course, to include a low-stakes grading format, is critical to students’ ability to explore in a self-directed fashion. The fact that different resources were cited as being in the top three helpful resources indicates that students were able to make choices that suited their learning. However, Figure 3 indicates that learning from people, specifically peers, was generally reported as more effective for the Fall 2019 cohort. While it is highly likely that this report of peer-to-peer learning is an artifact of our residential campus, the benefits of collaborative learning are well documented [7, 8]. Therefore, faculty encouraging peer collaboration in learning is an important element of the course.

It was our hope that the course structure would support a diversity of learning styles. Figure 3 seems to indicate that students felt free to draw on whatever resources they found most helpful. The paper also presented at this conference goes into further detail on how the instructions supported a diversity of students [3].

A little more than half of students indicated that they experienced the labs and p-sets as positive (42/74) with about 17% indicating a neutral experience and about 5% (4/74) indicating a negative experience and 20% not responding. If we interpret that non-response as negative, about 25% of this cohort indicated a negative learning experience. This is admittedly higher than we would like. However, we do not have comparisons of how other first-year engineering courses are experienced, but having over half of the students indicating a positive experience is encouraging.

Conclusions

This 10-module course on sensing, instrumentation, and measurement circuits has enabled novices of presumably different learning styles to effectively self-direct their learning in the presence of peer learning partners, peer coaches, faculty assistance and other resources. An important design element of this first-semester, first-year course is that there is a low-stakes, collaborative learning environment with a grading system the reward learning effort rather than accuracy of learning products. The instructional materials for these modules can be downloaded at no cost at Brian Storey's course website: http://isim.olin.edu/index.shtml and Olin College's course site: https://pages.olin.edu/isim. Overall slightly more than half students in the Fall 2019 cohort report a positive experience with these materials, with no statistically significant differences between the groups of students who self-identified as female, male or non-binary/not-identified. Future plans include developing a low-cost (<$100) device that replaces an oscilloscope, a function generator and a network analyzer and runs on a variety of computing platforms, including an Android® phone/tablet.

Acknowledgements

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References

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[8] Freeman S., Eddy S.L., McDonough M., K. Smith M.K., Okoroafor N., Jordt H., Wenderoth M.P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proc Natl Acad Sci USA 111*, 8410-8415.

Appendix I: Parts list by Lab (these parts also serve Problem Sets)
See below for sources and notes on individual components.

Lab 1	1	sensor	sensor rotary position 12mm SMD	goes up to 10k
Lab 2	2	sensor	120.4 Ohm thermistor	Add leads and silicone waterproof
Lab 2	2	R	10k	
Lab 2	2	R	50k	
Lab 2	4	R	20k	
Lab 2	2	R	1k	
Lab 2	2	R	0.5k	
Lab 3	3	R	121	
Lab 3	1	R	115	
Lab 3	1	potentiometer	10 ohm 1 turn pot	
Lab 3	1	chip	AD623 chip	
Lab 3	1	R	200	
Lab 4	1	sensor	Hs1101LF humidity sensor	https://www.digikey.com/products/en?keywords=HS1101LF
Lab 4	1	C	100pF	
Lab 4	1	C	120pF	
Lab 4	1	C	150pF	
Lab 4	1	C	180pF	
Lab 4	1	C	220pF	
Lab 5	2	chip	AD623 chip	
Lab 5	3	R	100k	
Lab 5	3	R	4.9k	
Lab 5	1	R	499	
Lab 5	3	C	1uF	
Lab 5	1	C	10uF	
Lab 5	6	sensor	body electrodes	3M 2560 Red Dot Multi-Purpose Monitoring Electrode
Lab 5	3 sets		alligator clips	https://www.adafruit.com/product/1008
Lab 6	1	sensor	pressure cuff	
Lab 6	2 sets	R & C	RC cutoff ~1hz	
Lab 6	1 set	R & C	RC cutoff ~10hz	
Lab 6	2	R	1k	
Lab 6	2	R	2k	
Lab 6	1	R	4k	
Lab 6			BPdata.csv - canvas	
Lab 7	1	chip	LMC6484A chip	
Lab 7	1	R	1M	
Lab 7	1	C	0.1uF	
Lab 7	1	R	100	
Lab 7	1		red LED	
Lab 8	2	chip	LMC6484A chip	
Lab 8	2	R	10k	
Lab 8	2	R	1k	
Lab 8	1	R	1M	
Lab 8	1		photodiode	
Lab 8	1	C	10nF	
Lab 8	1 set	R & C	RC cuttoff ~1hz	
Lab 8	1 set	R & C	RC cuttoff ~10hz	
Lab 9	1	chip	AD623 chip	
Lab 9	2	chip	LMC6484 chip	

Lab 9	2	R	2k
Lab 9	2	R	1k
Lab 9	3	C	10nF
Lab 9	2	C	1nF
Lab 9	2	C	10uF
Lab 9	2	C	1uF
Lab 9	2	R	50k
Lab 9	2	R	30k
Lab 9	1	R	4k
Lab 10	1	chip	LMC6484 chip
Lab 10	1	chip	SN74ATC08 logic chip
Lab 10	1 set	sensor	transmitter and reciever
Lab 10	2sest	R & C	40khz band pass + amplifier
Lab 10		R & C	non-inverting amplifier gain ~2.5x or about 20-100x
Lab 10	1	R	1k
Lab 10	1	R	5k
Lab 10	1	R	10k
Lab 10	2	R	20k
Lab 10	1	R	100k
Lab 10	2	R	200k
Lab 10	1	R	1M

Appendix II: Parts and equipment details

Parts

Component	Notes	Sources
photodiode	Osram Opto SFH 203 P IR + visible Light Si photodiode, Through Hole 5 mm package	DigiKey p/n: 475-2649-ND
Capacitors	Ceramic, ±5%, Through hole	Digikey, various p/n
Resistors	Metal film, ¼ Watt, ±1%axial	DigiKey various p/n
Chips	Op Amp, LCM6484: Through hole mount, 14- pin DIP package Instrumentation amplifier, AD623, Through hole mount 8-pin DIP package Quadruple 2-input positive AND gates, SN74ACT08 14-pin DIP package	DigiKey: LMC6484, https://www.digikey.com/products/en?keywords=LMC6484AIN%2FNOPB-ND AD623, https://www.digikey.com/product-detail/en/analog-devices-inc/AD623ANZ/AD623ANZ-ND/750974 SN74ACT08N, https://www.digikey.com/product-detail/en/texas-instruments/SN74ACT08N/296-4354-5-ND/375842
LEDs	Red, Green, Blue, 3 mm Round, 6 mm height, Radial T-1 clear package	DigiKey, various p/n e.g., P/N LTL-4266N, https://www.digikey.com/product-detail/en/lite-on-inc/LTL-4266N/160-1034-ND/121770
Prototyping board	5.5 cm x 17 cm, 830 tie points	Adafruit p/n 239, https://www.adafruit.com/product/239
Thermistor	120.4 Ohm, Gage factor = 2	Omega p/n KFH-3-120-C1-11L1M2R,
Wire strippers	Multisize wire stripper & cutter	Adfruit p/n 147, https://www.adafruit.com/product/147
Potentiometer	10 Ohm, 1 turn, 1 W ±5%	DigiKey p/n 3345P-1-100-ND, https://www.digikey.com/product-detail/en/bourns-inc/3345P-1-100/3345P-1-100-ND/2536476
Wire	140pcs U Shape solderless breadboard jumper cable wire Or 22 gauge wire, various colors	Various e.g., https://www.electronicshub.org/breadboard-kits-beginners/
Header pins	For testing prototype board points	Male breakaway headers, straight, 0.100" contact centers, ~6mm head and tail. Sullins, P-E-0.100-36-S-AB-N https://s3.amazonaws.com/catalogspreads-pdf/PAGE112-113%20.100%20MALE%20HDR.pdf

Equipment & software

Analog Discovery 2 ($279)
https://store.digilentinc.com/analog-discovery-2-100msps-usb-oscilloscope-logic-analyzer-and-variable-power-supply/

Waveforms (Free download)
https://store.digilentinc.com/waveforms-previously-waveforms-2015/

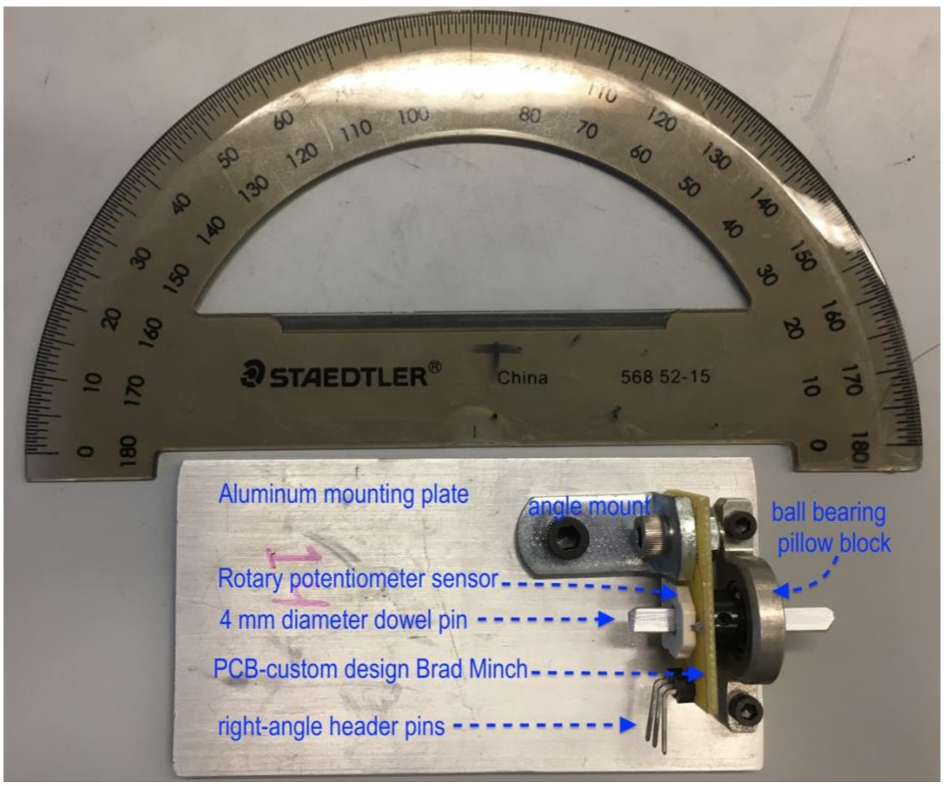
APPENDIX III: Lab fixtures

Lab 1: Pendulum

Parts list:

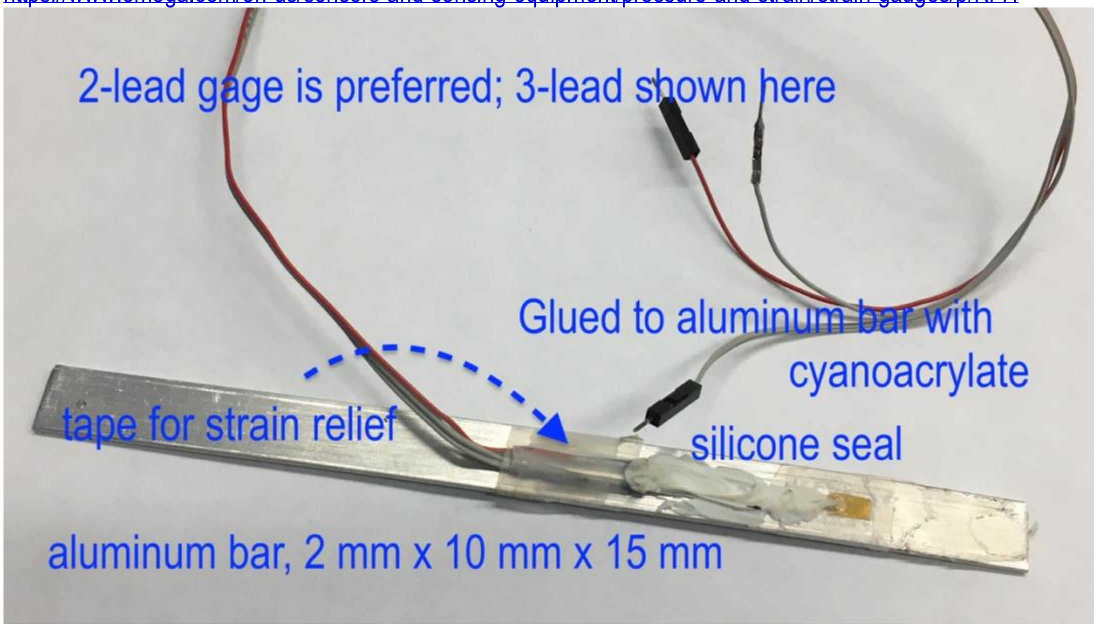
Sensor Rotary Position 12 MM SMD
    Bourns Inc. MFG P/N: 3382G-1-103G
    DigiKey P/N: 3382G-1-103GCT-ND
4 mm x 28 mm steel dowel pins, D profile (negative tolerance on 4 mm diameter)
Right angle termination breakaway header pins,
    Sullins P-E-0.100-36-S-BC-N (6 mm head, 8 mm tail)
Mounted miniature ball bearing pillow block w/4 mm inner diameter for shaft, loose fit
    spyraflo MFG P/N: PB0-SMR604ZZ
Printed Circuit Board (by Bradley Minch), design available via bradley.minch@olin.edu; https://www.customcircuitboards.com/

Mounting hardware (screws)
protractor
C-clamps to mount the aluminum plate to a table edge
Aluminum mounting plate
Pendulum: 1” x 12” x ¼” with hole diameter for light press fit to dowel pin

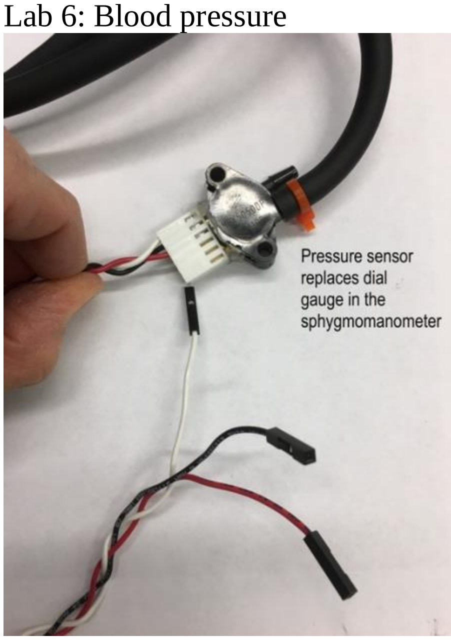


Lab 3: Aluminum cantilever with strain gauges

Parts list:
Aluminum bar (~2 mm x 10 mm x 15 mm, not critical)
C-clamps to mount the free end of the cantilever to a table
Pre-wired Strain GagesS, Item# KFH-03-120-C1-11L1M2R (pack of 10), 2 leads
https://www.omega.com/en-us/sensors-and-sensing-equipment/pressure-and-strain/strain-gauges/p/KFH



Lab 6: Blood pressure



Basic manual sphygmomanometer
https://www.medicalsupplydepot.com/Diagnostic-Products-1/Blood-Pressure-Monitors-2/Aneroid-Manual-BP-Sphygmomanometer-Kit.html

Replace dial gauge with a
Freescale Semiconductor Pressure Sensor MPX5050GP
(https://www.nxp.com/docs/en/data-sheet/MPX5050.pdf)

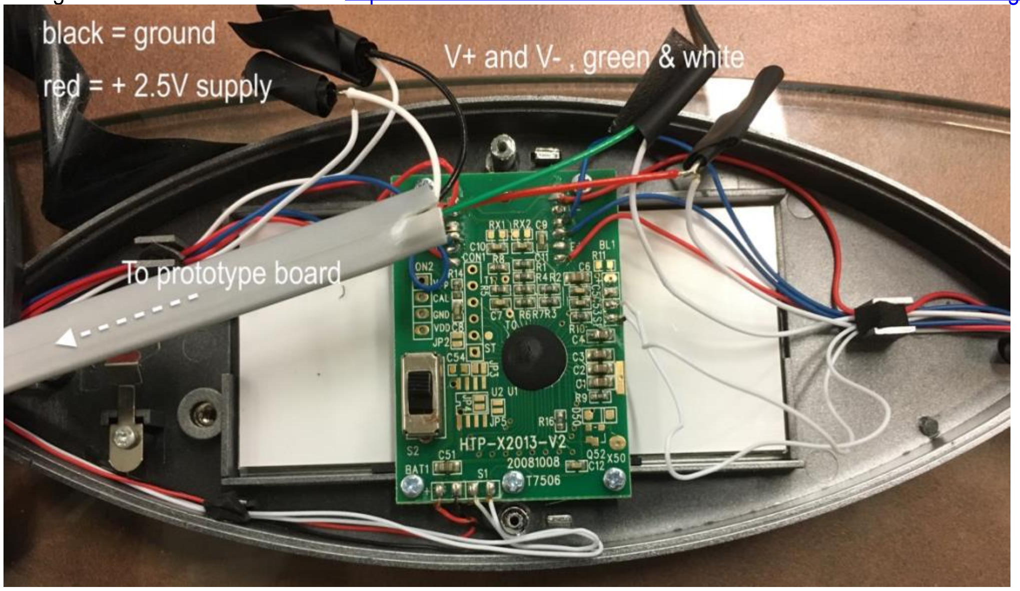
https://www.digikey.com/product-detail/en/nxp-usa-inc/MPX5050DP/MPX5050DP-ND/464057

Wiring:
Pin 1: Vout (White in image)
Pin 2: Ground (Black in image)
Pin 3: Vcc, 5 volts (Red in image)

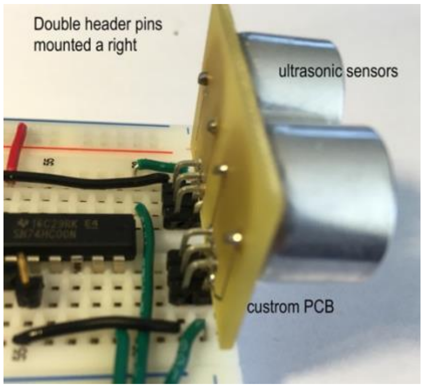
Lab 9: Ballistocardiograph

Bathroom scale with piezoelectric load cells

Wiring instructions can be found at https://www.instructables.com/id/Arduino-Bathroom-Scale-With-50-Kg-Load-Cells-and-H/



Lab 10: Ultrasonic echo location
Parts list:



40 kHz ultrasonic sensors
PUI Audio, Inc, MFG P/N UR-1240K-TT-R
DigiKey P/N: 668-1546-ND
https://www.digikey.com/product-detail/en/pui-audio-inc/UR-1240K-TT-R/668-1546-ND/6071958

Right angle termination breakaway header pins, double row
Sullins P-E-0.100-36-D-BB-N (6 mm head, 5 mm tail)
Printed Circuit Board (by Bradley Minch), design available via bradley.minch@olin.edu; https://www.customcircuitboards.com/

Alternative:
Adafruit Industries LLC, Ultrasonic Sensor, DigiKey P/N 1528-2711-ND
https://www.digikey.com/product-detail/en/adafruit-industries-llc/3942/1528-2711-ND/9658069

Image: Adafruit Industries