From Course Instruction to Bio-MakerSpace: Creating a Lab Space for Independent Investigation and Innovation

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Introduction

How can a teaching laboratory encourage independent learning in its coursework while also providing an opportunity for innovation and entrepreneurship? Traditional educational labs focus on teaching specific laboratory techniques or to experimentally demonstrate key theoretical concepts.[1,2] While important and necessary, this often does not lend itself to design. Examples of these include introductory chemistry and physics labs, in addition to many sophomore and junior level engineering courses. On the other hand, design labs encourage creativity but are often limited to specific courses, which in turn limits the breadth of resources available. For example, a lab tied to electronics design would be held in a "dry" electronics lab and a lab tied to mechanical design would be held in a "dry" machining lab. Often, with both laboratory models, extensive time is taken to teach students about the various tools and supplies through traditional lecture methods.

Unfortunately, these models tend to compartmentalize topics within students' minds which can be especially problematic in the context of Bioengineering or Biomedical Engineering (hereafter referred to as Bioengineering). Bioengineering programs tend to be extremely broad, encompassing chemical, electrical, material science, and mechanical engineering elements, as well as computer science. Oftentimes, students take lab classes, for example related to molecular biology, in a specific lab meant only for that area of study. A different lab class dealing with a different field would then be done in a different lab. The challenge with these models is that integration of different components, such a mechanical, electrical, and biologic, is not covered or explored in a practical manner.

Furthermore, these didactic models tend to discourage independent learning. Students are taught specific techniques, many times closely tied to the equipment or software being used. While the emphasis is that the equipment and software are typical of those used in industry or in research settings, the opportunity for students to learn to use these tools on their own is often discouraged due to the complexity or cost of these tools. For example, a Bioengineering lab might have a DNA sequencing device which is exuberantly expensive; consequently, usage is restricted and extremely controlled to prevent damage to the device.

This in turn stymies entrepreneurship and innovation where interdisciplinary work along with the ability to quickly learn to use a tool or technique is critical. In this paper, I will demonstrate how our Bioengineering educational laboratory and website, along with its undergraduate laboratory curriculum, promotes independent learning by students, encourages innovation, and helps to create a sense of community. A survey, completed by approximately 70 recent users of the lab, from current seniors to recent alumni, will help to better understand student perceptions of the lab.

Background

The University of Pennsylvania is an urban campus, next to the heart of Philadelphia. Unfortunately, being in a city makes space a limited and valuable commodity. An effect of this limitation is that the department has only one instructional lab. In addition, being an old program, the lab was originally designed for some of the more traditional Bioengineering fields, such as biomechanics and instrumentation.

About 15 years ago, in 2006, a new Bioengineering building was constructed reflecting the change in the field to areas related to molecular biology and tissue engineering, among others. The instructional lab was moved to a new home in a lab which contained chemical hoods and cell culture hoods, but was still nevertheless setup with stations designed for physiological and instrumentation studies (Figure 1).

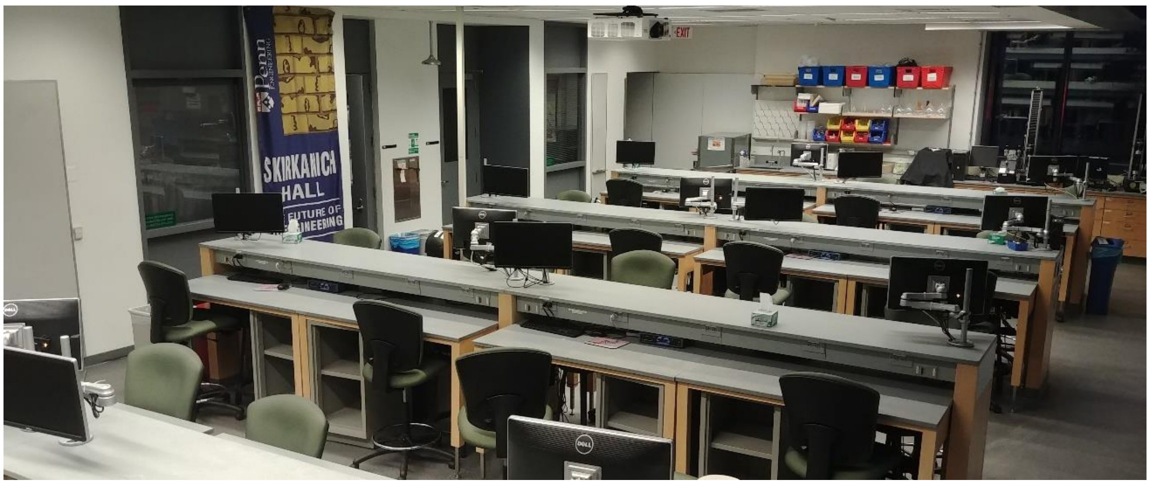


Figure 1: Main lab area with 16 stations each with data acquisition devices (Biopac & NI myDAQ) for physiological studies and general use

In time, the laboratory soon was equipped for molecular biology work, mechanical testing, hand tools (hammers, drills, etc.), electronics and test equipment, human and animal physiological study supplies, chemicals and chemistry work, and laser cutters and 3D printers (Figure 2 and Figure 3). This breadth allowed us to create modules for our lab classes which could, for example, have students grow cells with specific characteristics, and measure the concentration of these cells using their own custom-built spectrophotometer.

Figure 2: Part of the lab's "Projects Room". This side houses electronic components, hand tools (such as drills and hammers), molecular biology equipment, and two chemical fume hoods

Figure 3: Other side of the lab's "Projects Room". This side houses 3D printers, a cell culture hood, a CO_2 incubator, and microscopes

Moreover, as with many engineering programs, the department wanted to have more hands-on laboratory classes. Existing lab classes also needed to cover a broader range of Bioengineering topics. This was to help students see how the disparate topics for which they would have taken classes, come together in its application to biology and the human system. The biggest challenge, however, was that the department also wanted to move the senior design class out of the research labs where it was tied to faculty advisors, and instead, wanted to encourage student innovation and to allow students more independence. Students would have an idea and need to implement it using available resources and a limited budget. All of these changes were to be done in the instructional laboratory.

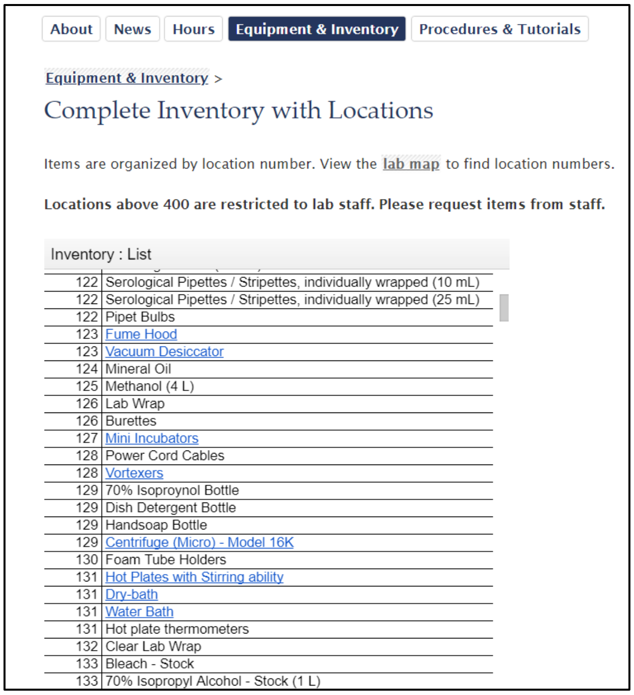
The challenge in this situation was with many different classes, supporting all of them would be extremely difficult. How does one switch from a lab class where cells are being grown and plated to a medical device class where students use microcontrollers and breadboards? At the same time, a project for another class might be approaching a deadline where an enclosure needs to be laser cut or a model needs to be printed on a 3D printer. How can a single lab handle such breadth? Additionally, how can one or two lab staff be able to train senior design students on equipment usage and constantly answer students on whether supplies or equipment are available and where they are located?

The Website

The primary solution for this challenge is through the extensive use of a laboratory website: http://belabs.seas.upenn.edu (Figure 4).[3] We felt that a detailed website would foster greater independence and in turn encourage innovation. This website maintains an inventory of the lab's

Figure 4: Website home page

supplies and equipment, as well as tutorials and guides for learning various techniques and tools. The inventory list contains every supply and piece of equipment available in the lab, along with corresponding location numbers (Figure 5). Even the most mundane article is listed. Location numbers are tied to specific locations in the lab. Laboratory users will search for the item on the web page and identify a location number.



About | News | Hours | Equipment & Inventory | Procedures & Tutorials

Equipment & Inventory >

Complete Inventory with Locations

Items are organized by location number. View the lab map to find location numbers.

Locations above 400 are restricted to lab staff. Please request items from staff.

Inventory : List

122	Serological Pipettes / Stripettes, individually wrapped (10 mL)
122	Serological Pipettes / Stripettes, individually wrapped (25 mL)
122	Pipet Bulbs
123	Fume Hood
123	Vacuum Desiccator
124	Mineral Oil
125	Methanol (4 L)
126	Lab Wrap
126	Burettes
127	Mini Incubators
128	Power Cord Cables
128	Vortexers
129	70% Isoproynol Bottle
129	Dish Detergent Bottle
129	Handsoap Bottle
129	Centrifuge (Micro) - Model 16K
130	Foam Tube Holders
131	Hot Plates with Stirring ability
131	Dry-bath
131	Water Bath
131	Hot plate thermometers
132	Clear Lab Wrap
133	Bleach - Stock
133	70% Isopropyl Alcohol - Stock (1 L)

Figure 5: Inventory List

Once a location number is found, the user can access the lab map to determine where the location number can be found (Figure 6).

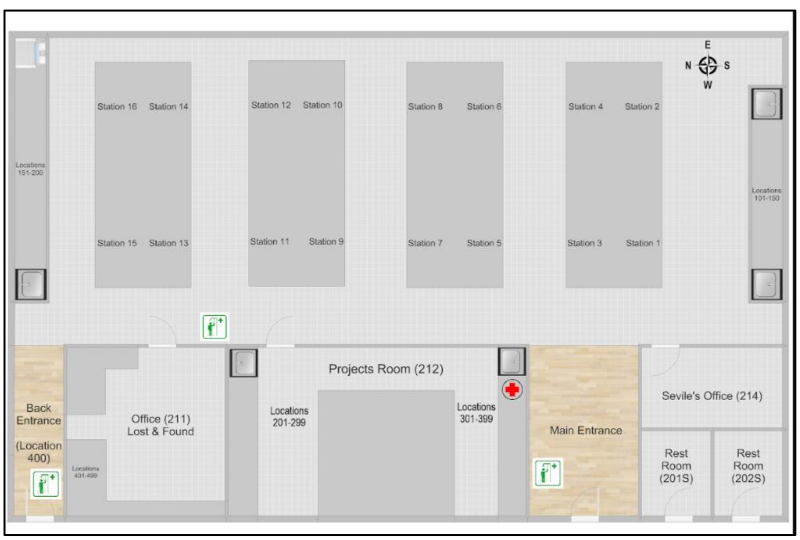


Figure 6: Lab Map with Location Numbers

For example, if students searched for "test tube holders" they would be led to location 118. The lab map would place the item on the south side of the lab (Figure 7) where students can identify what they need.

Figure 7: South side of lab with reference books, microwave, and fume hood.

While there is a logical placement of items (eg. Electronic components are grouped in one area and molecular biology supplies are grouped in another), certain items, such as PDMS or plastic bags could be anywhere. Also, since many areas of the lab are fixed based on the initial design, such as sinks, fume hoods, and chemical hoods, this prevented a fully sensible placement of supplies. Larger and oddly shaped equipment will of course need to be placed where ever they fit, so for example, we have Instron test systems for mechanical testing next to glassware and an incubator (Figure 8).

Figure 8: North side of lab with glassware, Instron mechanical test systems, and a covered incubator for an ongoing experiment; A laser cutter (not pictured) sits to the left

This full inventory also provides links to datasheets, or other relevant materials pertaining to the item. A resistor will bring up a picture of the resistor so lab users can identify the color bands. A centrifuge would bring up a manual. A more complex piece of equipment, such as an Instron test system, would bring you to a page with device specifications, manuals, and our own user guides for use of the device in our labs. We also provide inventory lists of subsets of this master list: mechanical supplies and equipment, electronic supplies and equipment, etc. These are helpful for users to quickly scan to see what supplies and equipment is available. For example, this is helpful if you wish to see all the electronics components available without having to go through the entire inventory list. Furthermore, the website has a separate inventory list of every piece of equipment and software, along with pictures (Figure 9). This allows users to easily scan to see what equipment is available in the lab.

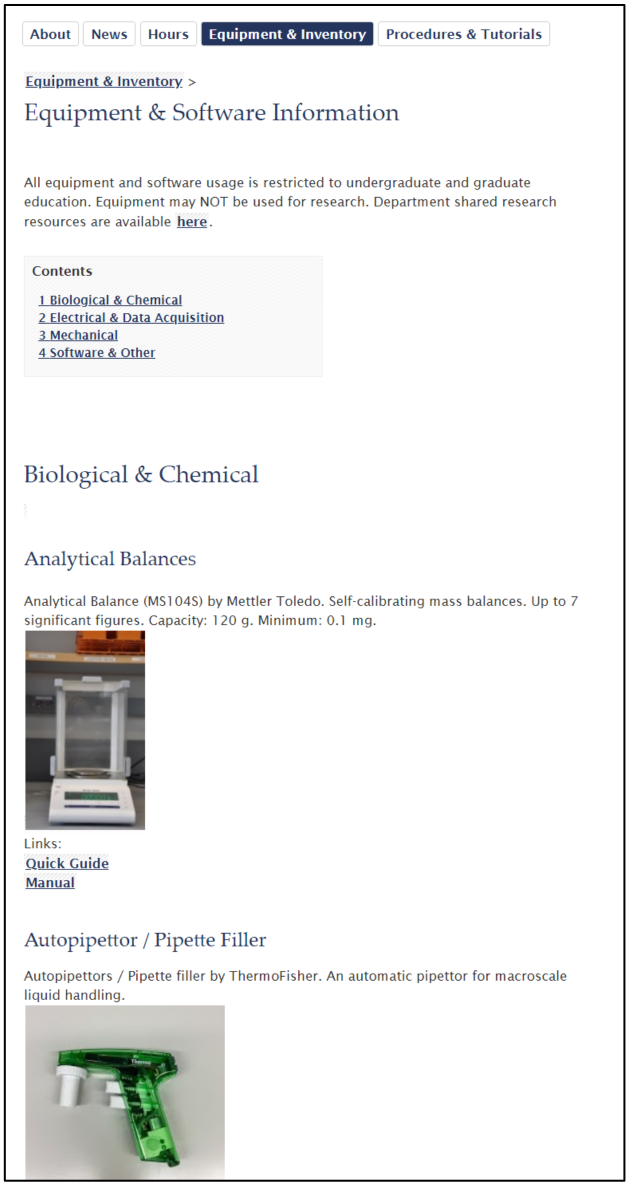


Figure 9: Selection from the Equipment and Software list

In addition, QR codes are placed throughout the lab which directly take the user to the inventory list on the website. QR codes are also on many pieces of equipment which take the user to the corresponding equipment listing.

The difficulty in such a system is on the backend maintenance. Our lab purchases new supplies and equipment frequently, and we often reorganize locations of supplies depending on the current needs of the courses. Updating the inventory list and updating manuals would be a nightmare, especially if it required uploading a new document and creating links, etc. The solution for us has been making use of Google's online software suite.[4] Our inventory list sits on Google sheets, and the webpage embeds this sheet. Any updates made to the inventory list will automatically update on the website. In the same manner, all equipment guides are written using Google docs. This allows for rapid updates without having to deal with uploading files and changing links.

The final piece of our website are the tutorials and protocols. We provide a full list of useful tutorials such as on basic electronics, designing a press-fit box using SolidWorks, or making and performing gel electrophoresis (Figure 10). Some of these tutorials are links to external websites, but they have been curated to identify what we believe to be the best training option. Another component of this list is debugging guides. We have created a number of both generic guides and guides specific to equipment to encourage individual learning.

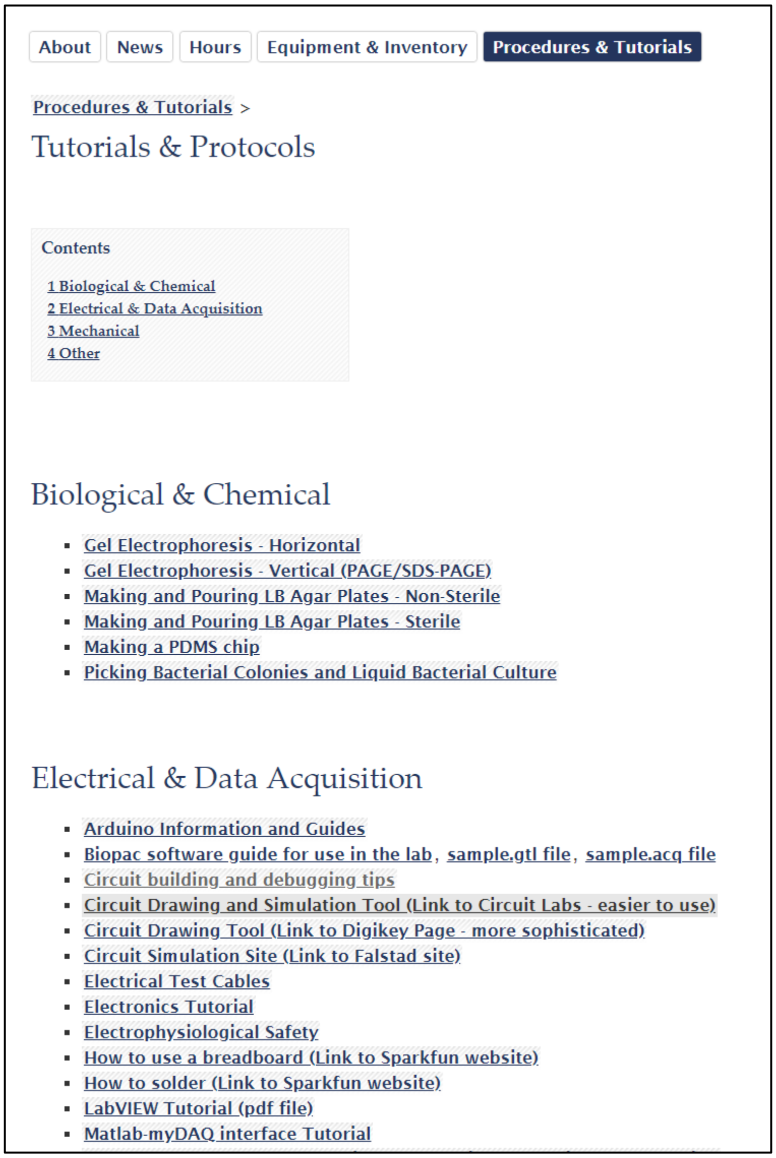


Figure 10: Selection from the Tutorials and Protocols list

For senior design students especially, these web tools help tremendously. By knowing beforehand what supplies and equipment are provided, they can determine early on how to make use of their budgets. Tutorials allow students to refresh themselves or to learn for the first time those specific skills which might be useful for their projects. These resources also relieve the lab staff of the tremendous burden of having to teach each individual student various skills, spending time showing students where things are located, or how to use the various tools. Surveyed students find the website to be incredibly useful, with over 75% feel the website encourages independent learning and encourages innovation.

The Lab Program

The challenge of any new technology is in adoption. While resources are available on the website to allow students to work on their own, how do you encourage them to use these resources? It is much easier to ask someone if they have something, where it is located, and how to use it, then to go through an involved process to get this information. In order to both handle the increasing number of classes held in the lab, and to encourage students as seniors to use the available resources, students need to be encouraged from their freshmen year to use the web resources.

One of the important methods of creating this change was by moving many of our labs to being project-based, following constructionist learning theory.[5] For most of our lab classes, students first do a few structured activities to understand the relevant theoretical concepts. The data then informs a design challenge which is open-ended, and many times makes use of resources not limited to the students' original list of materials found in their manual. In this way, students begin to make use of the lab's website.

Some of these guided tutorials involve learning a new skill or understanding how to use a piece of equipment. In general, our lab manuals will not contain this information; instead, students are expected to prepare themselves and find all the necessary tutorials on the website. In Bioengineering programs especially, this is important. One of our lab classes, for example, moves between microfluidics, synthetic biology, signal theory, circuits, CAD design, and 3D printed & laser cut fabrication – students learn the relevant skills tied to their theory classes through just-in-time skill training as provided by our tutorials. Thus, students quickly learn how to make a wax printed microfluidic device on one day (Figure 11), and later in the semester, learn to build and test a circuit using a signal generator and oscilloscope.

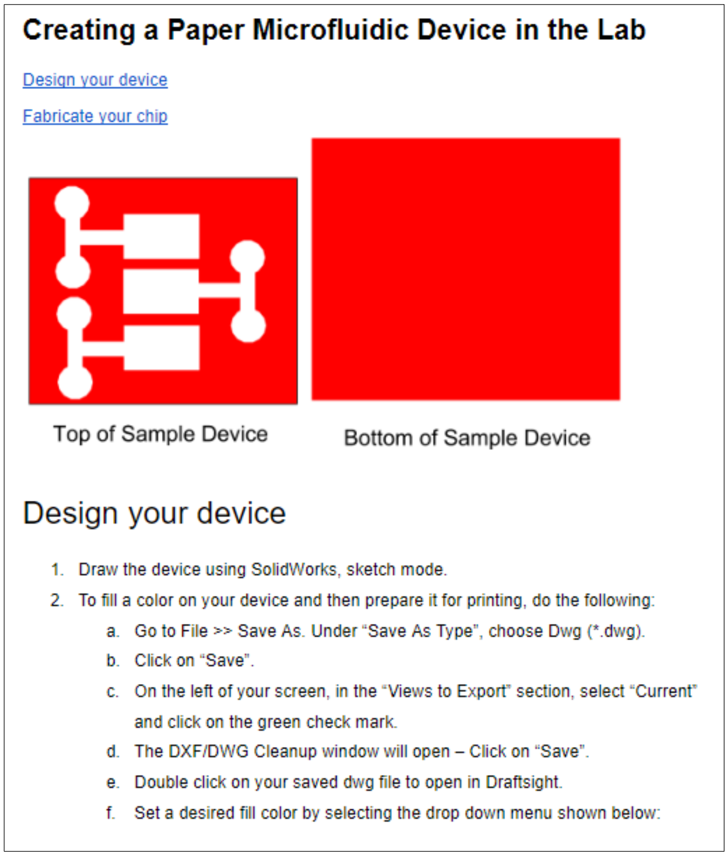


Figure 11: Guide to creating a wax printed microfluidic devices

Additionally, we have a variety of debugging guides available on the website to encourage students to solve any issues they might have on their own (Figure 12). Teaching Assistants and lab staff are required to direct students to these debugging guides before offering help.

The next component of this paradigm is the necessity for extended hours for the lab. In Bioengineering, where students might be working with circuits, growing cells, or measuring their own physiological signals, the lab cannot just be left open with free access. Instead, the lab is staffed outside of business hours on weekday evenings and parts of the weekend. Again, during these extended hours, students will be working on a variety of projects in a variety of fields, making it impossible for the staff to assist every person. The debugging guides are especially helpful here. Students are thus encouraged to learn on their own.

Finally, to help with transitions between lab classes and to allow for work outside of class hours, our lab modules are designed for students to find what they need and set their stations up themselves. When students are done, they are expected to clean up and put away everything. In the beginning of the lab program, students have quizzes and pre-labs where they must identify the locations of the necessary items and write down where the locations are within the lab. Teaching Assistants and lab staff are instructed to tell students to "Check the website," if asked where anything is located of if the lab has any supply. This encourages students to make use of the website's resources starting their freshman year and continues through their senior design class.

If you have problems with the Conductivity Meter:

The most important lesson here is (and for all engineering!): test things one at a time and <u>isolate the problem</u>.

Common steps:

1. Unplug the Biopac cable from the back of the conductivity meter.
2. Make sure conductivity meter settings are correct
    a. In the front: "E" for "Range"
    b. In the back: "Off" for the 3-option dial, and power switch on
3. Test to see if the conductivity cell and conductivity meter work with water, 25mM, and 50mM solution (syringe is good for this). Approximate expected values shown in table below:
    a. Values don't need to be exact – just needs to have 3 values to check linearity

Concentration (mM)	Value displayed on conductivity meter
0	0
25	2.50
50	5.00

4. If the meter is fine, connect the conductivity meter and Biopac with the Biopac cable. If not, talk to staff.
5. Do the same test as step 3, but with Biopac cable plugged in and Biopac running. The values should be very similar, and should be displayed on both the conductivity meter and Biopac. If this step is fine, everything is fine. If not, follow the next steps.
6. Check Biopac settings. MP35 → Set up Channels → View/Change Parameters → Gain

Figure 12: Sample of the "Using the Conductivity Meters" Manual's debugging help on the website

Senior exit surveys continue to demonstrate that our lab program is perceived as the best and most valuable component of the Bioengineering program. This has been a consistent perception, even well before the lab organization had changed, and was thus a relief that perception did not worsen. While not possible to measure at this point, our lab program has encouraged the adoption of using our website and encourages independent learning.

The Lab as Social Space and as MakerSpace

The primary required lab course in our Bioengineering program is during the junior year. Students meet for six hours a week, and generally spend 6 to 10 hours per week outside of the class time in the lab. The group dynamic and teaching environment which we have has helped to build a tremendous amount of camaraderie amongst each class, and students get used to being in the lab. The lab has turned into a social space.

Students constantly use the lab as a place to meet their friends as well as a study space, creating a community of practice (Figure 13 and Figure 14). Juniors and seniors have been found meeting younger classmates for the first time and sharing their experiences and offering suggestions. Situated across from the department's office, students who need to go to the office often stop in the lab afterwards until it's time for their next class. This in turn has led some students to use the space to fix their own personal things. For example, students have fixed everything from shoes, glasses, to laptop chargers using the equipment and supplies in the lab. Since the lab has so many classes, the lab cannot be closed to other students outside of a specific class. Instead, the lab's policy is to allow students to freely use the lab, as long as an open station is available, and they are not disruptive, even during scheduled class time.

Figure 13: After hours in the lab – Students working in three different classes are here, as well as students meeting for other purposes, including a start-up venture

Figure 14: After hours in the lab on a different day

To help encourage this social aspect of the lab and to promote this community of practice, we created a lab Facebook page as well as an Instagram page. Students seem to really enjoy seeing their pictures posted through "official" channels, especially images of them doing engineering. Both social media outlets have proven to be quite successful. We briefly attempted Twitter, but there was minimal interest in it and so it was cancelled. Pictures and videos vary from serious work, to an image of students watching the University's basketball team playing in the NCAA tournament on a projector during a lab class. In general, students don't perceive social media sites as encouraging community (just over 70%) compared to the community created by just being an open space (almost 99% of students agree). Nonetheless, it is a fun means to advertise student work to the rest of the department and school.

A further outcome of this free use of the space and its social dimension is the lab being used for independent projects. This begin with the University's iGEM team, but soon other students recognized the opportunities.[6] Recently, an interdisciplinary team won a competition by NASA to have their microfluidic device 3D-printed aboard the International Space Station.[7] In the same manner, students begin to use the lab for start-up ventures. This trend initially started with a senior design project that spun into a company which made use of microfluidic technology in a novel way.[8] As word spread, a second student, who was not in engineering, asked to use the lab to test out an idea, which also spun into a new company. She wished to design electronics to measure certain chemical reactions in biologics.[9] During this time, we gained clarity on intellectual property rules for the university, and its application to both students and lab space designed for educational use. In general, all work done in the lab, materials used, and support from lab staff is owned by the student. This combined with the breadth of resources that this lab provides encourages such work among students. Accomplishments by the student groups and start-ups are regularly posted on the lab's social media sites.

The lab provides the materials and tools for students with ideas to explore them in their own time. Students can navigate the space on their own and learn to use to the tools independently. The social draw of the lab encourages regular use by students such that when students think of an idea, the first place they think to go is this lab.

Results

A questionnaire was distributed to our current seniors, as well as a number of accessible recent alumni, and other users of the lab. The questionnaire sought the perception of students toward the lab, its website, its social media presence, and asked students to compare it to other more traditional educational labs that they've used. Results of this questionnaire are provided in Table 1. Based on student perception, our lab encourages both independent learning and innovation, while also providing a sense of community. In all categories for independent learning, over 90% of students feel very strongly that the lab accomplishes this. Lab users find the lab encourages innovation by over 90% as well.

Table 1: Questionnaire data in three categories

Category	Question	1	2	3	4	5	N	Mean	St Dev
Independent Learning	If something of mine were broken (eg. laptop charger), I know I could come to the lab to fix it	3	6	31	12	17	69	3.52	1.09
	In general, the lab encourages independent learning	0	0	5	25	38	68	4.48	0.65
	The breadth of equipment in the lab encourages independent learning	0	0	4	24	40	68	4.54	0.61
	Having tutorials and guides freely available on the website is useful	0	1	1	16	50	68	4.70	0.57
	If I need to know how to use a piece of equipment or tool, I know the information will be available on the website	0	5	0	27	37	69	4.41	0.82
	The database of equipment, supplies, and tutorials available on the lab website encourages independent learning	0	0	9	23	36	68	4.39	0.73
Innovation	If I wanted to work on an independent project, I know I could come to the lab to work on it	1	2	2	26	37	68	4.42	0.80
	In general, the lab encourages innovation	0	0	3	29	36	68	4.48	0.61
	The breadth of equipment in the lab encourages innovation	0	0	2	21	45	68	4.65	0.54
	Having a database on the website of all of the lab's supplies and equipment is useful	0	0	0	14	54	68	4.79	0.41
	The database of equipment, supplies, and tutorials available on the lab website encourages innovation	0	0	15	20	32	67	4.25	0.81
Community	The lab environment and open hours helps encourage a sense of community with the department and with fellow students	0	0	1	18	49	68	4.72	0.48
	The lab's social media pages (facebook & Instagram) encourages a sense of community with the department and fellow students	1	1	15	25	26	68	4.10	0.90

Users were also asked to compare their experience with this lab with traditional science and engineering labs which are open only for their specific classes. This was the best option to approximate a "before" and "after" lab scenario. Our students experience this type of laboratory environment in their introductory science labs, such as in chemistry and biology, and this was how our lab was, prior to the full implementation of the lab as a Bio-MakerSpace. Figure 15 shows that over 97% of users feel our lab encourages innovation and independent learning over these traditional formats.

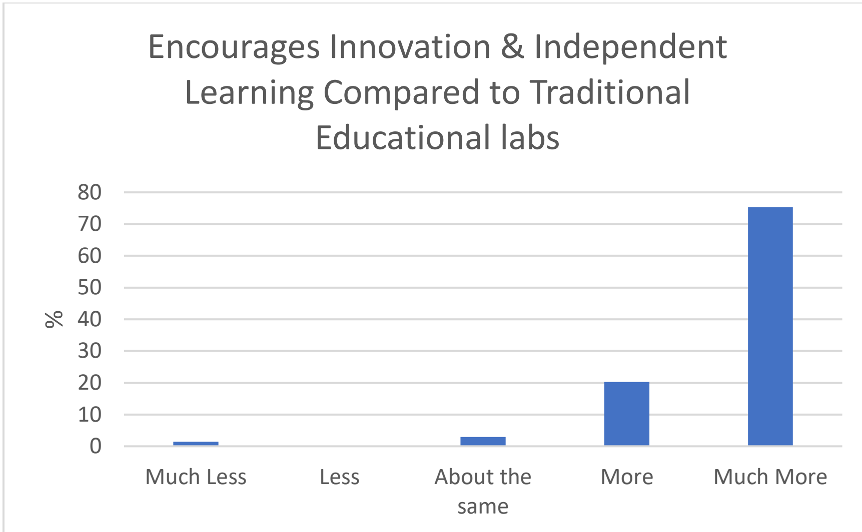


Figure 15: Bar graph showing student perception of innovation and independent learning encouragement of the lab over traditional educational labs

In addition, some of our lab users have used open engineering labs available in our mechanical and electrical engineering departments (Figure 16). Only 59% of users of both labs found our lab to provide greater opportunity for independent learning and innovation. Follow up questions tell us that the lab not being open 24-hours a day was the biggest drawback compared to these other labs. Unfortunately, with chemicals and equipment that are easily damaged, it is not possible for us to keep the lab open for such extended periods. Supervision at all times is necessary.

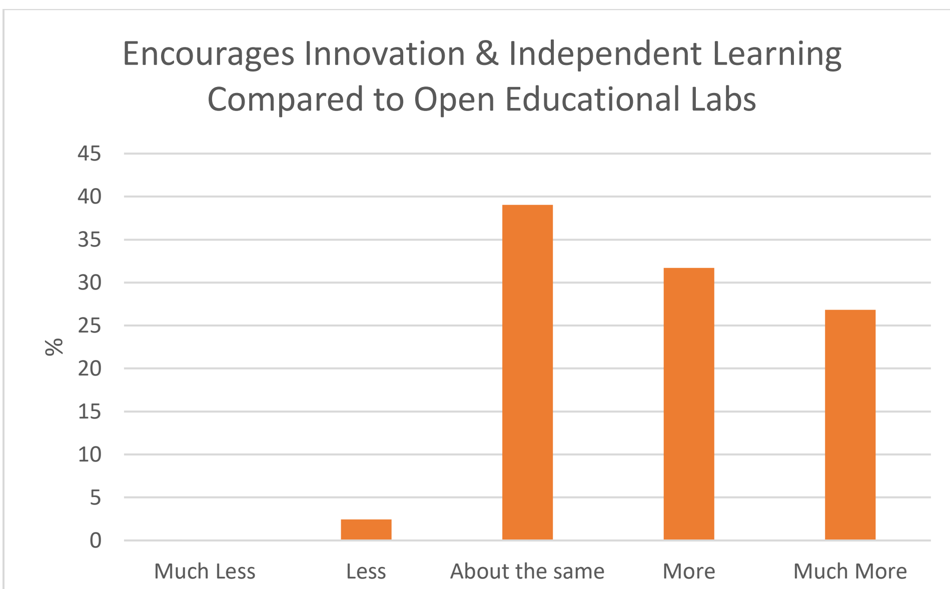


Figure 16: Bar graph showing student perception of innovation and independent learning encouragement of the lab over more open educational labs such as is often found in mechanical and electrical engineering departments

Finally, Figure 17 shows a plot of start-up ventures by students which have either started in or used our lab. Since the lab started being used as a Bio-MakeSpace in 2016, start-up usage has increased to four from just two over the previous entire decade.

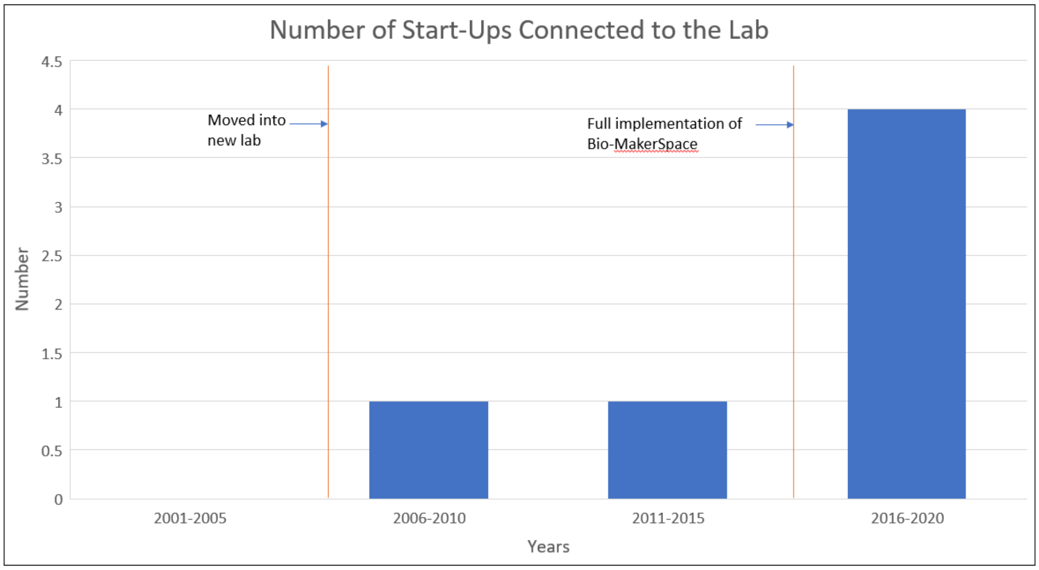


Figure 17: Lab usage of by student-led start-ups

Student comments reflected the data, with students mentioning the variety and availability of resources, easy access to documentation, and the sense of community as the best parts of the lab, while lack of storage and limited hours as being the least liked aspects.

In addition, the added complexity to student lab classes was evaluated through course reviews. As mentioned earlier, evaluations have remained consistent from earlier years and are generally positive with comments, as is often the case, ranging from the very good to the very bad. The most recent course evaluation had a comment representative of student's perception of the courses, "*this class is designed to be somewhat hands off in terms of the amount of guidance given to students. This proved to be a frustrating experience, especially at the beginning of the semester since I was not yet used to the high expectations. Despite all of this, I do feel like I gained a lot of knowledge and experience from this class.*"

Concluding Remarks

As our Bioengineering department grew, both in terms of faculty and offered classes, the needs of the laboratory have changed. Senior design set the bar incredibly high in needing to provide space and resources to projects that ranged from synthetic biology to electronics and prosthetic design. Unfortunately, due to the traditional limitations of time and space, the lab could not handle these changes without a major change to its organization and operation. Lab modules have been moved away from traditional experimental and procedural modules to project based. Students are expected to be able to prepare and take down their setups on their own and be able to do the same whenever they have time, outside of regular class time. Having a website with a database of all materials, equipment, and with tutorials, helps this process tremendously.

Furthermore, providing students with greater independence frees the time of the lab staff, course instructors, and teaching assistants from spending time on the more mundane activities. Rather than telling students where things are located, or how to do a simple procedure, more effort can be spent on dealing with the larger questions associated with a project. Available time can also be used for advising students, writing papers (such as this one), or developing new lab modules.[10]

Unfortunately, providing such independence to students, combined with restricted space size, limits the resources that can be available. Since our stations need to be used for molecular biology, animal and human physiology, drilling, chemistry, and so forth, all in addition to electronics, having traditional oscilloscopes and signal generators at each station is not feasible. Instead, we are required to use virtual devices (National Instruments myDAQ). While being able to do a DNA sequencing experiment would be exciting for students, the space such equipment would occupy compared to being able to obtain more accurate data by using outside services makes having the equipment not worthwhile. However, not having the device is in many ways a loss for students. Finally, sophisticated machining tools are not used in the lab due to safety concerns. While the lab is staffed at all open times, the size of the lab and the breadth of equipment would make it impossible for student-employees to keep a close eye on these more dangerous tools. Fortunately, machine shops are available in a nearby lab.

Moreover, while procedural based experiments are necessary and helpful, especially during the first two academic years for students, our lab model makes this difficult. Rather, some of this work is pushed to the sciences. For example, students learn biology and chemistry techniques and skills through laboratory classes offered in those respective departments. Other skills and education which students could gain through procedural labs are morphed into project-based labs with just-in-time skills learning sessions. One aspect of this that we are noticing is a weakness in students' intuition with electrical circuits. Possible solutions might be the introduction of more procedural-based labs where the learning is not as rushed as with the just-in-time model, all of which still needs exploration.

While the lab does provide extended hours into the evenings and on weekends, for students used to working through the night, this is a great limitation and is consistently mentioned as a drawback. Unfortunately, due to the range of equipment and supplies (including chemicals), a freely open lab is not feasible, such as is sometimes found in Electrical Engineering labs. Also, the availability of extended hours is dependent on the available schedules of student employees, which can be problematic.

Finally, having extended hours and open stations encourages the lab to be a social space, encouraging regular use. Students are now using the lab for their own independent projects and their start-ups, as well as for study spaces or just as a place to meet. For students, the lab has become a central locus for Bioengineering education.

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