

## **AC 2008-1165: A PROJECT-BASED ELECTRONICS MANUFACTURING LABORATORY COURSE FOR LOWER-DIVISION ENGINEERING STUDENTS**

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# **A Project-Based Electronics Manufacturing Laboratory Course for Lower-division Engineering Students**

## **Abstract**

This paper presents a project-based laboratory course on electronics design and manufacturing. The goal of this course is to provide lower-division engineering students a hands-on experience involving actual printed circuit board (PCB) design, layout, fabrication, assembly, and testing. Through project-based learning, students not only learn technical skills in designing and manufacturing an electronic device, but also develop their project management and communication skills early in their course of study at the university. The course outline and examples of the student projects are presented in this paper as well as project evaluations and students' feedback. This paper also presents the selection of a PCB design tool for the lower-division electronics manufacturing course.

## **Introduction**

The electronics industry in the United States and around the world continues to grow at a high rate due to the ever-expanding range of electronic applications. The \$1.3 trillion electronics industry has become a major sector in the manufacturing industry. Thus, it is of critical importance to increase production of engineering graduates who are capable of keeping the United States competitive in these rapidly-evolving areas of electronics manufacturing.

However, electronics manufacturing is not traditionally taught in a manufacturing engineering degree curriculum. Out of the 300 engineering colleges in the United States, there are only 24 ABET (Accreditation Board for Engineering and Technology)-accredited manufacturing engineering programs, and only a few of these programs offer electronics manufacturing related curricula. Based on a review of the curricula of ABET-accredited manufacturing engineering programs, only Boston University,<sup>1</sup> Oregon State University,<sup>2</sup> and Cal Poly San Luis Obispo have electronics manufacturing courses. Recently, the newly established manufacturing engineering program (not yet ABET-accredited) at Washington State University Vancouver began to offer a microelectronics emphasis area.<sup>3</sup>

It should be noted that electronics manufacturing is a multidisciplinary topic because it is relevant to the fields of materials engineering, mechanical engineering, electrical engineering, manufacturing, reliability, and statistical analysis. Therefore, various engineering programs may offer courses in electronics manufacturing as well. For example, Rochester Institute of Technology (RIT) has a Microelectronic Engineering Department that offers the only ABET-accredited B.S. program in Microelectronics Engineering in the United States.<sup>4</sup> Microelectronics Process Engineering degree program at San Jose State University,<sup>5</sup> currently being phased out, is hosted in the Chemical and Material Engineering Department. While over a dozen research-intensive universities such as Georgia Institute of Technology and University of Maryland have graduate-level courses on semiconductor manufacturing and microelectronics packaging, to the authors' knowledge, a very limited number of universities offer undergraduate-level electronics manufacturing courses, let alone a lower-division course.

People may argue that students in the United States do not need to learn electronics manufacturing because today American companies are increasingly moving their manufacturing offshore, especially to China and focusing only on high value-added core design functions. It is worthwhile to mention that a new Microelectronic Manufacturing Engineering program was established at Guilin University of Electronic Technology in China.<sup>6</sup> But the authors believe that a good design engineer should understand the manufacturing processes since designing products with acceptable cost yields can be a difficult task. This is why we advocate that electrical and computer engineering students should be educated on design for manufacturability (DFM).

Based on the experience of the Network Performance Research Laboratory (NetPRL) faculty at Cal Poly and feedback from Cal Poly's computer engineering industry advisory board, a knowledge and skills gap exists between the engineering curricula and professional practice. Students in computer engineering and electrical engineering were not prepared to develop complex systems requiring custom printed circuit boards (PCB) because PCB layout, fabrication, and assembly are not typically taught in most computer engineering and electrical engineering programs. The majority of electrical engineering programs teach basic electronics laboratories using solderless prototyping boards and circuit analysis using simulation software such as PSpice. But there is a wide gap between prototype design and analysis and the ability to implement an actual electronic device.<sup>7</sup> To fill the gap, several universities started to develop electronic manufacturing laboratories and offer courses for electrical and computer engineering students.<sup>7-10</sup> Under the support of a NSF ILI grant, the Electrical Engineering Department at Indiana University Purdue University Indianapolis (IUPUI) has developed several laboratory courses on electronics manufacturing.<sup>11-14</sup> But all of these courses are upper-division and most of them are technical electives. There is a need to have a required lower-division PCB design and manufacture course in engineering education.

This paper will present a project-based electronics manufacturing laboratory course. The goal of this course was to provide a hands-on experience for lower-division engineering students to design and manufacture an electronic device. Students acquire electronics manufacturing knowledge through a hands-on project involving printed circuit board design, layout, fabrication, assembly, and testing. Each student selects his/her own design project. Some examples of student projects include a power supply, a laser light show, a stepper motor driver, and a compression circuit for a guitar pedal. By selecting their-own projects to implement, students enjoy the laboratory experience and they are proud of the product that they created. This experience strengthens their confidence to take on further challenging design projects.

### **Teaching methodology**

Traditional teaching methodology is the lecture-based format, in which instructors present course materials on chalkboards or in PowerPoint format, then ask students to reproduce and/or apply the information on their homework or examinations.<sup>15</sup> This teaching methodology, which currently predominates in engineering education, may not be the best way to achieve learning outcomes.<sup>16</sup> There are two major drawbacks associated with the traditional teaching methodology. One is that it fails to develop the complete set of skills and abilities desired in a contemporary college graduate,<sup>17</sup> especially non-technical skills such as communication and

project management skills.<sup>18</sup> The other is that problem-solving skills can be developed only through practice, not by watching and listening in the lecture room.<sup>19</sup> That is why the Boyer Commission report<sup>20</sup> recommended to shift the undergraduate culture of receivers into a culture of inquirers, or from passive learning to active learning.

Project-based learning (PBL) can overcome the above two drawbacks. In project-based learning approach, the students are presented with a challenge project, then students decide how to solve the problem in a preset timeline and what activities to pursue. Thus, it shifts education from “Teacher-Centered” to “Learner-Centered” and it is an active learning method. Other variations of this approach include problem-based learning and inquiry-based learning. This PBL teaching method has gained increasing popularity in engineering education recently as evidenced by a significant number of papers on PBL appeared in educational literatures.<sup>21-25</sup> This teaching methodology will enhance the compliance with the ABET 2000 requirements including the ability to design a system, component, or process (ABET 3c), multi-disciplinary teamwork (ABET 3d), ability to formulate and solve problems (ABET 3e), and effective communication skills (ABET 3g).

### **Course Objectives**

IME 157 Electronics Manufacturing is an introductory course in the field of electronic manufacturing for manufacturing engineering, mechanical engineering, electrical engineering, and computer engineering students. Lectures introduce the major manufacturing processes, materials, and technologies of electronics packaging, surface mount assembly and printed circuit board fabrication. Labs are an integral part of the course and expose students to design, document and fabricate electronic units with emphasis on CAD/CAM. The learning outcomes of the laboratory component are that students will be able to:

- identify through-hole component types, values, and polarity;
- identify surface mount packaging types, pitch, and component orientation;
- use an Electronic Design Automation (EDA) tool to create schematics and layouts of electronic circuits;
- use an EDA tool to develop a component library, check design rules, and output manufacturing files;
- choose suitable trace width/space for both electrical current and manufacturability requirements, select angular ring size for through-hole leads and footprints for surface mount components;
- explain the materials and fabrication processes of printed circuit boards;
- select and order components kits online, and read component datasheets;
- operate various equipments used in PCB fabrication process;
- assemble PCBs through manual soldering and test PCBs;
- design a chassis and operate various equipment used in making a chassis for an electronic device;
- exercise project management skills and use the Gantt chart;
- exercise communication skills through preparing a proposal, writing a final report, and presenting in class.

## Details of Project

IME 157 Electronics Manufacturing is a lower-division engineering course and has no pre-requisite. The lecture meets twice per week for fifty minutes each and the lab meets twice per week for three hours each over the ten weeks of a quarter. We believe that laboratory work is very important component in engineering education and Cal Poly's teaching philosophy is "learning-by-doing".

Each student will work on two projects. The first project is a continuity tester. The purpose of this project is to guide students to design, manufacture, assembly, and test an electronic device. The second project is an open-ended project and selected by students. The overall schedule of the lab is shown in Table 1. The lab learning modules include

- Project selection and proposal writing
- PCB Design
- PCB Manufacture
- PCB Assembly
- Chassis Design
- Chassis Fabrication
- Device Testing and Inspection
- Final report and presentation

It is very challenging to accomplish all learning modules over a ten-week quarter.

Table 1. Overall Schedule of the Laboratory Course

Week	Activities	
	Session 1 (3 hours)	Session 2 (3 hours)
1	<ul style="list-style-type: none"><li>• Syllabus</li><li>• Lab safety training</li><li>• Project discussion</li></ul>	<ul style="list-style-type: none"><li>• PCB design tool training</li><li>• Proposal writing training</li></ul>
2	<ul style="list-style-type: none"><li>• Continuity tester chassis fabrication</li></ul>	<ul style="list-style-type: none"><li>• Design continuity tester board</li></ul>
3	<ul style="list-style-type: none"><li>• Soldering training</li><li>• 2<sup>nd</sup> project proposal due</li></ul>	<ul style="list-style-type: none"><li>• Manufacture continuity tester board</li><li>• 2<sup>nd</sup> project proposal approval</li></ul>
4	<ul style="list-style-type: none"><li>• Continuity tester board assembly</li><li>• Order 2<sup>nd</sup> project components and kits</li></ul>	<ul style="list-style-type: none"><li>• Continuity tester final assembly</li><li>• Start to design 2<sup>nd</sup> project board</li></ul>
5	<ul style="list-style-type: none"><li>• Continuity tester report due</li><li>• Students work on their own projects</li></ul>	<ul style="list-style-type: none"><li>• Students work on their own projects</li></ul>
6 - 9	<ul style="list-style-type: none"><li>• Students work on their own projects</li></ul>	<ul style="list-style-type: none"><li>• Students work on their own projects</li></ul>
10	<ul style="list-style-type: none"><li>• Final project presentation and report due</li></ul>	

## PCB Design Tool Selection

One of the significant lab activities is the use of a PCB design tool to layout a PCB. We have used OrCAD version 9.0 for several year in IME 157 and found that the learning curve of the tool was too steep for a freshman-level student in the ten weeks of a quarter. Many students had difficulty finishing the second project without open labs every Saturday and weekday nights. In the revised curriculum, we also scheduled a week (week 10) dedicated for final project

presentation. This makes time management more difficult. We decided to investigate which EDA tool is better for the freshman-level PCB design and manufacturing course.

There are over 50 PCB design tools available.<sup>26</sup> We divided them into three groups. The first group is the state-of-the-art professional EDA tools, for example, Allegro© of Cadence and Expedition© of Mentor Graphics. Both Cadence and Mentor Graphics have excellent educational packages for universities. Cadence claimed that over 200 universities in the U.S. have Cadence software licenses. Both companies' EDA tools are very powerful and have been used in university curricula. For example, Purdue University used Cadence EDA tools for the design of PCBs<sup>10</sup> and IUPUI used Mentor Graphics tools in their upper-division electrical engineering course.<sup>13</sup> We at Cal Poly have also used both tools in upper-division and graduate-level courses. However, formal in-depth training of these tools is needed before students are able to work on their own projects. We concluded from our experiences that both tools are not suitable for lower-division PCB design and manufacturing course. But we recommend these tools for upper-division, or graduate-level electrical engineering and computer engineering courses since these tools are widely used in industry and we believe students want and need to learn the leading technology to meet the industry demands.

The second group is free PCB design tools provided by PCB manufacturers such as PCB123<sup>27</sup> by Sunstone Circuits, expresspcb<sup>28</sup> by ExpressPCB, and PCB Artist<sup>29</sup> by Advanced Circuits. All these packages have schematics capture and PCB layout tools. All these tools are user-friendly and were developed to require no formal training or in-depth experience with PCB design. Thus, these tools are excellent choices for the freshman-level course. However, all these tools do not allow the user to export the industry standard Gerber, or ODB++ manufacturing format files. PCB design files can only be submitted and ordered through these manufacturers. Thus, we cannot use these tools to make our own boards in our lab or submit manufacturing files to other PCB vendors.

The third group is the medium or low-range PCB design tools such as Eagle©, CADSTAT, MCCAD, and DipTrace. We listed the following questions as the main selection criteria:

- How much does the tool cost? Free or lower cost is better since some universities and colleges do not have the budget to purchase specialized software. Prefer having student version or free version so that students can work on their own computers at home.
- What are limitations of the tools? *e.g.*, the number of pins, the board size, and the number of layers?
- Does the tool have autorouting and design rule check features?
- Can the tool export standard manufacturing format files such as Gerber, ODB++, etc.
- Does the software have comprehensive component libraries, both for schematic and layout? How easy is it to create a new custom component library?
- Is the tool easy to use overall?

The first author and two of his students downloaded and compared CADSTAT, DipTrace, Eagle, VUTRAX, MCCAD, and Free PCB. The results are shown in Table 2. Note that we do not list CADSTAT, VUTURE, MCCAD, and Free PCB in Table 2 because of the limit of the table size. These four PCB design tools did not meet at least one of our selection criteria.

We selected DipTrace as the PCB design tool for the lower-division engineering course on PCB design and manufacturing. The DipTrace freeware allows students to work on their projects on their own computers outside of lab. Students can export manufacturing files in the university lab where several license seats of non-profit version are installed. Eagle© was not selected mainly because of the board size limitation since some of our student project boards are larger than 160 mm by 100 mm. Note that the license fee for both DipTrace and Eagle is per seat (with no expiration date), while the license fee for both Cadence and Mentor Graphics tools are per year (with multiple seats, normally over 25 seats). Also note that both Cadence and Mentor Graphics EDA tools are only allowed to be installed on university computers that point to a license server. Thus, students cannot work on projects outside of the lab.

Table 2. Comparisons of Various PCB Design Tools

EDA tools		DipTrace		Eagle		PCB123, ExpressPCB PCB Artist	Allegro and OrCAD	PADS or Expedition
Version		Freeware	Non-profit	Freeware	Non-profit			
License cost		Free	\$125	Free	\$125	Free	\$2000 per year	\$200 or \$500 per year
CAD Limits	# of pin limit	250	1000	No	No	No	No	No
	Board size limit	None	None	100 x 80 mm	160 x 100 mm	No	No	No
	# of layer limit	2	4	2	4	No	No	No
Features	AutoRouting	Yes	Yes	Yes	Yes	Yes		
	Design rule check	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Library	Comprehensive library provided	Yes	Yes	Yes	Yes	Yes		
	Easy to create custom library	Yes	Yes	Yes	Yes	Yes	Require in-depth training	
Ability to export Gerber or ODB++ files		No	Yes	Yes	Yes	No	Yes	Yes
Overall ease of use		Yes	Yes	Yes	Yes	Yes	Require in-depth training	

### Continuity Tester Project

The purpose of the continuity tester project is to guide students in designing, manufacturing, assembling, and testing an electronics device. The project consists of a circuit board exercise and a chassis exercise. In the circuit board exercise, students go through the steps to design and produce a circuit board. The continuity tester consists of 12 components listed in Table 3. The schematic of the project is shown in Figure 1. Students were given the schematic of the project and all components. After finishing the DipTrace tutorial, students were asked to re-draw the schematic using the DipTrace tool. Students were guided to create libraries of all components, and lay out the circuit. Then students fabricated the PCB under the supervision of the instructor or a teaching assistant. The chassis exercise exposes students to basic sheet metal processes to fabricate an enclosure for the continuity tester circuit. After that, students were trained on how to solder components manually. Students also learned how to identify resistor values using the

resistor color codes, how to identify the polarity of the diode and the LED, and how to identify pin 1 of the surface mount component, U1.

Table 3: Bill of Materials of the Continuity Tester

ITEM	QTY.	REF.	DESCRIPTION
1	1	D1	Diode, 1N914
2	1	D2	LED, red, SIZE 1-3/4, Panasonic LN21RPHL
3	1	J1	Test lead, red, 12”L
4	1	J2	Test lead, black, 12”L
5	1	J3	Cable, 9V battery snap
6	1	R1	Resistor, 2 K ohm 1/4W, 5% tolerance
7	1	R2	Resistor, 10 K ohm 1/4W, 5% tolerance
8	1	R3	Resistor, 100 ohm 1/4W, 5% tolerance
9	1	R4	Resistor, 470 ohm 1/4W, 5% tolerance
10	1	R5	Resistor, 100 ohm 1/4W, 5% tolerance
11	1	S1	Switch, Panasonic EVQ-PAC09K
12	1	U1	IC, LM311M, surface mount component

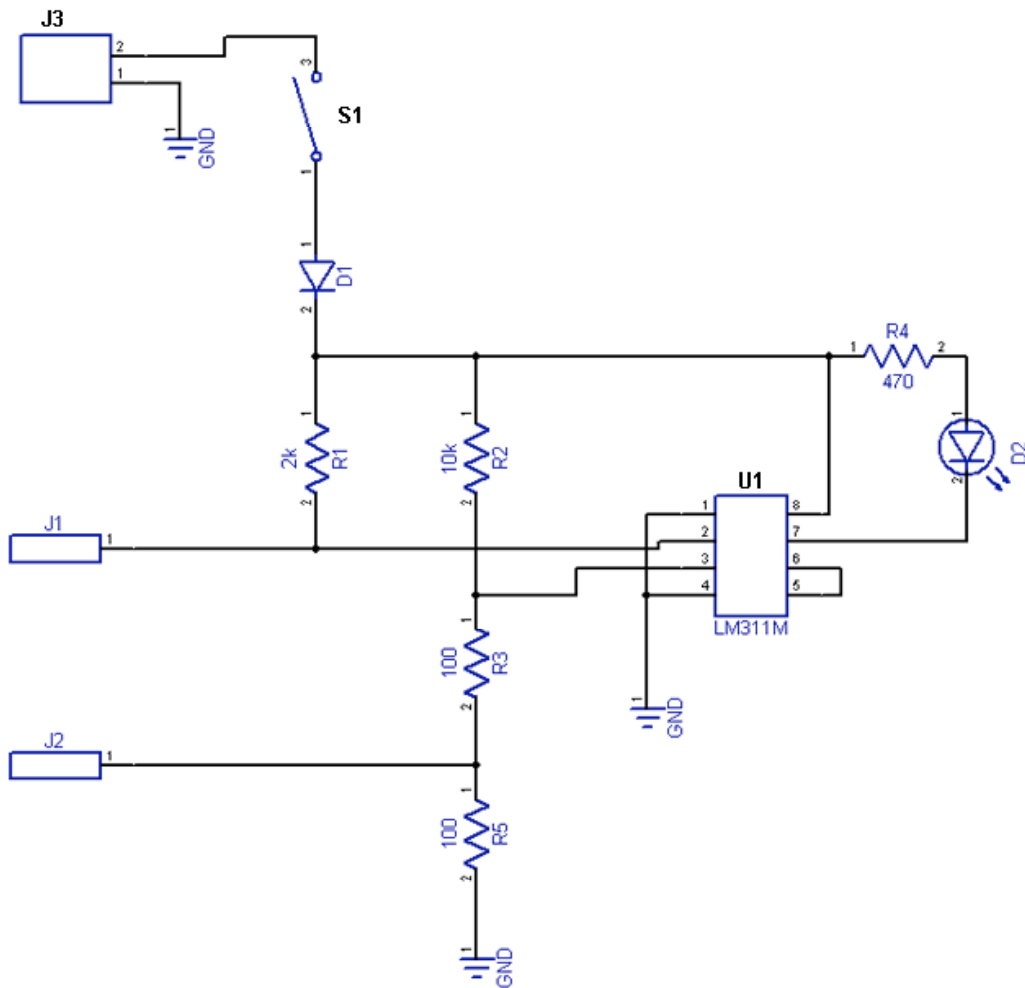


Figure 1. Schematic of the Continuity Tester Project



## Project Selection and Proposal Writing

Students were asked to select their own projects through Internet search. Two good sources are Jameco<sup>30</sup> and Omitron Electronics<sup>31</sup>. Students were advised to select a project with reasonable complexity (about 15 to 50 components) and affordable cost (\$10 to \$50). Students were asked not to use surface mount components with less than 1.25mm (or 50 mils) pitch due to the difficulty in manual soldering. If they have had experience in circuit design, students may design their own circuits and purchase components from Digikey<sup>32</sup>, Mouser Electronics<sup>33</sup>, or a Radio Shack store. But designing student's own circuits was not encouraged since it is not the focus of this class. Students were then asked to submit a proposal for the instructor's approval to make sure the project is manufacturable at the lab.

The requirements of the proposal format was given to students including formats and font size. The proposal format includes a title page, abstract (1-2 paragraphs), introduction (1-2 paragraphs), project description (3 pages maximum), schedule (Gantt Chart), and budget. The project description should include the function of the project, how the system works, how many components total, component types, and their pitch level.

## PCB Design

Students were instructed that the PCB design follow the flow chart shown in Figure 2. Students were asked to go through DipTrace tutorials provided with the software. A demo on how to create a component footprint library and how to export manufacturing files was given. In this process, students learned how to select trace width/space, pad sizes, and the size of the angular ring both for manufacturability and for current requirements. Students learned how to search for a datasheet of a component and find its physical dimensions. Students also learned to create a schematic and layout of an electronic circuit using the DipTrace.

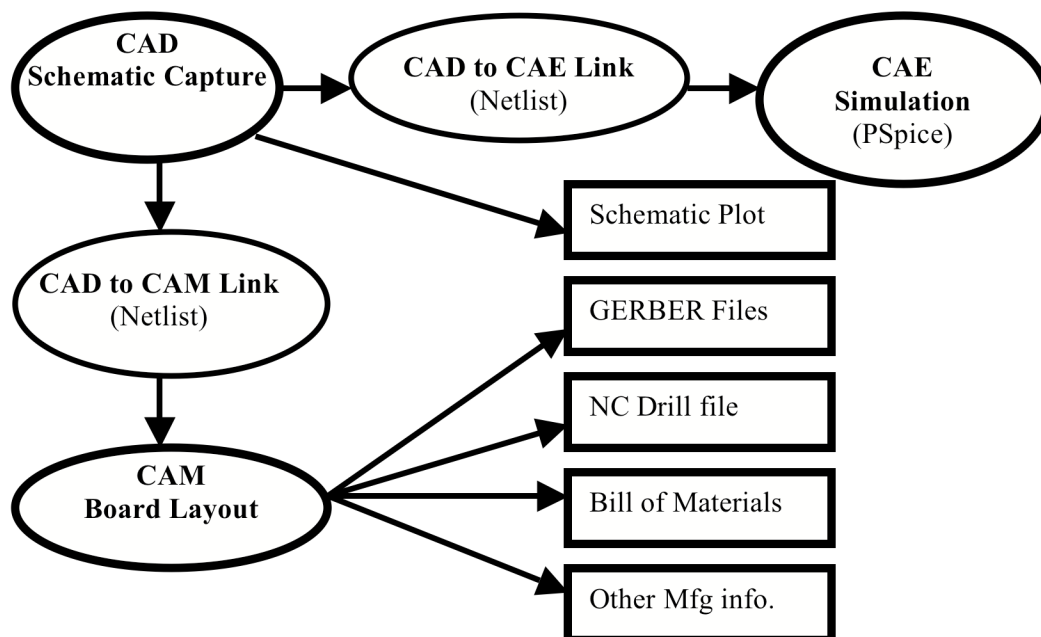


Figure 2. Design to Manufacturing Flow Chart for Electronic Products

## **PCB Manufacture and Assembly**

The detailed PCB materials and manufacturing processes are taught in lecture. Braun<sup>8</sup> summarized and compared four PCB manufacturing methods in a university environment: 1) commercial production of PCBs, 2) in-house facilities for photo-exposure, chemical etching and automated drilling, 3) use of pre-sensitized PCBs photo-processing and manual drilling, and 4) mill/dill machine. At Cal Poly, we have a dark room for photo-exposure, a Kepro (now D&L Products) Bench-top laminator, a Kepro bench-top developer, and a Kepro bench-top etcher for photoresist lamination, chemical developing and etching. Though we are unable to make multi-layer boards, the facility provides the capability to produce PCBs of up to two-layers and provides good educational training. The PCB manufacturing processes include drilling a fiber-class laminated board, making a photo-tool, laminating a dry photoresist onto the board, exposing the photoresist using UV, developing the photoresist, etching the board, stripping the photoresist, and cutting the board to size.

After the board was fabricated and holes drilled, students began to assemble the components on the board. In this process, students not only practiced manual soldering skills, but also learned how to identify various component types, values, polarity and orientation.

## **Chassis Design and Manufacture**

A chassis is also required for the electronic device. Although many students had learned engineering drafting in high schools, most did not have mechanical CAD experience. Therefore, hand-drafting drawings are acceptable and CAD drawings are a plus. Students were asked to design his/her chassis and make a mock-up using cardboard for approval before they were allowed to cut and bend sheet metal. The purpose of the mock-up is to make sure that students had a feasible chassis design to avoid the waste of sheet metal. In the lab, students were provided with 0.75 mm (or 0.030 inch) thick mild steel for making the chassis. In this chassis fabrication process, students used various tools including the metal shear machine, the sheet metal bender machine, the metal sheer notch maker, dial calipers, file, hole de-burr tools, hole punch machine, ruler, center punch, hammer, hand drill, and drill bits. After it was fabricated, the chassis was painted and labeled, and the PCB was connected to the chassis. Note that the overall operation and electronics are the main focus on the project, whereas the chassis merely needs to be functional.

## **Sample Projects**

*A Guitar Pedal:* Figure 3 shows a compression pedal for use with an electric guitar. The purpose of a compression circuit is to variably change the gain of the input to a constant desired output level. If the input is greater than the threshold, the circuit limits the gain, and if the input is less than the desired output, the circuit amplifies it. The compression pedal has a footswitch controller for turning the effect on and off, a volume knob to control the output level, and a bias trim knob to control the threshold compression level. It is powered by an internal 9V battery with an option to connect to a 9V DC wall-wart power supply.

***A stepper motor drive:*** The stepper motor driver shown in Figure 4 supports two 6-lead, unipolar stepper motors and allows for independent direction control, step mode (full-step, half-step, or wave), speed, and power.

***A laser light show:*** The project uses a laser pointer, some mirrors, and some motors to create epicyclical light patterns. In addition, it has one final mirror mounted on a speaker, which modulates the light pattern to the beat of the music. There are a total of four circuits: two motor control circuits (one for each of the two motors) that provide power to the motors and allow the speeds of the motors to be adjusted using a potentiometer, one audio circuit for the speaker which has an audio-in jack for the audio source as well as a potentiometer to adjust the volume of the speaker, and one power circuit which has a DC-in jack and a battery connector, allowing for two different power sources. The power circuit then takes the incoming DC and provides it to the other three circuits and to the laser pointer, all in the proper voltages.

***A power supply:*** The power supply uses a transformer to convert a 110-volt power from a wall socket into a variable DC power output for miscellaneous use.

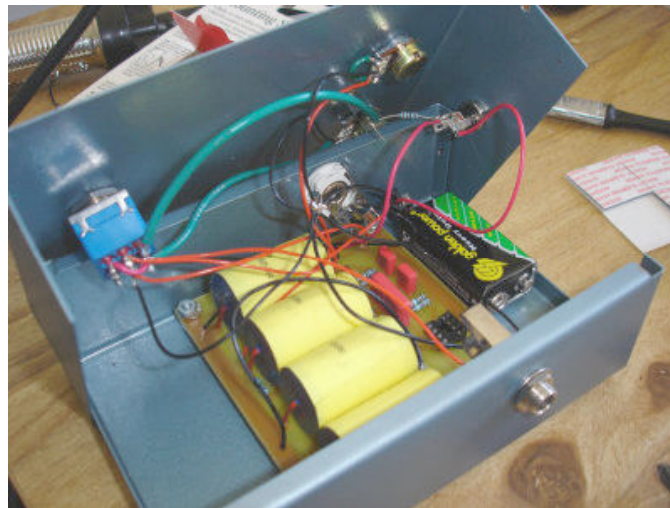


Figure 3. Sample Project 1: A Guitar Pedal

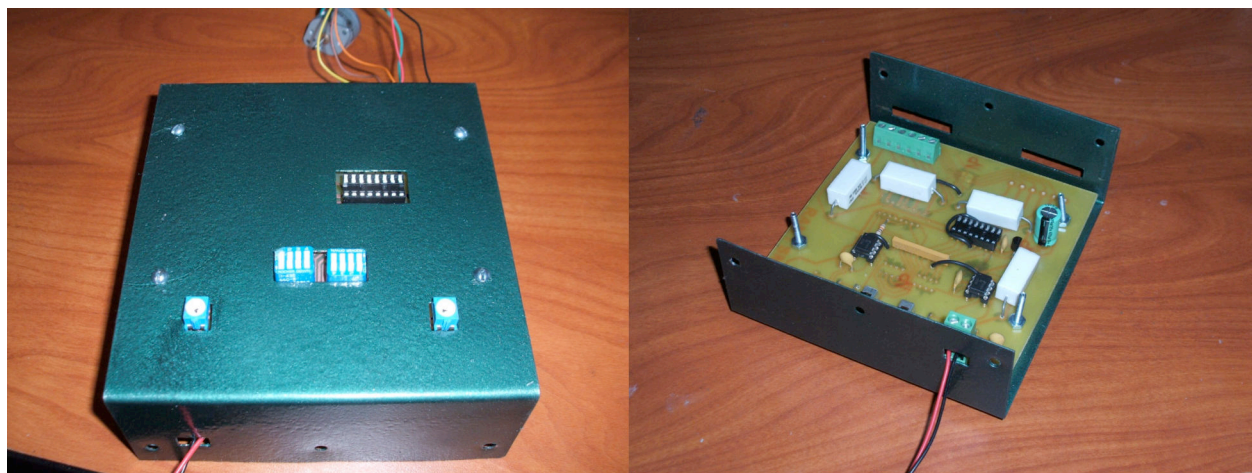


Figure 4. Sample Project 2: A Stepper Motor Driver





Figure 5. Sample Project 3: Laser Light Show

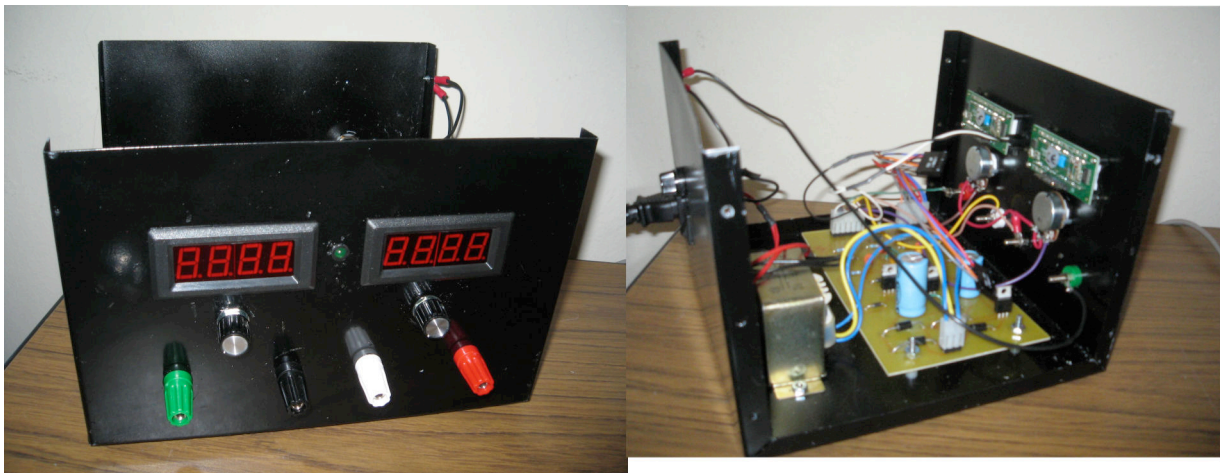


Figure 6. Sample Project 4: A Power Supply

## Project Evaluation

In the last week, students were asked to give a 10-minute presentation and demonstration of his/her project plus 5 minutes for questions and answers. Student projects were evaluated by five faculty members from three departments: Industrial and Manufacturing Engineering, Mechanical Engineering, and Electrical and Computer Engineering, as well as a community college instructor who teaches both circuits and mechanics. Students were also asked to evaluate their peers. The project evaluation rubric given to judges is shown in Table 4. What we found was that the evaluation scores from student peers were consistently higher than that from faculty members.

Table 4. Project Evaluation Rubric

Criteria	Presentation	Technical Content
Score = 5	<ul style="list-style-type: none"> <li>• Presentation was clear</li> <li>• Slides were very well thought and to the point</li> <li>• Presenter was very knowledgeable and self-confident</li> <li>• Presenter rarely looked at notes and has eye-contact</li> <li>• Presenter's answers to the questions indicated an exceptional understanding of the project</li> </ul>	<ul style="list-style-type: none"> <li>• The project was working</li> <li>• The project was appropriate for a student beyond the presenter's current level.</li> <li>• Board schematic and layout were correct</li> <li>• The quality of board fabrication and soldering was excellent</li> <li>• The quality of chassis design and fabrication was excellent</li> </ul>
Score = 4	<ul style="list-style-type: none"> <li>• Presentation was clear</li> <li>• Slides were understandable and enhanced the presentation</li> <li>• Presenter spoke clearly</li> <li>• Presenter referred to notes but didn't read notes and has eye contact</li> <li>• Presenter answer questions to the satisfaction of the class</li> </ul>	<ul style="list-style-type: none"> <li>• The project may or may not working</li> <li>• The project was appropriate for a student at the presenter's current level</li> <li>• Board schematic and layout were correct</li> <li>• The quality of board fabrication and soldering was acceptable</li> <li>• The quality of chassis design and fabrication was acceptable</li> </ul>
Score = 3	<ul style="list-style-type: none"> <li>• Presentation was clear</li> <li>• Slides were understandable</li> <li>• Presenter spoke clearly</li> <li>• Presenter referred to notes but didn't read notes</li> <li>• Presenter answer most of the questions to the satisfaction of the class</li> </ul>	<ul style="list-style-type: none"> <li>• The project was not working</li> <li>• The project was appropriate for a student slightly below the presenter's current level</li> <li>• Board schematic and layout were correct</li> <li>• The quality of board fabrication and soldering was O.K.</li> <li>• The quality of chassis design and fabrication was O.K.</li> </ul>
Score = 2	<ul style="list-style-type: none"> <li>• Presenter was unsure of the research and his/her work</li> <li>• Slides were difficult to read</li> <li>• Presenter read most of the presentation from the notes</li> <li>• Presenter could answer a few questions</li> <li>• Presentation exceeded 12 minutes.</li> </ul>	<ul style="list-style-type: none"> <li>• The project was not working</li> <li>• The project was appropriate for a student well below the presenter's current level</li> <li>• Board schematic and layout had some issues</li> <li>• The quality of board fabrication and soldering was O.K.</li> <li>• The quality of chassis design and fabrication was O.K.</li> </ul>
Score = 1	<ul style="list-style-type: none"> <li>• Presenter was totally disorganized</li> <li>• No slides or transparencies</li> <li>• Presenter was unable to answer any questions.</li> <li>• Presentation exceeded 12 minutes or too short to be effective.</li> </ul>	<ul style="list-style-type: none"> <li>• The project was not working</li> <li>• The project was inappropriate</li> <li>• Board schematic and layout had many issues</li> <li>• The quality of board fabrication and soldering was unacceptable</li> <li>• The quality of chassis design and fabrication was unacceptable</li> </ul>

### Advice to Future Students

In the final project report, students were asked to provide advice to future students of this course. One recommendation made by almost every student was to manage time well. They suggested future students start the project early since every student had to repeat at least one step during the project. Several students even recommended that the instructor place stiffer due dates for the board layout and the board fabrication.

The second recommendation made by many students was to select a good project. One student wrote, "Do not choose an overly simplistic design, as you will learn very little, and become bored. Conversely, do not choose an overly complex design, as you will be constantly frustrated and pressed for time." The third recommendation was design for manufacturability. Students learned that the manufacturing process for narrower copper traces was not stable and it is difficult to make reliable solder joints on small pads.

### **Students' Feedback**

Students were asked to provide their honest feedback on this laboratory course. Some of students' feedback is copied below:

"Being a freshmen and learning the whole process of PCB fabrication and putting it to use on my own project is what am proud of. ...After this project I can't wait to take a higher level class to get to apply my newly learned knowledge on some projects in more advanced [courses] in which I can challenge myself even more."

"Now I have a better understanding of the advantages and disadvantages of through-hole mounting as opposed to surface mount technology. ... the hands-on experience in the lab was very enlightening. Another part of the learning process that I appreciated was the chassis design and fabrication. Being able to construct precision parts out of sheet metal was another key factor that had to be considered in the project design."

"Overall, this was a very educational experience. I feel that the laboratory component of this class, although very rigorous, supported the concepts presented in the class very well. Throughout the project, every aspect of the electronics manufacturing process was new to me, and I feel that I now have intimate knowledge of the art. From soldering, to etching, to board design, I felt that I truly experienced Cal Poly's 'learn by doing' philosophy."

"This is probably the most satisfying project I've ever done."

"This project provides a good challenge through having to learn new software and having to critically think through the issues that arose throughout the process. Also, it tests your patience, and your ability to follow instructions. These are great characteristics that will serve as a great tool for yourself and will carry through in the future when working for your future employer."

"This project has really opened my eyes to the world of Electronic Manufacturing. Before this class, I could not tell you one thing on the process of creating PWBs, and chassis. I now fully understand how boards are created, and also how to create these boards on the computer and then transform them into a physical object. My skills in soldering, chassis design, and computers has improved dramatically over this quarter. A PWB will never look the same now that I have some idea how they work and how the components are installed onto it. It is amazing to me the technology that I use everyday without knowing it, and how all of Electronics Manufacturing affects my life, and the whole world."

## Summary and Conclusions

The paper describes a lower-division project-based hands-on laboratory course on electronics manufacturing. It is clearly shown from the students' feedback and the students' projects that the course provides a solid foundation of PCB design and manufacture and all learning outcomes have been achieved. Students were proud of making some things useful by themselves. The hands-on experience makes the learning experience enjoyable. This project experience better prepares students for advanced electronics circuit study. With the adoption of the DipTrace tool, it is it feasible to make two electronic devices in a ten-week quarter. Through project-based learning methodology, students not only learn technical skills in designing and manufacturing an electronic device, but also exercise their project management and communication skills in the early stage of college study.

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