# An *Improved* "Intuitive Calculus" Project, Using Electronic Filters, for a First-Year Engineering Math Laboratory

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*Abstract* - **According to National Science Foundation (NSF) research, engineering mathematics courses with a laboratory ("hands-on") component are more effective in helping students grasp concepts, than lecture-only approaches. Beginning in 2008, California Baptist University (CBU) received NSF funding through Wright State University to develop a first-year Engineering Math course (EGR 182) with laboratory projects. Our new College of Engineering currently offers nine degrees and all freshmen must take this course. The lab projects aim to illustrate key mathematic concepts via hands-on experiments representing each discipline. In a previous FYEE paper (2014), we reported on a calculus-themed project using electronic filters to illustrate calculus' two fundamental operations: integration and differentiation. The "intuitive calculus" lab's primary objective is to help students see a simple and applied way of understanding these two operations. Simply put, integration is a "smoothing" function, and differentiation is a "roughening" function. In engineering language, they're known as a *low-pass filter* (LPF) and a *high-pass filter* (HPF), respectively. Following a novel pre-lab assignment, students build and evaluate simple low- and high-pass "RC filters" (using one Resistor, one Capacitor). Next, they repeat the experiments, but using equivalent *digital* filters. In all cases, the *smoothing* and *roughening* operations are observed, via an oscilloscope, by applying filter input signals and noting how the output is affected—as a function of frequency. In this paper, we introduce a new, lower-cost, easier-to-use implementation of the digital filters and an overall improved lab project. Our new design uses the microcontroller-based "Programmable System on Chip" (PSoC) technology. Included is a built-in, easy-to-configure digital filter block. We also use PSoC's ability to generate a sum-of-2-sinusoids signal (at two different frequencies) for filter input that nicely illustrates the filtering process. Compared to our previous design, we show that the PSoC-based lab project is much cheaper (less than $30 per lab station), easier to create, and easier to pass on to colleagues at other universities who have little or no electronics background.**

*Index Terms* - lab project, mathematics with engineering applications, calculus, microcontrollers, PSoC 5LP

## INTRODUCTION (AND REVIEW OF PREVIOUS WORK)

As reported in our previous work [1], the National Science Foundation (NSF) funded an initiative at Wright State University (WSU), circa 2004, to "redefine the way engineering mathematics is taught" [2]. The goal was to increase student retention, motivation, and success in engineering. The WSU model focuses on a novel first-year engineering math course, taught by engineering faculty, which includes lecture, lab, and recitation. The course uses an application-oriented, hands-on approach—and only covers the math topics that students actually use in their core engineering courses. Klingbeil et al. reported in 2013, based on careful assessments, that the results have been encouraging [3]. They also point out that a student's success in engineering is strongly linked to his/her success in math "and perhaps more importantly, on the ability to connect the math to the engineering". That is, to see the relevance of math to engineering.

Beginning in 2008, California Baptist University (CBU) received NSF funding through WSU to develop this new type of first-year engineering math course (EGR 182) and create laboratory projects. Our new Gordon and Jill Bourns College of Engineering offers ABET-accredited degrees in Civil, Mechanical, and Electrical and Computer Engineering, plus six other degrees. All freshmen must take EGR 182. The lab projects aim to illustrate key mathematic concepts via hands-on experiments representing each discipline.

## HANDS-ON APPROACHES TO ENGINEERING EDUCATION

The use of hands-on or learn-by-doing approaches is becoming widespread in engineering education. Another name for this is "problem-based" learning. The *STEM Lab Report* states [4]:

"Throughout higher education in engineering, colleges are requiring students to pull their gaze from a text-book to perform real-world, hands-on, team-based project learning. In short, they are teaching students to become engineers by having them work as engineers."

Furthermore, they claim that research shows that such "project-based" learning works at all ages, even as early as pre-school. As an example of this, Ghalia [5] showed how even high school geometry students' outcomes improved by using electrical engineering hands-on projects to illustrate geometry and its importance to solving real-world problems in radar. Observations in the classroom also indicated greater student interest (i.e., enjoyment). Aloul et al. [6] stated that first-year engineering courses often use problem-based curriculum to "…ensure that students find relevance in the Physics and Math courses being taken in the first two years of engineering."

Drawing from the above references, the key benefits of hands-on approaches for students are better outcomes, seeing the relevance of math (and engineering) with real-world examples, deeper understanding, more enjoyment, and persistence in engineering.

### EGR182 – Introductory Mathematics for Engineering Applications

CBU's EGR 182 is a 4-credit course. Based on the WSU model [2], it has a lecture and lab, but no recitation component. However, tutorial sessions are provided twice weekly throughout the semester. As in the WSU course, the lecture addresses only the "salient math topics" which are needed in the core engineering courses—such as trigonometry, vectors and complex numbers, systems of equations and matrices, and calculus. We use the textbook developed by the WSU authors [7].

The weekly lab session meets for 90 minutes and provides hands-on lab projects that illustrate selected math topics from the lecture material. Students work in teams of two to perform the lab experiments and write a carefully formatted report. A substantial part of the lab grade is based on the written report, since we believe that good writing is important in an engineering career. A nearly-complete sample lab report is provided for the first lab report, to serve as a guide to proper writing. In lab one, the MATLAB software tool is introduced, and this tool is woven into nearly all of the other labs during the semester.

### Intuitive Calculus Lab Project

This lab project runs for two sessions and consists of a pre-lab assignment plus five hands-on circuit exercises. In session one, the instructor gives a short introductory lecture, interacts with students over their completed pre-lab material, and gives a demo of the first hands-on exercise. Students then perform three exercises (focusing on analog filters). In session two, the instructor reviews the material by asking the class a series of questions on what was learned so far. He then gives a demo to prepare them for the final two exercises—which focus on digital filters. In this lab, students are not required to write a lab report, but each team must submit a provided "journal" sheet with observations and measurements made while performing the exercises. The grade for this lab is based on the pre-lab and the journal submission.

*I. Novel Pre-Lab Assignment*

The pre-laboratory assignment (consisting of seven problems) is intended to introduce the students to the "intuitive calculus" aspects of the lab, but to do so by making them think in a different way. One of the objectives is to teach them that engineers must learn to communicate difficult/complicated concepts in easy-to-understand ways—for the average person. The first question appeals to their own experience with math: "Have you ever been in a math class where the language used to convey the meaning behind the mathematics lost many of the students? Describe that experience and its consequences."

The key question in the pre-lab asks the students to draw three stacked graphs (which, unknown to them, could represent an object's displacement, velocity, and acceleration—showing integration as you go from top to bottom and differentiation going the other way). Figure 1 shows the ideal solution to this question. First, they are asked to draw, in the center graph, a triangular-shaped "signal" (or wave shape). Next, they are asked to sketch, in a graph above, the derivative of the triangle wave, and in a graph below, the integral. Finally, to bring home the lesson, they must: "Look at the three graphs you have drawn and describe in one 8th-grade-language-word the difference in the shape of the graphs as you go from a) top to bottom (integration) and b) bottom to top (differentiation)." Many students do respond with terms similar to "smoother" and "rougher".

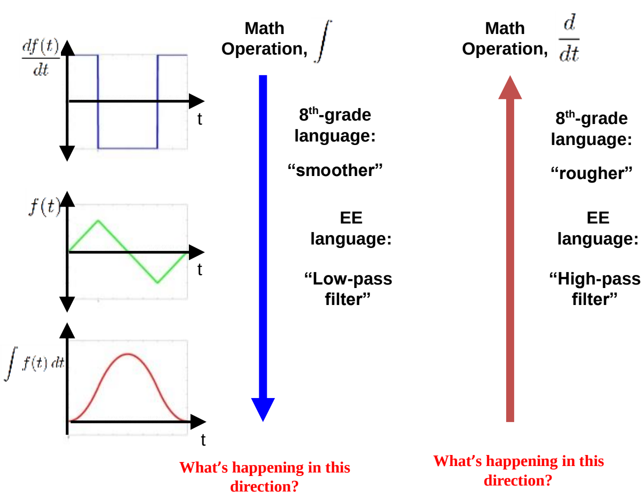


FIGURE 1
Ideal Solution to Key Pre-Lab Question.

*II. Lab Manual Introduction to Signals, Filters, and PSoC*

As part of the pre-lab, students must read the lab manual which provides simple introductions to signals, filters, and the Programmable System-on-Chip (PSoC). PSoC is a type of (programmable) digital microelectronic circuit ("chip"). Over one billion of these devices have been sold and it is a powerful vehicle for implementing digital filters. Our purpose in using a PSoC board in this project is to expose students to digital filters, in contrast to simple analog filters. We use the PSoC boards like we use oscilloscopes—both are complicated "instruments" (like an automobile), but students don't need to know what's "under the hood", just how to "drive" them.

The practical application aspect of the lab—implementing calculus in filters—is summarized in Figure 2 (taken from the lab manual). The calculus *math operations*—shown in the left column (with integration and differentiation symbols)—correspond to the filter *signal operations* on the right.

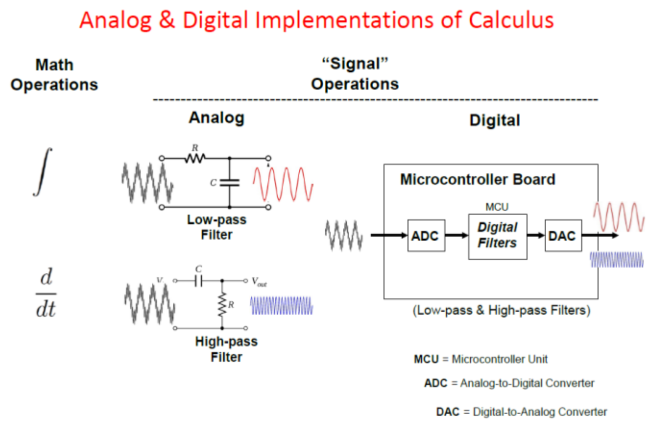


FIGURE 2
ANALOG & DIGITAL IMPLEMENTATIONS OF CALCULUS.

Integration (smoothing) is implemented by a LPF—either an "Analog" one (composed of one Resistor and one Capacitor), or a "Digital" one (composed of more complex parts). The input signal shown represents the sum of two sinusoidal waves at two different frequencies (and two different amplitudes). As its name denotes, the LPF "passes" the lower frequency sinusoid to its output, as shown, by rejecting or smoothing away the higher frequency component of the original signal.

Conversely, differentiation ("roughening") is implemented by a HPF, in either analog or digital form. As Figure 2 depicts, given the same input signal, the higher frequency component is "passed" to the output, while the lower frequency one is rejected. Thus, calculus can be implemented—and illustrated—in the two types of electronic filters shown.

*III. Five Hands-On Exercises*

For the hands-on portion of the lab, student teams use laboratory equipment to build and evaluate five relatively easy-to-assemble circuits. In previous labs, they were introduced to, and practiced using, several basic "instruments" that are now used altogether: breadboard, power supply, digital multi-meter, function generator, and oscilloscope.

*A. Exercise 1—Seeing and Hearing a Sine-wave, Un-filtered*

First—as a point of reference for what follows—students listen to an *unfiltered* sinusoidal voltage waveform played on a speaker and viewed on an oscilloscope (as the frequency is swept from low to high—which creates a siren-like tone). Many seem delighted by this "audio-visual" experience—especially when asked to record the highest frequency they can hear. They observe and hear a sine-wave whose amplitude remains constant over frequency, because it is unfiltered. This will later be compared to sine-wave amplitudes that diminish in certain frequency regions due to the filtering action (smoothing or roughening).

For this exercise, the voltage signal (waveform) is provided by the function generator.

*B. Exercises 2-3—Analog RC Filters (Low-Pass, High-Pass)*

In the next two experiments, students build and evaluate simple low- and high-pass "RC filters" (made from one Resistor, one Capacitor—Figure 2), respectively. They observe the LPF *smoothing* operation by sweeping the input frequency from low to high and noting how higher frequencies are increasingly attenuated (but lower ones are "passed"). Conversely, the HPF *roughening* operation is observed by sweeping the input frequency from high to low and noting how lower frequencies are increasingly attenuated (but higher frequencies are "passed").

The lab manual also introduces the filter concept of the *cutoff frequency*, $f_c$, which is the point where the frequencies that are being attenuated are reduced to the "half-power point" (equal to signal output voltage attenuated by 0.707) [8]. In exercises 2-5, students are required to estimate and record in their journals the value of $f_c$ for each filter.

Note that the typical function generator can only provide a single-frequency sinusoidal signal—and not the sum of two sinusoids with different frequencies (as portrayed in Figure 2). Due to this limitation, the filter operations (smoothing, roughening) are observed by sweeping the input signal's frequency to the filter and noting how the output diminishes over certain frequency ranges, depending on filter type (LPF, HPF).

However, as explained later, this paper introduces a feature of the PSoC technology that allows a "sum-of-2-sinusoids" signal to be generated as a filter input. Students can now use this signal in addition to the function generator's output, to illustrate how filters work.

*C. Exercises 4-5—Digital Filters (Low-Pass, High-Pass), Using PSoC*

In the final two experiments, students repeat the previous two but using a *digital* LPF and HPF implemented in a provided PSoC circuit board (Figures 2 and 4). We developed the digital filters to show students that digital techniques are a popular and powerful way to implement math operations, such as calculus, in real-world applications.

## PSoC Explanation and Enhancements

*I. Lower Cost, Easier to Design With*

In our previous work, the digital filters were based on Field Programmable Gate Array (FPGA) technology—another type of programmable digital circuitry. FPGAs are very popular and effective, but somewhat more difficult to design with, and the circuit boards are generally more expensive than the PSoC board introduced here.

In this paper, we report on an alternative digital filter implementation using a different technology. As mentioned, our new lab project design is based on a popular hardware-programmable *microcontroller* system, known as the Programmable System on Chip (PSoC). PSoC is essentially a computer-on-a-chip with other special programmable electronic building blocks. Included is a built-in, easy to configure digital filter block.

Figure 3 is a photo of the small PSoC circuit board used.

FIGURE 3
PSoC CIRCUIT BOARD ("PSoC 5LP KIT").

Figure 4 shows the lab hook-up of the PSoC on a breadboard, plus associated components, along with a companion Liquid Crystal Display (LCD), and interconnect-wires and oscilloscope probes. See the Appendix for more details.

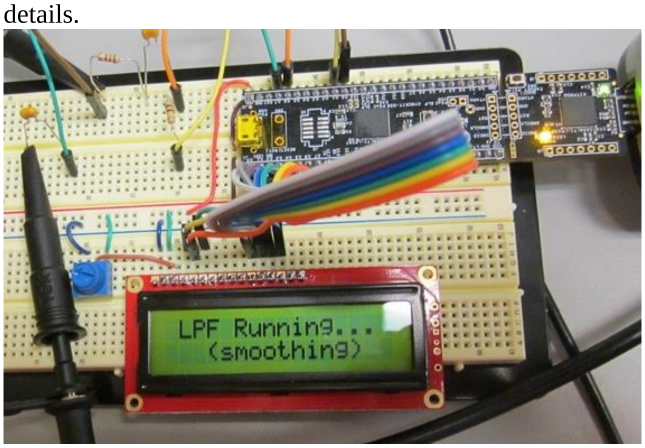


FIGURE 4
LAB EXERCISE CIRCUITRY—RUNNING THE LPF OPERATION.

*II. Novel Learning Enhancement: Sum-of-2-Sinusoids as Filter Input Signal*

In this improved lab project, we conceived and implemented what we believe is a novel learning enhancement. It was realized that PSoC can be programmed to contain both a digital filter and a "waveform generator" to drive the filter. PSoC has the ability to add two sinusoidal signals together, using its built-in Digital-to-Analog Converter (DAC) block—see Appendix schematic (WaveDAC8 blocks). As previously stated, standard lab instrumentation (e.g., Function Generators) can only provide single-sinusoid signals for driving circuits. For this calculus-themed project, filtering a signal that is composed of two sinusoids (at two different frequencies) allows students to more directly see how filters work (and implicitly how calculus works). That is, depending on parameters chosen, one sinusoid will be removed (filtered out) and the other retained. Figures 5 and 6 show oscilloscope traces of this action. In Fig. 5, the top trace, generated by PSoC, is the sum of two sinusoids (whose frequencies are 1 kHz and 10 kHz). This was applied as the LPF's input signal. The bottom trace, the LPF output, shows that smoothing (integration) has kept the 1 kHz signal but rejected the 10 kHz component. Analogous traces are shown in Fig. 6 for the HPF (where frequency measurements shown are slightly affected by "noise")

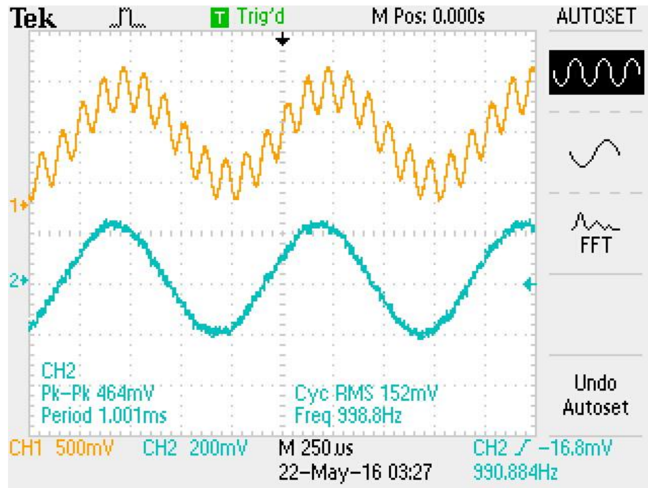


FIGURE 5
OSCILLOSCOPE TRACES—LOW-PASS FILTER.
(TOP = LPF INPUT: SUM-OF-2-SINUSOIDS, BOTTOM = LPF OUTPUT)

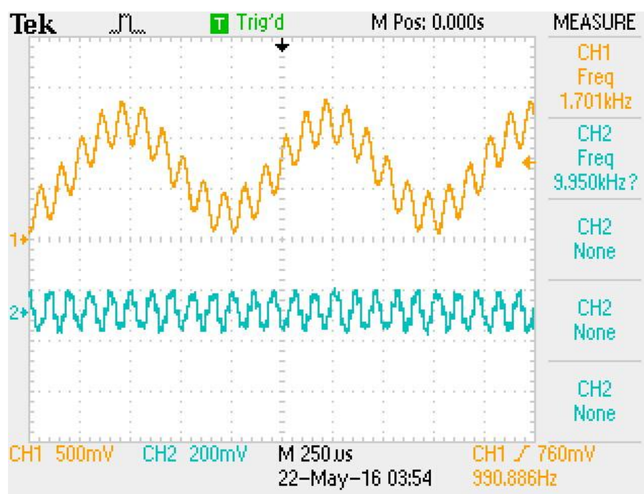


FIGURE 6
OSCILLOSCOPE TRACES—HIGH-PASS FILTER.
(TOP = HPF INPUT: SUM-OF-2-SINUSOIDS, BOTTOM = HPF OUTPUT)

## DISCUSSION AND CONCLUSION

This paper presents an improved version of a complete lab project aimed at helping students see a simple and applied way of understanding the two fundamental operations of calculus. Integration and differentiation are presented as "smoothing" and "roughening" operations, respectively. Then, they are implemented in hands-on lab exercises as low-pass and high-pass filters—for students to observe and evaluate—in a simple, fun, and enlightening manner.

Many engineering disciplines use calculus—and they use filters (whether implemented electronically or by software tools such as MATLAB). Therefore, we believe that this "intuitive calculus" project is both novel and applicable to a wide audience of engineering students.

Furthermore, compared to our previous design, we show that the PSoC-based implementation of this lab project is much cheaper (less than $30 per lab station), easier to create, and easier to pass on to colleagues at other universities who have little or no electronics background. In addition, using PSoC, we effectively embed a "waveform generator" instrument within our design that creates the sum-of-sinusoids signal which more strongly aids in the visualization of the filtering action.

Finally, as previously reported, after running the original version of the lab for two semesters (approx. 100 students), no statistical data has yet been acquired regarding final grade improvements. However, preliminary analysis of responses to the pre-lab assignment indicated that many students can see the "smoothing" and "roughening" way of understanding integration and differentiation, respectively. Also, in-lab observations of students working on the hands-on exercises revealed a positive interest in seeing a real-world application of calculus. This new version of the lab project is slated to be employed in fall 2016.

## FUTURE WORK

In terms of pedagogy, we plan to explore ways to assess the effectiveness of this method for "intuitively" conveying calculus concepts. Also, we may explore technical enhancements such as embedding both the LPF and HPF in one design (perhaps selectable by a user switch on the PSoC board), and as a "boot-loadable" design running on batteries. Thus, the PSoC would not require connection to a PC, nor design software to be installed.

## ACKNOWLEDGMENTS

We would like to acknowledge the National Science Foundation for funding that enabled the creation of our EGR 182 course and this new lab project. Additionally, we are grateful to Wright State University for their leadership and collaboration in developing this type of course.

## APPENDIX: PSOC DETAILS—FOR SETTING UP THE PROJECT

The digital filters in this paper are implemented within the "PSoC 5LP" small prototyping circuit board made by Cypress [9]. See Fig. 3. Current price of this "kit" is $US 10. After soldering two sets of header pins (not part of kit) into the board, it can be mounted on a breadboard, as shown in Figure 4.

Cypress provides the (high quality, easy-to-use) design software (*PSoC Creator*) for free, downloadable from their website [10]. The PSoC 5LP board can be directly connected to a PC's USB port, or by extension cable, to power the board and to allow the *Creator* software to program the actual PSoC 5 chip with the filter designs. The LPF and HPF are separate projects which must be alternately programmed into the PSoC board to implement a filter.

This PSoC 5LP design (Creator schematic for LPF shown in Fig. 7) was adapted from two Cypress Application Notes: CE95316 and AN69133 [11], [12]—which include zipped reference design files, to help a designer get started. Creating the HPF (from the LPF) only required one simple parameter change within the menu for the "Digital Filter Block" of Fig. 7. Creator ver. 3.2, SP1 was used for this paper.

The LCD (Fig. 4) is available at Sparkfun, for $US 14 [13]

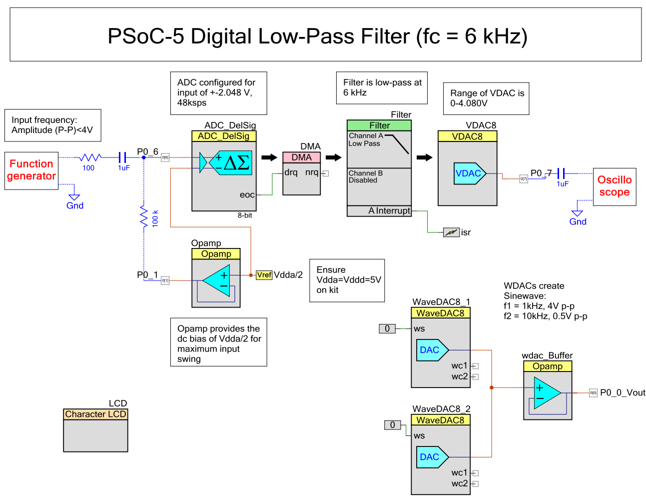


FIGURE 7
PSOC CREATOR (V. 3.2) SCHEMATIC FOR LPF DESIGN.

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