

## **Using Guitar Pedals to Introduce Amplifier Design and Printed Circuit Board Layout in an Electronics Course**

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### Abstract

One of the foundational learning outcomes of upper level engineering electronics courses is the analysis and implementation of discrete amplifier design. While it is relatively straight-forward to implement these designs in the lab, the application of amplifiers in practice may be difficult for students to understand.

A simple application of discrete amplifier circuits is the analysis and design of guitar effects pedals. Effects pedals, and in particular overdrive, fuzz, and distortion circuits, demonstrate keystone concepts of electronics, including single stage amplifier design, multistage amplifier design, clipping, biasing, and variable parameter control. In addition, the implementation of these amplifiers in a small package size (within a metal enclosure) provides an excellent avenue for exposing students to printed circuit board (PCB) layout and prototyping. One benefit of these circuits is that they can be used with an input device (guitar) and an output device (audio amplifier) and students can physically observe (and hear) the results of their design. One particular benefit of this approach is a greater understanding of frequency response characteristics, as students are able to hear the results.

In this work, several lab projects were developed for an upper level engineering electronics course to leverage guitar pedal design for teaching discrete amplifier design and PCB layout. This paper presents these projects, resources for implementing the projects, as well as assessment results from the initial offering of this course. In addition to direct assessment of the amplifier design course objectives, qualitative student survey results are presented. Both the direct assessment and student survey results suggest that this approach was effective in helping students better understand amplifier analysis and design.

### Introduction

Universally, electrical engineering programs require courses in analog electronics. These courses often possess at least one specific student learning outcome related to amplifier analysis and design. The analysis and design of amplifiers is most often achieved by calculation, and basic lab exercises abstracted from the application to real world scenarios. The lack of obvious real-world connection affects the student's ability to conceptualize and perform amplifier design [1]. Furthermore, assessment results from previous offerings of the first electronics course in the EE sequence suggest students struggled to understand amplifier design. To address these concerns, there was a desire to integrate these topics for both remediation and content extension into the second course in the electronics sequence, which was offered for the first time in the course of this research.

As a result, lab project ideas were sought which allowed for the simultaneous integration of amplifier design and analysis content with real world application. Desirable factors included easy data visualization and projects that would provide a feeling of accomplishment or gratification to the students. One approach that meets these requirements is the design of guitar effects pedals. Two attractive factors for project selection emerged: that guitar effects pedals had been used by other programs in electronics courses, and that audio engineering topics were an excellent option as a real-world application for engineering students.

Several previous studies mention the use of guitar effects pedals or audio amplifiers as projects within the context of electronics courses. Mashburn, et al. [2] employed the analysis of a guitar distortion pedal in a sophomore level engineering fundamentals course in their 1996 research. In 2001, Dyer, et al. [3] suggested that macroelectronics, rather than microelectronics, was the gateway to student understanding of electronics, because students are able to see discrete components. As a part of this work, they had at least one group construct guitar effects pedals. In other studies [4],[5] there are passing mentions of students building guitar effects pedals as a part of analog design courses, but no further context is provided. Pan, et al. [6] used the hands-on experience of designing and building guitar effects pedals in an electronics manufacturing course to expose students to PCB layout and manufacturing techniques.

In addition to these studies, evidence suggests that Audio Engineering topics are helpful in many engineering disciplines. McPheron, et al. [7] suggests that hands on application valuable for learning design fundamentals, and that audio applications are effective in teaching engineering lessons. In 2015, Stokes and Doering [8] also espoused the benefits of audio engineering topics, stating that these topics reinforce EE concepts, and that they capture the interests of undergraduate EE students who are also musicians. Miller and Herrera's 2018 study also describes the creation of a simple audio amplifier to aid in engineering student understanding [9].

As an extension of the existing literature on the use of effects pedals within engineering education, 5 different lab projects involving the design and implementation of guitar effects pedals were created for the Analog Circuit Design course, which is the second course in electronics at Anderson University. In this paper, a description of each project is provided, as well as a link to a repository of course resources. Direct assessment is provided for the initial run of this course for the ABET Student Outcomes (SOs) addressed by these projects. Student survey results are also presented as a form of indirect assessment.

## **Lab Projects**

This section outlines the five total lab projects developed over the course of this research. These projects were implemented in the second electronics course in the EE sequence. Each project is described in brief and some examples of student work from these projects are shown. After the projects are described, they are mapped to the SOs they address. At the end of the section, a link is provided to a GitHub repository containing all resources used in this course.

### Project 1: Introduction to kiCAD and PCB Fabrication

In this project, students watched a training video on kiCAD, then synthesized a new layout for a PCB design in kiCAD. After converting the file to Gerber format, they used a PCB mill to produce a PCB which they populated with components and verified using test and measurement equipment. kiCAD was chosen because it is a free, open-source software, perfect to expose students to the principles of PCB layout. Figure 1 displays an example kiCAD PCB layout generated as a result of this project. This PCB shows the layout for a discrete BJT amplifier with connectors intended to accommodate amplifier test and measurement.

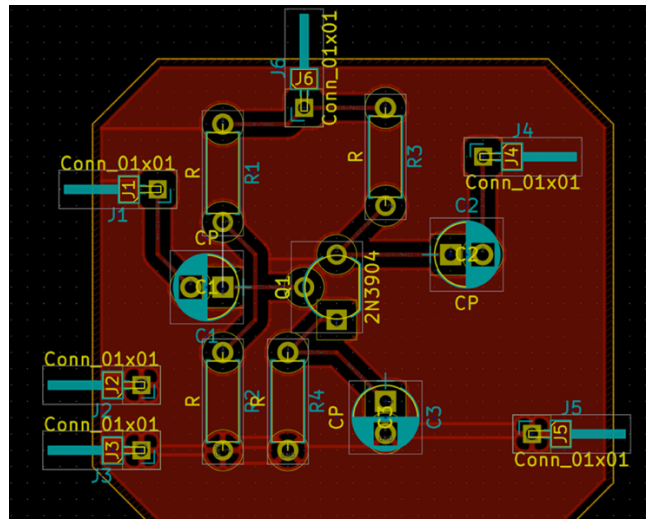


Figure 1: kiCAD PCB layout showing a discrete BJT amplifier

### Project 2: Fuzz Face

In this project, students analyzed and built their first guitar effects pedal in the form of a transistor amplifier known as a ‘fuzz’ circuit. Students were required to read the Fuzz Face analysis found at <https://www.electrosmash.com/fuzz-face>, and verify bias point calculations from the values given, simulate the time domain response, and prototype the circuit on a breadboard. The circuit given directly from the reading did not work to bias specifications, so students were required to adjust their design to achieve the desired response. Then, they designed, fabricated, populated, and verified a PCB for the circuit. In addition to traditional analysis and simulation, students also qualitatively tested the circuit using a guitar and audio amplifier.

### Project 3: Tube Screamer

This project leveraged an overdrive effects pedal called a Tube Screamer to help students learn about operational amplifier circuits and frequency domain analysis. Students read the Tube Screamer analysis at <https://www.electrosmash.com/tube-screamer-analysis>. They were required to simulate the circuit for bias point, transient, and frequency domain analysis and then to prototype the circuit on a breadboard, testing different diode clipping configurations. Then, they were required to design, fabricate, populate, and verify a PCB for the circuit. In addition to traditional analysis and simulation, students also qualitatively tested the circuit using a guitar and audio amplifier. Figures 2 shows the simulation for the tube screamer circuit. The circuit makes use of multi-stage amplification, with two distinct operational amplifier stages and two emitter follower amplifiers used to isolate the input and output from the gain stages. Students are able to see several

electronics topics in a single circuit, including op-amp differential amplifiers, BJT amplifiers, diode clipping circuits, and voltage regulation. Figure 3 shows the frequency response of the simulation circuit, which students had to interpret with their understanding of system frequency response parameters.

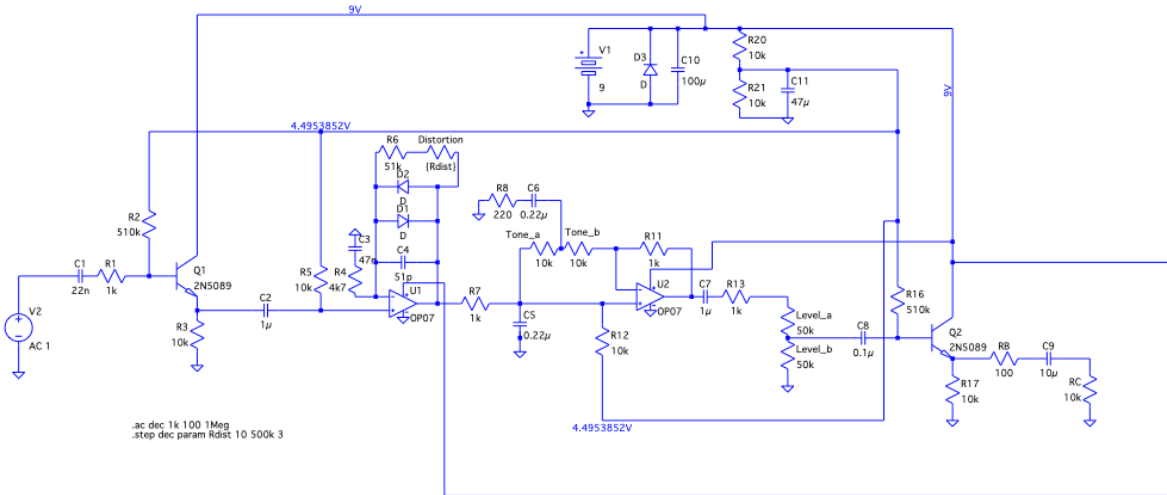


Figure 2: Simulation circuit for a Tube Screamer.

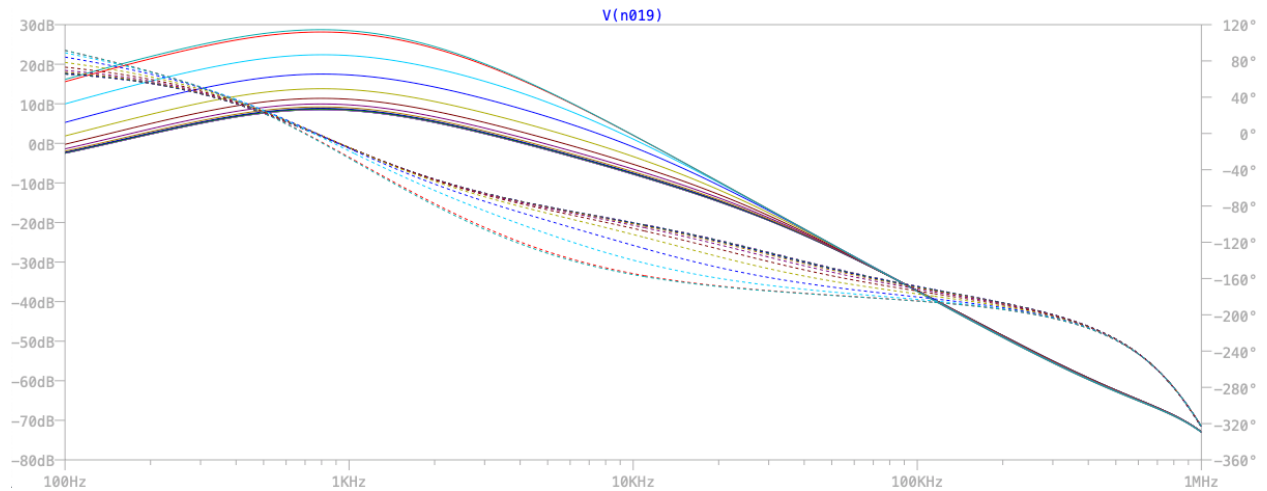


Figure 3: Frequency domain response for a Tube Screamer

#### Project 4: Blues Breaker and ProCo Rat

Project 4 is a simulation only project designed to expose students to additional effects circuit architectures in a compressed time frame rather than the multi-week analyze/design/build/test sequence of Projects 1, 2, and 3. Students are required to complete simulations to analyze the transient and frequency response of two operational amplifier effects pedals, the Blues Breaker overdrive, and the ProCo Rat distortion and interpret the data to better inform the final design project.

### Project 5: Design Project

Students were required to design their own guitar effects pedal which implements discrete amplifier circuits based on knowledge gained in projects 1-4. Realistic constraints and requirements were introduced. The constraints were:

- DC power supply voltage was limited to 0-9V, which is what is commonly available for guitar pedals
- The PCB dimensions had to be small enough to fit inside the provided metal enclosure
- PCBs had to be single sided
- Components had to come from the general supply available in the lab, no special orders were allowed

Requirements for the design were:

- A minimum of two amplifier stages using op-amps, BJTs or MOSFETs
- At least one parameter had to be adjustable using a potentiometer

Students were required to analyze the circuit as thoroughly as possible through calculation and simulation and fine tune in a prototype using test and measurement equipment. Students then were required to design, fabricate, populate, and verify a PCB for their circuit, documenting all test procedures. Figure 4 shows a resulting PCB for this project, which contains components and test leads populating the single sided copper board which was fabricated in a desktop PCB mill. Figure 5 shows the kiCAD PCB layout used to produce the physical object in Figure 4. Figure 6 shows the circuit design and simulation data for the same circuit along with measurement data for the completed PCB, demonstrating reasonable agreement between the simulation and practice.

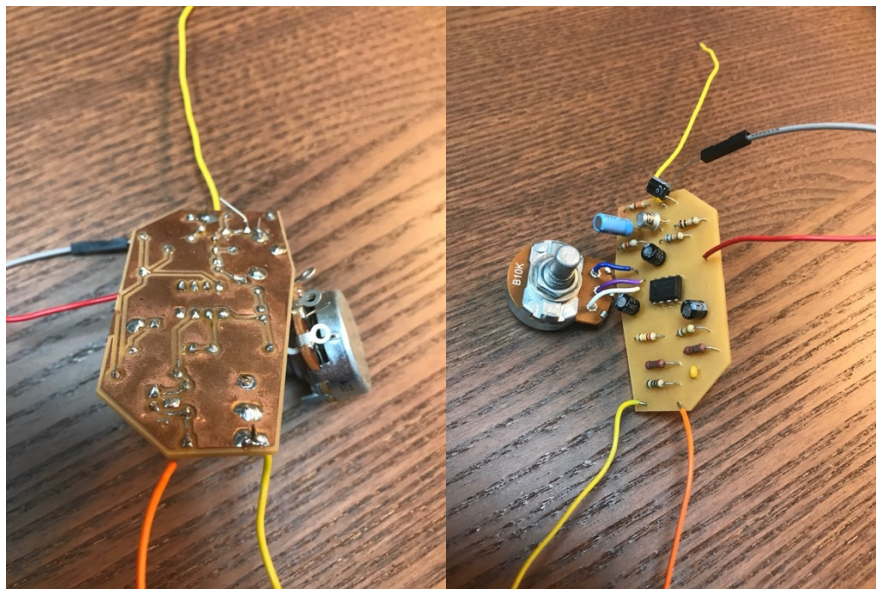


Figure 4: Resulting populated PCB for Project 5

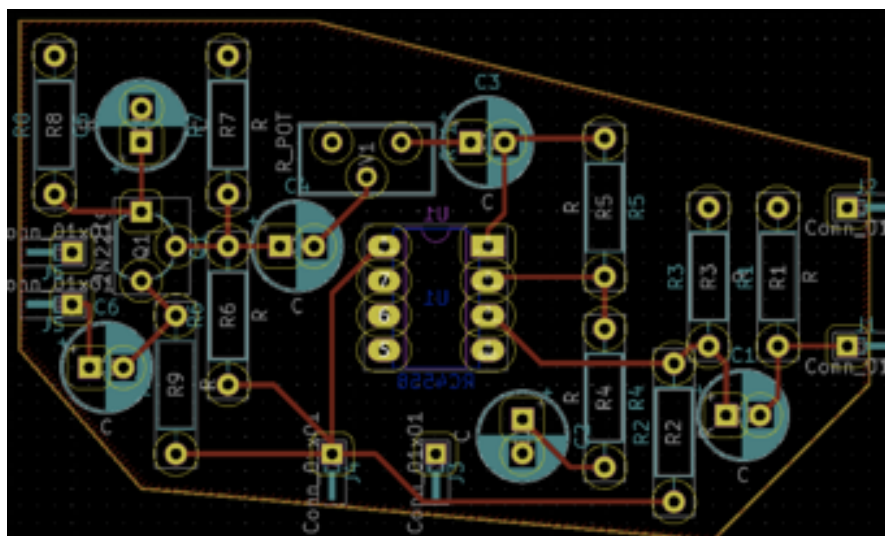


Figure 5: PCB layout for Project 5

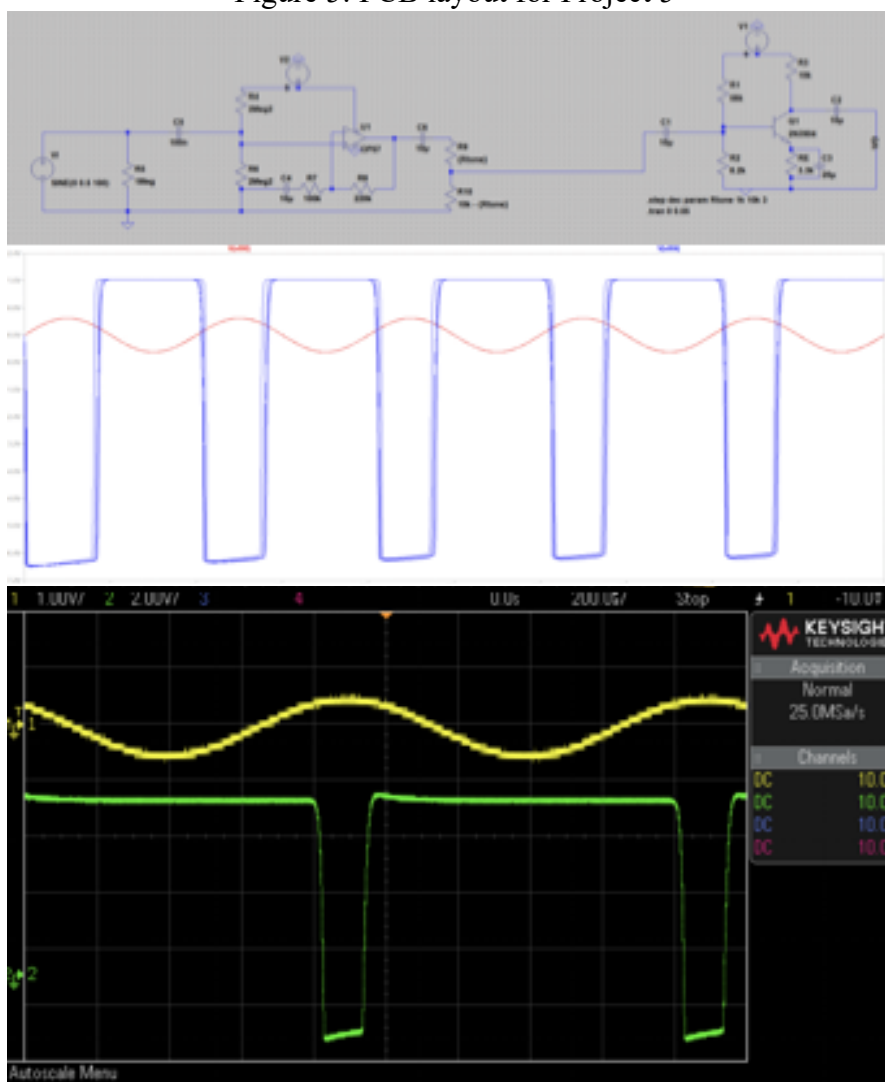


Figure 6: Simulation data and measurement data for Project 5

The lab projects presented in this work specifically relate to 4 of the 7 ABET Student Outcomes [10]. These outcomes are listed in abbreviated form along with their justification below:

- **ABET Outcome 1:** An ability to identify and solve complex engineering problems
  - **Justification:** Mathematical analysis of discrete amplifier systems requires application of bias point and small signal analysis techniques, which are direct applications of engineering science
- **ABET Outcome 2:** An ability to apply engineering design to produce solutions that meet specified needs
  - **Justification:** The final project requires students to design an amplifier to meet specified constraints.
- **ABET Outcome 6:** An ability to develop and conduct appropriate experimentation and interpret data
  - **Justification:** The majority of these labs require both experimental work and simulation. Students are asked to draw conclusions based on interpreting resulting data.
- **ABET Outcome 7:** An ability to acquire and apply new knowledge as needed
  - **Justification:** The application of new software requires students to acquire new skills through self-directed study. In these projects, students develop skills in kiCAD and LTspice for PCB layout and advanced simulations.

Table 1 provides a map of each SO to one or more lab assignments.

Table 1: SO Map by Lab Assignment

Outcome	Labs
SO1	Lab 2, Lab 5
SO2	Lab 5
SO6	Lab 2, Lab 3, Lab 4, Lab 5
SO7	Lab 1, Lab 4

The pertinent resources for these projects, as well as the bill of materials are available through a GitHub repository at <https://github.com/bdmcpheron/GuitarPedals>.

### Assessment Strategies

Direct assessment for this work is implemented by evaluating student performance for each SO addressed by the projects in the course. Assessment data from the first electronics course motivated the addition of these topics in the second electronics course, which was offered for the first time as a part of this work. As a result, historical data is not available, and direct measures of student achievement are used rather than comparing against a historical average. As a benchmark, a mastery level is set at 83% for each SO, as this is the minimum percentage to earn a grade of ‘B’ in the course. Basic achievement of the SO is set to be 73%, the minimum to earn a ‘C’, as students are required to average at least a 2.0 to graduate.



In addition, a 9 question Likert scale survey was used to assess student self-efficacy of the achievement of course outcomes. The following statements were rated, with 1 being strongly disagree and 5 being strongly agree:

1. Building guitar pedals in ACD lab helped me better understand the design of discrete amplifiers
2. Building guitar pedals in ACD lab helped me better understand the design and analysis of multistage amplifiers
3. Building guitar pedals in ACD lab helped me analyze the frequency response of electronic circuits
4. Building guitar pedals in ACD lab helped me improve skills in implementing and testing circuit designs in hardware
5. ACD lab improved my skills in PCB Layout
6. ACD lab improved my skills in PCB Fabrication
7. ACD lab improved my ability to simulate complex electronic circuits
8. I enjoyed designing and building guitar pedals
9. I would recommend guitar pedals as the subject of lab experiences in an Analog Circuit Design course at another university

### Assessment Results and Discussion

The results of direct assessment are shown in Table 2, which displays the average achievement in the course for each of the SOs addressed by the lab projects presented in this work. Compared to the 83% mastery benchmark, the average rating is above mastery for each outcome. However, it is also important to see how each student performed individually, as a few very high scores can affect the mean in such a small sample size. Table 3 shows the results for each SO broken out by student. These results show that three of the four students averaged above mastery on all four SOs, and the fourth student achieved mastery on all but one SO, falling just short of basic achievement in the final SO. While these results are promising, the small sample size means these results cannot be generalized. The particular cohort in this course will dramatically affect the result with such small numbers.

Table 2: Direct Assessment of SOs Addressed by Lab Projects

Student Outcome	Average Achievement
SO1	88.9%
SO2	84.5%
SO6	87.6%
SO7	93.3%

Table 3: Student by Student Direct Assessment

Student	SO1	SO2	SO6	SO7
1	85.5%	89.8%	89.4%	93.3%
2	94.8%	88.6%	89.4%	93.3%
3	84.9%	87.3%	86.3%	93.3%
4	90.6%	72.2%	85.3%	93.3%
<b>% Mastering</b>	<b>100%</b>	<b>75%</b>	<b>100%</b>	<b>100%</b>

In addition to direct assessment, students were asked to rate their perception of their achievement of course outcomes, as well as their feelings about the lab projects in this course. A summary of these results is shown in Table 4. Again, the results have limited application, with a small sample size, but they indicate students generally felt that the lab projects helped them learn.

Table 4: Results of indirect assessment using Likert scale survey

Question	Average	Standard Deviation
1	4.75	0.5
2	4.5	1
3	4.75	0.5
4	4.75	0.5
5	5	0
6	5	0
7	4.75	0.5
8	5	0
9	5	0

## Conclusions and Discussion

In this paper, a set of 5 projects were introduced to integrate hands-on, real-world experiences to electronics amplifier design and analysis into the second electronics course at Anderson University. This work builds on previous work by a number of researchers to use guitar effects pedals for this purpose. One contribution of this work is a repository of the course materials developed.

While this study suffers from limitations of a small sample size, the results are promising for future study. These labs will be refined, and data from future offerings of the course will be collected to possibly provide more meaningful results. A succinct summary of this work was provided by a student completing the course survey, in their own words: *These labs were some of the best ways to visualize and implement the theory in a real-world application. Pedals are dope!*

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