A PROJECT-FOCUSED SYNTHESIZER CURRICULUM FOR EARLY ELECTRONICS EDUCATION IN THE CAL POLY AUDIO ENGINEERING SOCIETY

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ABSTRACT

A Project-Focused Synthesizer Curriculum For Early Electronics Education In The Cal Poly Audio Engineering Society

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This thesis discusses a project-based analog synthesizer system design curriculum created for the Audio Engineering Society club at Cal Poly. The curriculum presents electronic circuit designs, including bills-of-materials and schematic diagrams, with accompanying accessible explanations targeted at engineering club members, enabling them to create and understand a hobbyist-inspired analog audio synthesizer design. Contrary to a formal engineering curriculum which takes a long time to progress, the design selectively introduces electrical engineering topics on an “as-needed” basis, as deemed necessary by the system’s design. Where possible, hobbyist explanations are leveraged to quickly arrive at exciting applications and motivate the development of foundational intuitions. This represents a first in engineering club educational strategy by ensuring that a project-based curriculum is easily available to club members and accessible without advanced topic knowledge.

ACKNOWLEDGMENTS

I knew my parents would be unable to help me with my engineering studies from the moment I solved an integral and my dad said, “Wow! I remember doing that, but I have no idea how calculus works anymore.” That said, my parents have been some of my strongest advocates, supporting me throughout my studies. Similarly, my siblings have rarely helped me in school; nevertheless, I have no doubt that the journey would be a million times more difficult without them in my life. My family is always there for me, and never more than a phone call away.

Engineering is difficult, but it doesn’t need to be done alone. I’ve relied on so many friends to help me be successful in my classes, commiserate during the difficult times, and motivate each other to be the best we can be. Surprisingly, a lot of my friend group exists outside of engineering (shoutout to dance & the arts), and those friends have helped just as much: keeping me sane, happy, and reminding me that I’m a valued part of many different communities.

I owe a big thank-you to the Audio Engineering Society at Cal Poly, which is the reason I came to this school initially. It’s been difficult, and the club has almost “died” multiple times — but it’s been so worthwhile to see what it’s becoming. I’m so grateful to have shared the experience of keeping it alive and to be part of its success with my fellow officers.

Finally, I’m grateful for the guidance of my professors at Cal Poly, who helped me to shape this thesis into what it is. To Dr. Wayne Pilkington, for placing faith in my idea to craft this curriculum in the first place, and to Dr. Bridget Benson for helping me to focus it in its early stages of development.

I can’t emphasize enough that none of this work would be possible — or at least, it would look very different — without the support of all of these people. I am so lucky to have you all in my life.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Chapter 1

INTRODUCTION & PROBLEM STATEMENT

Undergraduate electrical engineering curricula span a vast array of interconnected topics and rely on myriad fundamental concepts which require many courses over years of study to formally introduce and develop. Domain knowledge extends far beyond the imagination and comprehension of those unfamiliar with the field, making it a challenge to efficiently navigate the knowledge space to acquire the needed skills and intuition. Even at universities such as Cal Poly, which emphasize hands-on approaches, it is common to see electronic components and applications introduced as late as the third or fourth year of study. For most of their time in undergraduate studies, students may have a poor understanding of what constitutes an analog electronic system design, or even how fundamental electrical principles can be applied to build and understand useful analog circuits with recognizable functions.

This may not be recognized as a problem for the university, where slogans like, “Ready Day One” suggest an ultimate goal to fully prepare students for their careers by the time they graduate. This emphasis on terminal learning objectives may miss opportunities to leverage what students already understand “today” to motivate them onward toward that goal; by engaging their curiosity for later topics well before their formal coverage by the curriculum. [1]. Undoubtedly, eager students may feel impatient and dissatisfied with the curriculum’s relatively slow rate of knowledge acquisition — it certainly can feel like a flawed system which says, “Not yet.” However, regardless of how harsh it may be to hear, the fact that “learning takes time” is a feature of the university, and more broadly, a fundamental reality of learning any topic deeply. In stark contrast to a university, student clubs are not interested in a “Ready Day One” approach, instead desiring to accomplish something “today.” Deadlines aren’t four years in the future, but are instead on the order of mere weeks or quarters, and the slow-and-steady approach — a feature in the university context — presents a liability and a promise of failure to individuals seeking to do something “now.”

Motivated students can overcome this challenge with self-learning; and with access to the Internet, it seems plausible that anyone should be able to teach themselves anything. It is true that educational resources are more abundant than ever; however, there are numerous assumptions that this response fails to address. Critically, unlike a university curriculum, good “maps” to self-education with respect to club-specific goals may not exist. Students may spend weeks blindly pursuing topics which are irrelevant to their goals, or even be unable to articulate their goals in the first place — a problem which is compounded by the “unknown unknowns” inherent to any sufficiently complex field [2]. Compounding this need of effective curriculum maps is the realization that even the most motivated student has a limited budget of time and energy for such self-learning. As indicated by Cal Poly’s recommended outside study time of “25-35 hours/week” [3]. degree coursework alone requires considerably more dedicated time than a full-time job; accounting for the typical additional 16 hours that students spend in the classroom each week. For these reasons, effective self-directed learning is challenging, and most students would have difficulty achieving much success on their own.

Most clubs develop workarounds to deal with this asymmetry: for example, established clubs commonly feature senior students leading and mentoring more junior members, and this is one of the critical functions of an advisor. Regardless of who is leading, though, this solution ignores the considerable time and effort that such roles demand. Developed problem spaces are rich with their own vocabulary, technologies, histories, and applications which take time to understand deeply and are not covered in typical curricula. While an engineering degree prepares an individual with the tools to understand niche problem spaces, it does not explicitly teach to particular outcomes in that space: for example, how to build a home audio system, a MIDI controller, a desktop speaker, or a synthesizer. As a result, anybody looking to lead a club project “from the ground up” must devote countless hours to the research and synthesis of topic-specific knowledge in advance of meetings. Additionally, there are hidden time costs in considering how to package this information for digestibility amongst club members: sequencing of club “curriculum”, creating useful analogies, and developing efficient methods of instruction. All of this demands impressive time availability which most people in university simply cannot afford to give.

Importantly, the structure of the university system virtually guarantees that qualified candidates who meet the aforementioned criteria are in short supply. By design, knowledge rests most heavily in the ranks of those nearest to graduation — yet often, these are the students with the least availability and who face an imminent departure from the university. The result is a small and tenuous supply of capable leaders, and a fragile ecosystem for project leadership.

The Cal Poly Audio Engineering Society presents a case study of these issues through multiple attempts at club-sponsored design projects. Unlike established design-oriented clubs which annually iterate on a pre-existing design or topic space, Cal Poly's AES has no history of a completed system design project to fall back upon. Mostly, the club's attempted system design projects have ended far short of their goals, despite having talented and capable engineering students at the helm. This thesis, therefore, seeks to remedy this problem by providing CP AES with a complete system build via a musical synthesizer, including bill-of-materials (BOM), schematics, and an educational structure that addresses issues of complexity, progression, and accessibility to members at any level.

The thesis begins by analyzing club history to discern factors which contribute to project success or failure. It demonstrates the effectiveness of project-based curricula via case studies and presents an overview of existing synthesizer-oriented engineering resources, demonstrating the significance of this thesis curriculum. The paper then describes the synthesizer's design, specific goals and challenges of the project, and a proposed method of integration into the existing club structure. Finally, the paper discusses suggestions for furthering the curriculum, as well as how this educational approach might be further evaluated in future research on student recall, membership retention, and overall engagement.

Chapter 2

BACKGROUND

2.1 What Is A Synthesizer?

An audio synthesizer (synth) is an electronic instrument that uses "some form of digital or analog processing to produce audible sound" [4]. One way to create an analog synth is via a "modular" configuration, where the most common modules are voltage-controlled oscillators, filters, amplifiers, and envelope generators (ADSRs) [5]. Professor Kent H. Lundberg of MIT describes each of these modules succinctly; rephrased below for relevance to this discussion:

- **VCOs** are voltage controlled oscillators (the output frequency is voltage controlled, usually from the keyboard) and are the primary signal source for your synth. The output waveform is sometimes sinusoidal, but is usually chosen to be a waveform rich in harmonics. Sawtooth oscillators are usually preferred.
- **VCFs** are voltage controlled filters and are used to filter the VCO output as low-pass, band-pass, band-cut or high-pass filters. The cutoff (or center) frequency and the filter resonance are controlled by the input voltage, which can dynamically change the harmonic content of the note as it is played.
- **VCAs** are voltage controlled amplifiers and are used to create an evolution in volume as the sound is played.
- **ADSRs** are envelope generators (named for their function: attack, decay, sustain, and release) that are used to control the VCF and VCA modules.

Connecting all of these modules together forms the fundamental basis of most common modular synthesizer configurations. The Cal Poly Audio Engineering Society would like to be able to build a synthesizer approximating this definition.

2.2 Introduction to the Cal Poly Audio Engineering Society

The Cal Poly Audio Engineering Society (AES) is a student-run professional engineering club that seeks to understand and build audio equipment, and connect students to career opportunities in the professional audio world. The club describes its mission broadly as “making sound … engineering speakers, circuits, synthesizers, and anything audio” [6]. Importantly, the club brings together students with passion in audio, and focuses their efforts on a common goal.

Club foci change quarterly and year-to-year. At an organizational level, CP AES has led workshops on a broad assortment of audio-focused projects including assembly of DIY speaker cable kits, class-A amplifiers, and modular synthesizer components such as voltage-controlled oscillators. On a more individual level, the club has served smaller teams in quarter- or year-long projects designing FX pedals, tube amplifiers, electric guitars, and DACs. Each of these projects has achieved varying degrees of success; however, projects typically have poorly defined goals. While single-session DIY & kit-based workshops have been successful, few of the club’s long-term projects have ever reached a status approximating completion.

AES meetings are currently structured as a lecture + lab format, with “general meetings” every Thursday from 11am-noon, and “build sessions” on Saturdays from 10am-noon. General meetings typically feature lecture-style presentations, or info sessions with industry professionals. Lecture content is loosely focused around current projects, in the form of build session updates and teaching related engineering concepts. By comparison, build sessions have a strong “lab” focus and are much less organized: students split off into groups and work in small teams to make progress on their particular project. Most projects are headed by one or two more experienced upperclassmen, who define the goals for their project and each individual session.

According to the campus’s student life portal, Cal Poly Now, CP AES currently boasts 23 members, and the Slack channel has 70 interested members. Typical turnout for a general meeting or lab session is approximately 5-10 students; these students are very committed and show up consistently throughout the year. Beyond this core membership, the club has indicated issues with retention. Most clubs experience an unavoidable drop in attendance as students prune extracurriculars throughout the year; however, there is evidence that membership could be higher: in general, the club thrives when it has projects to offer its members.

2.3 Case Study of Past Project Efforts

The CP Audio Engineering Society has attempted many design projects and other long-term educational initiatives in recent years. Completion is rare, especially in comparison to established “design” clubs such as Formula or Cal Poly Racing, and projects typically end far short of their goals despite strong lead engineers. As the following case studies demonstrate, projects are more likely to fail when they are complex, new, and lack supporting resources. Successful projects rely on low complexity or the existence of supporting resources that empower members and create structure.

2.3.1 “Failed” Projects

From 2018 - 2019, CP AES pursued a home audio system design project, complete with input selection, signal conditioning, preamplifier, amplifier, and signal manipulation (e.g. filtering, multiband EQ). While the project leads were extremely capable engineers — one works at a leading professional music engineering company, and the other designs custom loudspeaker systems — they were unable to simultaneously research audio systems, design the system, and sequence the information to mentor and guide other members in their efforts. I came to Cal Poly because of AES, yet I quit because the endeavor seemed doomed. The project was abandoned as other students similarly became disillusioned and membership dwindled to 4 officers.

From 2021 - 2022, I led the AES in a new system build: a modular synthesizer. In an effort to avoid the pitfalls of the home audio system design, I hoped that a modular design would break the project into smaller, more manageable chunks. The club completed one module — a basic square-triangle oscillator, but the effort was personally unsustainable: I burned out. I lacked the knowledge and experience to design the system outright, so I spent hours researching each week to get “ahead” and outpace the club, guiding students in discoveries I had made sometimes less than 24 hours prior. In hindsight, the biggest resource in this project was the fact that I had already learned the square-triangle oscillator topology in a related course, EE 409; this allowed me to focus my efforts preparing for build sessions by focusing on the specific implementation and troubleshooting anomalies seen during the previous week’s lab, or create lecture content to introduce the material to younger engineers.

2.3.2 Successful Projects

Three AES projects from the past four years stand out as having completed their objectives: a speaker design project, an embedded-systems MIDI note generator, and a digital signal processing (DSP) workshop series.

2.3.2.1 Desktop Speaker Design

Desktop speaker design is the only AES project to be repeated every year since its inception in 2018. The endeavor takes most of a quarter (approximately Weeks 2 - 8), and involves teaching students about speaker cabinet and driver anatomy, understanding Thiele-Small parameters, designing an enclosure, and assembling a speaker using raw materials and an off-the-shelf driver. Brian Hillenbrand, who pioneered the project, attributes its success to low baseline complexity and pre-established structure. Low baseline complexity is ensured by the option to use full-range drivers, ensuring students can simply build a box and mount the driver without worrying about crossovers and amplifiers. As Hillenbrand says, “you don’t have to know a lot, even on the leadership side. If a lot of people have done it before, you can … follow what someone else has done … and rely on that to help you through it” [7] The project also benefits from having pre-established structure — students who know what to expect, and can therefore set milestones and lead new members through the process. Brian mentions that “it was more successful when [the next officers] took over … [They] were good at structuring [the project] so it actually occurred.” Much of the project’s current structure emerged from prior experience: knowing what to expect creates the ability to set milestones and expectations, and create a schedule with a finite timeline.

2.3.2.2 MIDI Note Generator

AES's MIDI note generator project was offered in Fall 2020, and is another workshop series that reached its stated goals. The final product outputs MIDI note data to a software synthesizer to create sound, using encoders and buttons for user input. Cal Poly alumnus Michael Erberich, who had graduated with a BSME and was working part-time on embedded systems, designed and presented a project-based, 6-week curriculum to teach microcontroller fundamentals to AES members. Erberich describes the demographic of AES as presenting a unique challenge, noting that "people in AES are likely to be EE or adjacent, but this is not guaranteed. They are also likely to be freshmen, or new to engineering in general" [8]. This places additional demands on the workshops, as the content "can't go into domain-specific details that would be lost on people" and needs to "literally build [up] every piece of theory that is relevant."

Reflecting on the experience, Erberich emphasizes time as being his scarcest resource, and wishes that he "had a year prior" to create the series. He describes preparing for workshops as "an endeavor" that was "down to the wire," noting that, between a part-time job and two classes at Cal Poly, "most presentations were unrehearsed." Despite knowing the material well, he found it challenging to sequence material and present it in a logical progression, explaining how he "started with the end-goal and worked backwards, laying out everything [students] would need to know" for the series to make sense.

One flaw he notices in the original course is its lack of "parallel content," or early hands-on lab activities. He suspects that this made the course "dry" and "theoretical," leading to a lack of engagement until the project's introduction halfway through the series. He also insists that the workshop "needs to be paced" in order to be taught within a quarter. This involves planning and seems to be easier now that the course content exists.

2.2.3.3 AES DSP Workshop Series

AES's Digital Signal Processing workshop series condensed the theory and applications of DSP into 5 weeks of instruction, guiding students to build (among other deliverables) a delay and

8-band audio equalizer. Conducted via Zoom during Spring 2020, the series began by introducing signals & systems fundamentals, and rapidly moving through the z-plane, poles, and zeros, to develop intuitions and create functional projects. I planned and led the project, basing the series on Professor Pilkington’s EE419/459 DSP course, which I had taken the quarter prior. This fact undeniably drove the success of the project, because students in DSP become “local experts” in a niche domain relative to their peers (who do not typically take the course). The curriculum was already developed by Dr. Pilkington, and I already had knowledge of the domain and project implementations, freeing me to focus on creating an educational experience that maximized knowledge transfer and student engagement.

Chapter 3

LITERATURE REVIEW

3.1 Support For Applications-Focused Learning

Existing research on curricula developed for clubs is difficult to find; however, more generally, research supports the efficacy of design-oriented curricula for teaching engineering concepts.

For example, the results from studying a hybrid robotics curriculum at Texas A&M "illustrate the consistent efficacy of the curriculum" across a two-year evaluation period [7]. The curriculum spans two elective courses which are designed to have "corresponding laboratory activities" supporting "theoretical concepts underlying … robotics design competition topics." The researchers find that "students prefer hands-on laboratory activities with respect to lectures" [8], supporting the idea that application of engineering principles and concepts is essential for student engagement. The authors assert that the curriculum has produced a "successful robotics educational model for other academic institutions to follow" [8].

More recently, in "Teaching Introduction to Electronic Circuits in a Studio Format," the authors discuss the need for students to "directly implement what they learn in lecture to a practical and useful real-world example or problem" or risk "[becoming] disinterested in the subject" [9]. The paper compares a "studio" to "traditional" lecture-lab format, but in the process shows that student engagement is increased by "providing students with multiple opportunities to directly apply what they are learning in lecture to real-world applications in a laboratory setting."

There is an abundance of literature showing the effectiveness of project-based learning across engineering disciplines, with the most common benefits being motivation and preparedness. Project-based motivation appears to increase, with students feeling "responsible for the learning process" and interested in "real-life applications of various fundamental topics" [12, 13]. Additionally, students report being motivated by the "peer to peer teaching and increased interaction" that a project-based environment provides [12]. Project-based engineering also appears to build preparedness for future careers. Opportunity to engage with applications allows students to develop their mental models regarding “the knowledge and skills they will need … to become successful engineers” [13], and prepares them for the challenges of industry [14]. Given that clubs share many of these desired outcomes, the results appear to support the development of project-based curriculum for engineering club use.

3.2 Case Studies: Project-Based Curricula

Large projects and systems demand a great deal of background knowledge that students don’t initially possess. However, when given the proper resources, students can quickly learn and grow to meet the demands of complex environments. Multiple existing curricula at Cal Poly demonstrate how student groups can achieve success when provided with supportive learning resources.

3.2.1 Cal Poly’s EE 143 Electronics Lab

The course description for EE 143 (Electronics Manufacturing & Circuit Analysis Lab) doesn’t do the class justice: “Use of electrical and electronic test equipment. Introduction to engineering design flow (design, simulate, build, test). PCB design and manufacturing.” Across nine lab sessions, the class starts students from complete fundamentals as basic as breadboard anatomy, voltage division, and op-amp buffers, and gradually introduces more advanced topics including transistor switches, PCB design, and system integration, to produce a complete 4-bit DAC. The final system deliverable [15] features signal flow from music source → signal conditioning → Arduino → DAC → speaker driver → speaker — a full system design that would be difficult to achieve as a fully student-driven project, but becomes possible with a lab manual sequencing course content for students to follow.

3.2.2 Cal Poly’s EE 459: Digital Signal Processing Lab

EE 459 at Cal Poly applies concepts from Signals & Systems courses to explore digital signal processing techniques and applications across a series of nine project-based labs. Students use MATLAB to create low/high/bandpass/bandstop filters, decode DTMF sequences, create custom FIR & IIR filters to specification, and implement delays. The final project is an 8-band graphic equalizer with reverb / delay. Content from the corresponding EE 419 lecture sets up each week's lab by supplying students with the most relevant and essential knowledge to successfully implement their challenging assignments. Projects of this complexity would not be easily achievable by students, nor in such a short timeframe, if not for the supporting material and course structure. In fact, this is the same course on which the 5-week AES DSP workshop series is based, and to which it owes its successful completion.

3.2.3 Solar Regatta Club

The SMUD California Solar Regatta competition is an "educational competition open to all high schools, colleges and universities in California" where students "design, build and race their own solar powered boats. They are judged for speed, distance, maneuverability and more" [16]. On May 14, 2022, Cal Poly's Solar Regatta student club competed for the first time, winning awards in 3 out of 10 categories: Best Drive Train, Best Presentation, and Best Slalom.

Cal Poly's team formed as a consequence of two Mechanical Engineering senior projects: "Up a Creek" and "Without a Paddle", which split work between hull structure and propulsion systems for the solar-powered boat [19,20]. According to the propulsion systems lead, Nathan Carlson, the senior project "started from scratch but then some of the guys stuck around and got the club started the next year." He insists that the project "set up the club" by providing an initial design that could be learned, mastered, and iterated upon to improve. The project and the successful club which it spawned provide examples of project-based applications and demonstrate their effectiveness more broadly beyond the Electrical Engineering department.

3.3 Conclusions From Educational Applications And Projects

Research seems to support that students learn better and are more engaged when they apply classroom knowledge to solve real-world problems. Without opportunities to challenge themselves with applications, students risk becoming disinterested in subjects that they might otherwise be motivated to pursue.

Cal Poly provides countless examples of what effective project-based environments resemble, both in the classroom and beyond as clubs. Students can successfully learn and apply engineering concepts to build complex systems — even early in their education — when given resources and structure. This last condition is essential to recognize: in all cases, faculty or more experienced students put in tremendous effort to lay the groundwork for new students to benefit from. This hints that a system build project which benefits AES should provide resources that promote accessibility and understanding in order to be successful.

Finally, most project-based opportunities for students to apply their learning are partly or entirely digital. While this is hardly a negative, it means that there are few opportunities for students to learn and understand what an analog system is. Anecdotally speaking, most students tend to reach for a microcontroller to solve EE problems, and the fact that an analog solution might exist (or even be better, in some cases) is hardly considered.

3.4 Synthesizer Design Resources

Clearly, any synthesizer system design that AES pursued must be supported by proper student resources. Because of the history of synthesizers, educational resources are abundant. However, project-oriented curricula specifically geared toward the needs of an engineering club are in short supply. Available resources might be classified into three tiers: low-level (*e.g.* electrical engineering lectures), mid-level (*e.g.* DIY & hobbyist communities), and high-level (*e.g*. kits).

Exploring each of these resources highlights respective strengths and weaknesses with respect to the club's goal. Understanding the educational landscape provides insight into existing and possible resources, and hints that an ideal solution for an engineering club seems to straddle the low- to mid-levels.

3.4.1 Low-Level Resources

Low-level resources are complex, thorough, and geared toward a college curriculum in engineering. These resources are abundant, but are dense, dry, and threaten to overwhelm students. They contain answers to almost any question a student might have, but often have heavy prerequisites that make such knowledge inaccessible to anyone without domain expertise. Cal Poly offers a broad electrical engineering curriculum that can be applied to synthesizer design, and some schools such as Georgia Tech offer synthesizer-specific electrical engineering courses. Both of these are excellent, but suffer from the problems typical to low-level resources, and therefore are not recommendable for club purposes.

3.4.1.1 Cal Poly Electrical Engineering Curriculum (EE 306/7/8, EE 409)

The Electrical Engineering curriculum at Cal Poly requires three courses that cover transistors, and one course that teaches electronic system design. The following are course descriptions [19]:

- EE 306: Semiconductor Device Electronics. Internal operation, semiconductor physics, terminal characteristics, models and application of diodes (LEDs, solar cells, and photo-diodes) and transistors (field-effect and bipolar).
- EE 307: Digital Electronics and Integrated Circuits. Analysis, design, application and interfacing of integrated logic circuits, including NMOS, CMOS, TTL, ECL, and other logic families.
- EE 308: Analog Electronics and Integrated Circuits. Analysis and design of integrated circuits for use in analog applications. Gain, frequency response, and feedback of linear small-signal amplifiers.
- EE 409: Electronic Design. Design of electronic systems and subsystems using analog and digital integrated circuits. Design principles and techniques. Analysis and design of feedback amplifiers; operational amplifier applications. Design of analog/digital and digital/analog converters. Power supply design. Emphasis on IC implementation.

The first three courses are a series, typically taken by students in Fall, Winter, and Spring quarters. EE 306 covers device physics and models of diodes and transistors; EE 307 and 308 split coverage of transistor applications in digital and analog domains, respectively. Finally, EE 409 applies and builds on knowledge from the prior year in a quarter-long project. The entire series takes 4 quarters to complete, and according to the EE Flowchart, is not typically completed until the middle of the 4th year [20]. Even if the courses can be taken earlier, the sheer amount of content contained imposes an impossible demand for students interested in learning enough theory to work on analog synthesizers. Arguably, all of the curriculum is important to truly becoming an electrical engineer; however, the content is too dense to learn quickly, and only a fraction of it is required to begin understanding and building analog synthesizers.

3.4.1.2 GA Tech’s ECE 4450: Analog Circuits for Music Synthesis

The elective course ECE 4450, taught by Professor Aaron Lanterman at Georgia Tech, applies electrical engineering knowledge to the analysis of existing popular synthesizer architectures. The course description lists the topics covered: “Circuits from classic analog synthesizers: voltage-controlled oscillators, filters, and amplifiers; nonlinear waveshapers. Operational transconductance amplifiers. Exploitation of dynamic resistance of semiconductors. Hands-on projects” [21]

The course syllabus also lists student learning objectives:

1. Analyze circuits employing operational transconductance amplifiers.
2. Analyze linear and exponential voltage-to-current converters.
3. Analyze sawtooth-core and triangle-core voltage controlled oscillators.
4. Exploit the nonlinearities and dynamic resistance of semiconductor devices.
5. Analyze various voltage controlled filter configurations, such as Sallen-Key filters, state variable filters, and the Moog ladder filter.

Lanterman’s lectures are in-depth and do not shy away from complex circuits — the schematics he analyzes are from flagship analog synthesizer manufacturers including Buchla, Moog, and Roland, among others. Using proven, professional designs gives his lectures realism and validity beyond theoretical coverage of the topics. He also posts videos of his lectures to YouTube, meaning that — in theory — anyone can watch his lectures to learn from his course.

Unfortunately, the series is hardly “introductory,” and is undoubtedly complex. It can be extremely valuable to electrical engineers with domain familiarity, but in aiming to cover so much difficult content, Lanterman is forced to trade accessibility for breadth and rigor. This potentially makes it a good resource for student leaders in CP AES, but not suitable as a primary curriculum for club use.

3.4.2 Mid-Level Resources

Mid-level resources flirt with complexity, but typically make pragmatic decisions about its pursuit with respect to a larger application goal. They frequently leverage analogies and focus on intuitions, aiming to be accessible while still exploring the complexities that engage more-experienced engineers. Content is self-contained or sequenced more deliberately, avoiding fragmented explanations that rely on background knowledge from other sources. Resources at this level are hard to find, especially those which are compelling and are well-produced. YouTubers Moritz Klein and AudioPhool are good examples of mid-level complexity, with thoughtful information sequencing, intuition-builders, and clear application goals.

3.4.2.1 Moritz Klein’s YouTube Channel

Moritz’s first video released on YouTube in 2020, and he has released more than 30 videos in the past two years, leading viewers through his build process for most popular synth modules including step sequencers, oscillators, filters, amplifiers, envelope generators, and noise generators [22]. He has over 35k subscribers, and has recently found additional success in a partnership with Erica Synths to create an educational “EDU” series of synth kits [23].

Moritz’s videos are typically 15-25 minutes in length, and have excellent production quality, featuring clear narration, excellent explanations and analogies, beautiful hand-drawn schematics and pictures, and captivating aesthetics. He sequences his content across multiple videos, showing thoughtful development of his designs, and contextualizes his presentations to minimize explanatory fragmentation. Moritz’s schematics are simple, emphasizing clarity and intuition over the complexity which might yield higher accuracy, making them ideal for educational use.

Moritz is not a university-trained electrical engineer, so his understanding and explanations are more firmly rooted in analogies and intuitions. This is a benefit in many ways, primarily in that all of his content remains highly accessible regardless of individual level; however, it does impact the accuracy and depth of his explanations. This thesis won't explore these mistakes in detail — he is very good about highlighting where they occur via video annotations or description notes, and a meticulous accounting seems unnecessary. Moritz's explanations do seem to "bottom out" short of what an engineering club might desire, but are an excellent starting point for what a club curriculum might resemble.

3.4.2.2 The AudioPhool's YouTube Channel

The AudioPhool also began uploading videos to YouTube in 2020, and has posted more than 25 videos in the past two years [24]. Where Moritz Klein's channel covers DIY synthesizer design by introducing electrical engineering concepts, AudioPhool's channel feels like the reverse: an EE focus that uses synthesizers as motivation. The channel covers topics such as RC filters; "explainer" videos for components such as capacitors, transistors, and op-amps; and voltage-controlled filters and amplifiers. The channel currently has 6k subscribers.

From his Patreon page, the AudioPhool is an electrical engineering student — a fact which comes across in his videos [25]. He frequently uses a whiteboard to analyze circuits, diving into the math which non-EEs such as Moritz trade for abstractions. For example, his video on a transistor-based VCA explains the schematic using variables such as g_{min}, leveraging AC models to dive into more complex topics than can be achieved with intuitions alone. This does make his videos somewhat less accessible to complete beginners, but the depth is convenient for students familiar with such topics. The video topics are noticeably less "sequenced" compared to Moritz's videos, but concepts are well-developed and do not suffer noticeable fragmentation.

3.4.3 High-Level Resources

High-level resources skirt most or all complexity, instead favoring successful arrivals at applications. Math is rarely employed and frequently avoided, and intuitions are liberally applied.

System explanation hovers around a “black-box” model discussing inputs and outputs, or occasionally delves deeper but is not legible, so the goal typically favors engagement over depth. Most high-level resources are DIY kits which, minus some assembly, are equivalent to off-the-shelf products. MkxErica, Moritz Klein’s EDU collaboration series with Erica Synths, is a good example of this kind of product. Other examples are DIY kits from MFOS, AI Synthesis, or Look Mum No Computer. Such kits are typically expensive — MkxErica products, which have quality explanations, are upwards of €45 per module. (Honorable mention: LMNC’s modules are usually around $25+, but are not as polished.) CP AES has purchased and assembled kits like AI Synthesis’s Ai1011 before, but experience shows this does not yield much educational benefit due to the “black box” nature of the kit. At around $100, it is expensive for students, especially considering CP AES dues are anywhere from $0 - $20 / year.

Chapter 4

AES SYNTHESIZER CURRICULUM

The CP AES Synthesizer curriculum which this thesis proposes gives students a developed and tested path toward building a complete system, ideal for student education and well-suited to mastery of fundamental electrical engineering concepts. Beyond typical offerings such as schematics and bills-of-materials, the project also provides complete background information and explanation of all systems and subcircuits — complete with simulations for building and testing intuitions, as well as more rigorous explanations (*e.g.* formulas) that support an academic perspective. Content is sequenced to provide a logical progression that avoids fragmentation or explanatory gaps, ensuring approachability across club demographics. Appendix A contains a copy of the curriculum material for reference.

The curriculum is also extremely valuable for club leadership, creating a structured roadmap to reference with respect to quarterly timelines. Further, curriculum material lends itself to rapidly generating lecture and presentation material, lowering the time costs of instruction and allowing project leadership to focus on the delivery of existing material.

4.1 System Description

The AES synthesizer design features four subsystems: a voltage-controlled oscillator, high- and low-pass filter, voltage-controlled amplifier, and a gate-triggered envelope generator with ADSR parameter control.

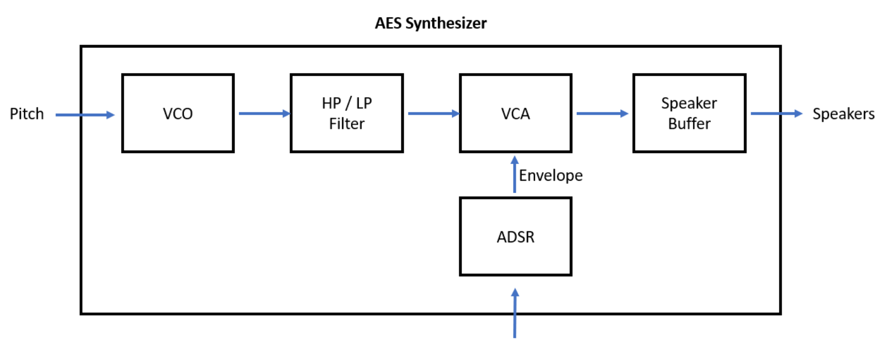

Figure 1: AES Synthesizer System Block Diagram.

The system runs on a split-supply ±12V/GND, conforming to power specifications typical of Eurorack / modular configurations [26]. For simplicity, all modules are designed to accept and output control voltages (CV) within 0-5V. Similarly, the final output signal has a range of 0-5 V_{pp}.

The voltage-controlled oscillator uses a sawtooth core relaxation oscillator, with pitch controlled via voltage input to a BJT operated in the forward-active mode. This controls capacitor discharge rate and offers typical output frequencies in the range from 20 Hz - 2 kHz, or approximately 5 octaves. CV input is tuned to a root note and scaled to follow 1V/octave tuning, via a user-adjustable passive mixer that maps signals from CV to BJT input range. Overall range and accuracy varies depending on components used; typical accuracy is between 2-3 octaves without significant drift. The BJT is minimally temperature-compensated via a pnp-npn emitter follower which counteract temperature drift effects.

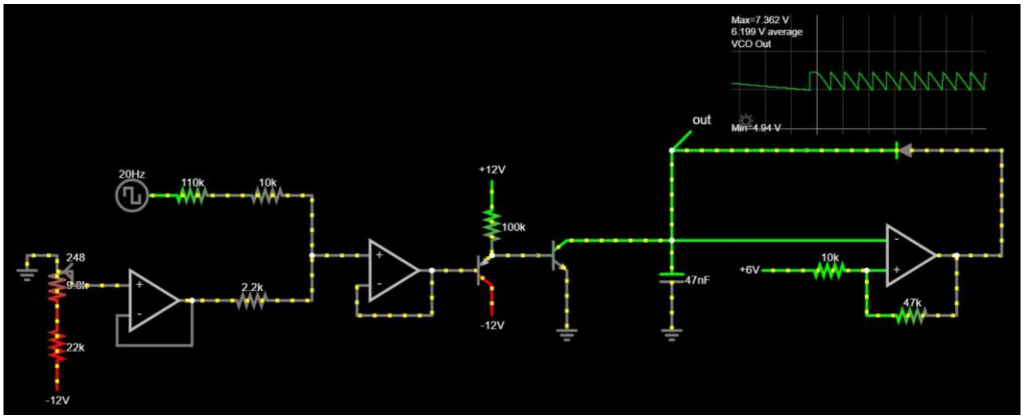

Figure 2: Voltage-Controlled Oscillator Schematic

The filter consists of a high- and low-pass, controllable via potentiometer knobs. As the first module in the series, it is relatively simple in implementation. Instead, trade-offs in filter range vs sensitivity encourage students to experiment with the design, making value judgements based on preference, ease of use, and controllability.

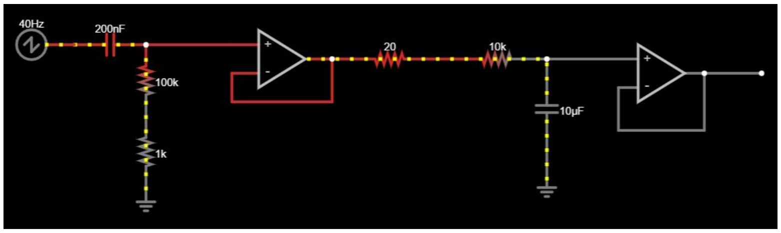

Figure 3: Passive Filter Schematic

The voltage-controlled amplifier implements a transistor-based and op-amp based differential amplifier in two separate stages. After a filter that removes DC offset, the input is sent to a matched-npn long-tailed pair. Current through the transistor “tails” is controlled via an inverting op-amp, which accepts CV input to provide a negative sink between 0 and -5 V. Both the inverting and non-inverting outputs are then sent to an op-amp configured as a differential amplifier — this removes any common offset from the two outputs and also provides any additional gain required by the circuit.

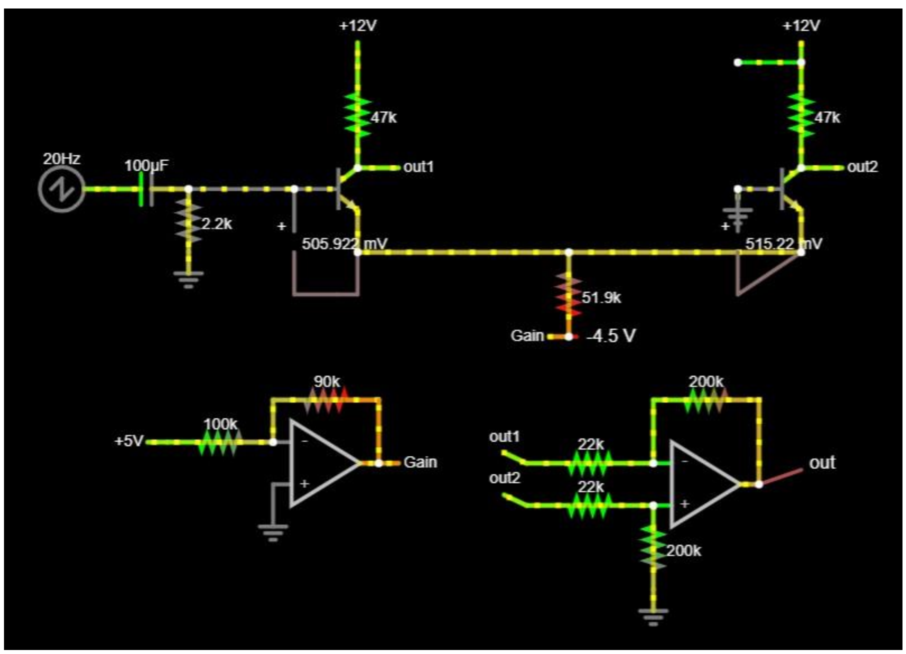

Figure 4: Voltage-Controlled Amplifier Schematic

Finally, the ADSR generates voltage envelopes via a combination of RC networks to create controllable time-varying signals with a maximum period of approximately 3-4 seconds. It is the largest of all of the subsystems, but maintains accessibility by reapplying design principles covered in the previous three modules. Due to issues sourcing ICs at the time of this thesis development, the ADSR runs with the addition of a 10V power rail.

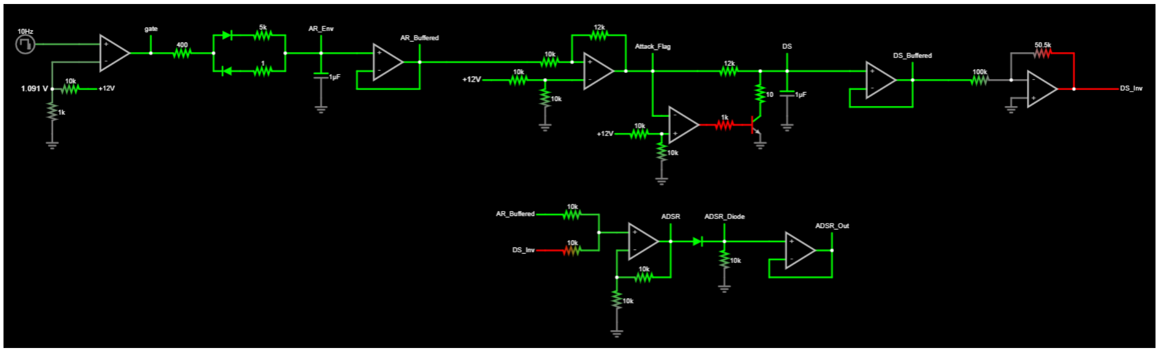

Figure 5: ADSR Envelope Generator Schematic

4.2 Curriculum Goals

This series seeks to familiarize students with content from the introductory Circuits series, as well as EE 306/307/308, and 409. While the topics and courses referenced target juniors and seniors, existing resources and curricula indicate that the knowledge to build synthesizers can similarly be made accessible even to those with little experience. Therefore, the primary goal of this thesis is to provide a curriculum that presents a complete, verified system build, in a way that maximizes opportunities for success at both the individual and club level.

The curriculum provides students with thorough explanations by ensuring that all subsystems, circuits, and their relevant underlying theory are explored. Intuitions are established for general concepts via analogies (*e.g.* current flow and pressure) and equations, which are naturally expanded to circuit implementations. All circuits are presented in schematics with links to interactive simulations on Falstad, a SPICE-based interactive simulator [27]. This encourages rapid experimentation and allows students to easily verify their understanding and test their mental models. (Bonus: Students learn how to use the Falstad simulator, which is a powerful tool for SPICE-based simulation.) Because of the gap between theory and practice, milestones are broken up by “Build Notes” which detail specific problems and troubleshooting that can be expected when translating designs to the breadboard — for example, slew rates, parasitic capacitances, or diode reverse leakage currents.

The curriculum also serves the club by providing a framework and structure for club meetings and lectures. Good presentations require forethought and planning, as well as definitions, formulas, simulations, and any other instructional content. A curriculum provides this content automatically, freeing club leadership to focus on the delivery of content without spending time needlessly reproducing it. Additionally, because the curriculum establishes a roadmap to a completed synthesizer, it assists in planning future meetings and lecture/lab content by giving leadership additional information.

4.3 Challenges in Club Curriculum

Sequencing material to create a logical progression is difficult. The curriculum achieves this by presenting subsystems in an order that considers prerequisites, and by leveraging previously explained ideas to develop later subsystems. For example, covering filters first (despite their placement second in the signal chain) allows introduction of RC networks and voltage division — RC networks appear again in the oscillator core and envelope generator, and the high-pass RC filter allows the amplifier to receive an unbiased input; voltage dividers are repurposed in the hysteresis of the oscillator and for scaling throughout the rest of the synth.

Similarly, BJTs are introduced as a replacement for the oscillator's discharge resistor; the amplifier later develops transistor theory to explore small-signal AC models, and in the envelope generator, they are operated as switches to produce discrete logic. Every idea is introduced either directly or via previous content, so that the feeling of fragmentation is minimized.

Another question for a club curriculum is that of depth: too much, and students will be intimidated or scared away, but too little causes "watering down" until it looks like the DIY kits that failed to teach much beyond soldering. To this end, the scope of this project has been limited via the following rule of thumb: do not make the best synth *ever*, but make the best synth for teaching and learning. One example of where this maxim limits the material is in temperature compensation. The synth uses a simple pnp-npn emitter follower and hopes that the pair's response to temperature changes is approximately the same. This does provide temperature compensation, but production synths feature far more advanced circuitry to achieve this, including NTC resistors or temperature-compensated exponential circuits such as those explained by Rene Schmitz [28]. While these would produce far better compensation, the level of complexity would increase dramatically, and virtually guarantees losing student understanding and interest. It may benefit one or two students, but would be disastrous for the club as a whole. Instead, these designs are mentioned in the curriculum “Future Work” as possible improvements, which can be pursued by students after they master the original curriculum material.

Limited time each quarter presents another challenge to this curriculum. The limitations on depth & complexity discussed above assist in reducing time required to complete the curriculum. That said, there is a lot of material, and the club’s momentum risks grinding to a halt if time is not carefully managed. The curriculum needs to propose a tentative schedule to keep the project on-track and ensure completion within a reasonable timeframe. One quarter seems reasonable to deliver a few subsystems of material to students, but the entire project seems like a longer-term endeavor. Of course, future club leadership will determine the exact implementation, but in an attempt to answer this question, the next section on “Integration into Club Structure” presents one possible schedule for the curriculum’s execution. (Cal Poly is transitioning to semesters in 2025, but the problem of adopting this curriculum will be more readily solved by future leaders [29].)

To address issues of logistics, the club can purchase most parts used in this project in bulk ahead of time. Because the build uses some of the most common component values and part numbers, storing enough components for the following year’s builds will be relatively inexpensive. This is recommended because students may burn ICs, resistors, diodes, or other parts, and replacement parts will impose a time delay which could be devastating to a fast-moving group. Regarding cost, AES has a history of addressing financial issues by covering costs for students in need, and this project is well-suited to this solution when necessary.

Finally, this curriculum will need to be able to grow with the club. As members build the system and develop their mastery of the material, they might iterate improvements discussed in the project’s “Future Work” such as additional oscillators, noise generators, effects, or other innovations. Leaders may find better ways of explaining advanced topics. Additionally, while Build Notes sections contain many troubleshooting tips and solutions, it can never be complete, and new challenges might be resolved which need to be documented. To address this, the entire project is hosted through Github, a popular version management tool. All of the files can be downloaded, modified, and updated via “commits” or “forks” that empower anyone to modify the material as necessary. This will ensure that the curriculum is always up-to-date and can continue to be improved by future membership.

4.4 Integration Into Club Structure

4.4.1 Meeting Times & Agenda

CP AES regularly meets on Thursdays for 1-hour general meetings, and weekends for 2-hour build sessions. General meetings are frequently used for info sessions and socials; however, build session are already very oriented toward projects, so the longer meeting time and “lab” focus means that the curriculum could be entirely implemented at these meetings alone.

Based on past projects and workshop series, it can be assumed that relevant background information could be taught in 1-2 build sessions, and that subsystems will generally take between 5 and 8 weeks to build. By this estimate, a full system could take most of the school year to build. One vision of how this could work is a “tiered” structure, where students spend the first year building their synthesizer and mastering the information; in following years, they can move into positions of leadership, training the next generation of students and solidifying their own knowledge in the process. At the same time, these students might begin to iterate improvements as they engage with further EE coursework and develop as engineers, improving subsystems and leading teams in this process via senior projects or other independent coursework. This ensures that knowledge is transferred from year to year, and that everyone has the opportunity to master material and participate in the project in some meaningful way.

4.4.2 Proposed Schedule

The table on the following page presents a sample schedule for build session content to follow. Assuming that the first week's session will require some orientation to the system and its roadmap, coverage of fundamentals begins in Week 2 and is assumed to require 2 weeks (based on past club experience). Content starts slowly; for example, Week 4 of Fall quarter is a simple "breadboarding" lab to create a DC-blocking output buffer. Content increases pace as students gain familiarity with electronics and engineering.

Schedule pacing considers the following milestones and educational objectives:

- The filter requires teaching RC filters; a day for implementation; and a day to formally introduce buffers and implement a filter cascade. (A 4^{th} session is budgeted as margin.)
- The oscillator requires teaching comparators and hysteresis; implementing a triangle and sawtooth core; adding voltage control via BJTs; temperature compensation; and input biasing to accept CV.
- The amplifier requires understanding various common-emitter simulation behaviors; understanding and building a differential pair; gain control via current source adjustment; adding a differential amplifier; and input filtering to remove DC offset.
- The envelope generator requires building an AR envelope generator; using BJTs as logic switches; and summing signals to produce a full ADSR
- System integration is generally difficult and full of troubleshooting.

This schedule concludes in Week 5 of Spring, leaving the club with 5 weeks to the rest of the academic year. This suggests that build sessions could move at a slightly slower pace than proposed, but an attempt to account for Hofstadter's Law might warn against strongly endorsing this conclusion. (Hofstadter's Law: "*It always takes longer than you expect, even when you take into account Hofstadter's Law*.") [30]

Table 1: Proposed Build Session Schedule

Quarter	Weeks	Topic
Fall	1	System Overview & Roadmap
	2, 3	Fundamentals
	4	Breadboarding & Output Buffer
	5, 6, 7, 8	The Filter
Winter	1, 2, 3, 4	The Oscillator
	5, 6, 7, 8	The Amplifier
Spring	1, 2, 3	The Envelope Generator
	4, 5	System Integration

Chapter 5

CONCLUSIONS & FUTURE WORK

5.1 Further Development

Some of the possible improvements that can be made to the system are mentioned briefly in this report, such as better temperature compensation or additional VCOs. There are many ways to iterate on the design, and suggestions litter the curriculum as notes or in “Future Work” sections.

Additionally, some of the curriculum will undoubtedly need to be updated. Students may find sections which are more confusing and could benefit from novel explanations or better progressions. Alternatively, educators in the club might decide that further depth is needed in some sections, and rewrite those to expand upon what currently exists.

Although membership skews toward Electrical Engineers, AES is not just a club for EEs. The synthesizer exists as a breadboarded design, so students could pursue a project translating this to a PCB, creating a chassis, adding an ergonomic keyboard, or creating a better user experience with professional aesthetic designs. This curriculum provides many possible routes toward “spin-off” projects that would work well for individuals or groups to tackle.

Finally, while this curriculum provides a framework for its immediate adoption into CP AES, it is expected for the project’s implementation to evolve a year or two from its conception. As members stay on for subsequent years, one suggestion might be to have multiple “levels” of the design which exist in parallel. Senior members can iterate and document improvements to specific subsystems in following years, while junior members can lead incoming students through the original build guide to prepare them for next steps. This would create a continued “handing down” of knowledge and provide a path leading students from beginner to mastery.

5.2 Follow-Up Research

Memory studies have long shown the effectiveness of “spaced repetition” in retention and mastery. [31] One suspected effect of this curriculum is that it creates a “spacing effect,” which would maximize retention amongst AES members by exposing them to essential electrical engineering knowledge across multiple sessions and contexts. For example, RC circuits are first presented in the “Fundamentals” chapter, and the “Filters” section references these concepts to teach passive RC filters; later, the oscillator core uses an RC circuit and reminds about time constants to approximate a “linear” sawtooth shape; finally, the envelope generator combines multiple RC networks working together to create ADSR. (This is another reason that the filter does not include band-pass/stop or any RLC resonance circuits — despite their potential for application, these topics do not appear anywhere else in the synthesizer’s operation. This means that they do not benefit from any spacing effect, and the effectiveness of covering these topics is therefore questionable.) Similarly, op-amps, comparators, and BJTs appear multiple times throughout each subsystem. It is reasonable to assume that involvement in the AES synthesizer project might reinforce these concepts and help students be more successful in their classes, as well. Follow-up research might therefore investigate whether there is a significant difference in knowledge or competency, testing students across time to track their mastery of EE material relative to their peers.

Finally, research could investigate whether this project boosts student engagement, based on the positive effect of applications in learning and the motivation that such structure might produce. Comparisons could be made within-major, comparing AES EE students versus typical EE student attitudes, or within the club, tracking membership across quarters or administering surveys before & after meetings.

REFERENCES

[1] Cal Poly, *Ready Day One | Cal Poly*. YouTube, 2019.

[2] N Taleb. *The Black Swan: The Impact of the Highly Improbable*, 1st ed.London: Taylor and Francis, 2017.

[3] Cal Poly. "Study Advisory: Study 25-35 Hours Per Week." College of Liberal Arts. https://cla.calpoly.edu/student-resources/study (accessed Aug. 31, 2022).

[4] Masterclass. “How Do Synthesizers Work? Definition, History, and Role in Producing Music.” Masterclass | Articles. https://www.masterclass.com/articles/how-do-synthesizers-work (accessed Aug 31, 2022).

[5] K. H. Lundberg. “So You Want To Build An Analog Synthesizer?” http://web.mit.edu/klund/www/weblatex/node2.html (accessed Aug 31, 2022)

[6] Cal Poly Audio Engineering Society. “Cal Poly Audio Engineering Society.” https://www.calpolyaudio.club/ (accessed Aug. 31, 2022)

[7] M. Yilmaz, S. Ozcelik, N. Yilmazer, R. Nekovei. “A Two-Semester Project-Based Robotics Curriculum,” American Society for Engineering Education. 2012. Accessed: Aug. 31, 2022. doi: 25.117.1-25.117.17.

[8] M. Yilmaz, S. Ozcelik, N. Yilmazer and R. Nekovei, "Design-Oriented Enhanced Robotics Curriculum," in IEEE Transactions on Education, vol. 56, no. 1, pp. 137-144, Feb. 2013, doi: 10.1109/TE.2012.2220775.

[9] B. Benson, F.W. DePiero “Teaching Introduction to Electronic Circuits in a Studio Format.” *2017 ASEE Annual Conference & Exposition*. Columbus, Ohio. Jun. 2017, doi: 10.18260/1-2—28919.

[10] Frank, M., Lavy, I. & Elata, D. “Implementing the Project-Based Learning Approach in an Academic Engineering Course.” *International Journal of Technology and Design Education*, 2003. doi: A:1026192113732.

[11] H. A. Hadim and S. K. Esche, "Enhancing the engineering curriculum through project-based learning," *32nd Annual Frontiers in Education*, 2002, pp. F3F-F3F, doi: 10.1109/FIE.2002.1158200.

[12] K. Gavin. “Case study of a project-based learning course in civil engineering design,” European Journal of Engineering Education. 36:6, 547-558, doi: 10.1080/03043797.2011.624173.

[13] R. Savage, K. Chen, L. Vanasupa. “Integrating Project-based Learning throughout the Undergraduate Engineering Curriculum,” Journal of STEM Education, vol. 8, no. 3, Mar. 2008. [Online] Available: https://www.learntechlib.org/p/173698/.

[14] J. Uziak. “A project-based learning approach in an engineering curriculum, ” in Global Journal of Engineering Education, vol. 18, no. 2, 2016. [Online] Available: http://www.wiete.com.au/journals/GJEE/Publish/vol18no2/12-Uziak-J.pdf

[15] *EE 143 Lab Manual: Lab 9*, 1st ed. Cal Poly, San Luis Obispo, CA. 2021.

[16] SMUD. “California Solar Regatta,” Solar Regatta. https://www.smud.org/en/In-Our-Community/Workshops-and-education-resources/Teachers-and-students/Solar-Regatta (accessed Aug. 31, 2022).

[17] T. Duncan, S. Neuman, K. Kreitzman, A. Offhaus. “California Solar Regatta – Hull Team: Up a Creek.” San Luis Obispo: California Polytechnic State University, Jun. 2020. Available: https://digitalcommons.calpoly.edu/mesp/559/

[18] N.H. Carlson, N.D.M. Banks, A.R. Larson, E.S. Rinell. “California Solar Regatta.” San Luis Obispo: California Polytechnic State University, Jun. 2020. Available: https://digitalcommons.calpoly.edu/mesp/557/

[19] Cal Poly. “Courses A-Z : Electrical Engineering (EE)” College of Engineering. https://catalog.calpoly.edu/coursesaz/ee/ (accessed Aug. 31, 2022)

[20] Cal Poly. “B.S. In Electrical Engineering Suggested 4-Year Academic Flowchart.” College of Engineering. https://flowcharts.calpoly.edu/downloads/mymap/17-19.52EEBSU.pdf (accessed Aug. 31, 2022).

[21] A. Lanterman. “ECE4450 Course Syllabus,” Georgia Tech. https://www.ece.gatech.edu/courses/course_outline/ECE4450 (accessed Aug. 31, 2022).

[22] M. Klein, “Moritz Klein – YouTube,” YouTube. https://www.youtube.com/c/MoritzKlein0/videos (accessed Aug. 31, 2022).

[23] Erica Synths. “Shop DIY Kits.” https://www.ericasynths.lv/shop/diy-kits-1/ (accessed Aug. 31, 2022).

[24] The AudioPhool, “The AudioPhool - YouTube,” YouTube. https://www.youtube.com/c/TheAudioPhool/videos (accessed Aug. 31, 2022).

[25] The AudioPhool. “The AudioPhool Is Creating Electronics & Music Videos | Patreon.” Patreon. https://www.patreon.com/TheAudioPhool (accessed Aug. 31, 2022).

[26] R. Gaston “Eurorack and Line Level Signals - Perfect Circuit.” Perfect Circuit. https://www.perfectcircuit.com/signal/eurorack-line-level (accessed Aug. 31, 2022).

[27] P. Falstad. *Falstad Circuit Simulator.* (2022). Falstad. Accessed: Aug. 31, 2022. [Online] Available: http://falstad.com/circuit/

[28] R. Schmitz. “A tutorial on exponential convertors and temperature compensation.” SchmitzBits. https://www.schmitzbits.de/expo_tutorial/ (accessed Aug. 31, 2022).

[29] Cal Poly. “Temporary Adoption of a Three-Year Catalog (2022-2025).” Academic Programs and Planning. https://academicprograms.calpoly.edu/academicpolicies/temporary-adoption-three-year-catalog-2022-2025 (accessed Aug. 31, 2022).

[30] D. Hofstadter. *Gödel, Escher, Bach: An Eternal Golden Braid*, 20th anniversary ed. 1999, p. 152.

[31] H.L. Roediger III, M.A. McDaniel, P.C. Brown. *Make It Stick: The Science of Successful Learning*. 2014.

APPENDICES

Appendix A

CP AES SYNTHESIZER BUILD GUIDE