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Integrating Theory and Practice in Signals and Systems Education: A Lab-Centered Curriculum

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Abstract

This paper presents a hands-on, lab-centered learning approach in an undergraduate Signals and Systems course within the Electrical and Electronics Engineering Technology program, designed to align with ABET accreditation requirements and program educational objectives. The course integrates a series of structured laboratory experiments that focus on key concepts such as time-domain and frequency-domain analysis, signal processing, frequency response and filtering, and system modeling. These hands-on labs, involving circuit analysis, RLC filters, op-amp circuits, audio boosters, volume unit meters, and timing circuits, aim to enhance students' practical skills while reinforcing their theoretical knowledge. The course culminates in a comprehensive final project, where students integrate their skills to design and implement a multi-functional signal processing system. By engaging in these activities, students develop competencies in problem-solving, critical thinking, and the use of modern engineering tools, directly addressing ABET student outcomes. Additionally, the course emphasizes designing, simulating, and analyzing real-world systems to prepare students for professional engineering practices. Preliminary assessments indicate that this approach not only fulfills ABET requirements for practical application and experimentation but also supports a deeper understanding of signals and systems concepts. This paper discusses the course design, the role of laboratory work in achieving program objectives, and its potential for implementation in similar engineering curricula.

Introduction

Signals and Systems is a foundational discipline in engineering, playing a critical role in various industries such as telecommunications, audio engineering, control systems, and medical devices. Its applications range from designing filters for signal processing to developing advanced communication systems and autonomous technologies. This multidisciplinary field equips engineers with the tools to analyze and manipulate signals, making it indispensable for addressing real-world challenges in technology-driven environments. However, the complexity of these concepts presents significant challenges for students to master and for educators to effectively teach, requiring innovative pedagogical approaches [1].

To ensure students gain both theoretical and practical expertise, engineering and engineering technology programs must align their courses with ABET criteria and associated performance indicators. These indicators outline specific competencies students must achieve, such as the ability to apply engineering principles, design systems to meet defined needs, and conduct and interpret experiments. Meeting these objectives requires a pedagogical shift from traditional theory-based teaching to a more hands-on, experiential approach and student-centered activities [2]. Research has shown that experiential and project-based learning approaches are particularly effective in achieving these outcomes. These methods not only promote deep conceptual understanding but also improve critical thinking, teamwork, and problem-solving skills by simulating real-world engineering challenges [3][4]. For example, studies have demonstrated that project-based learning and design-based methods promote collaboration and enhances students' ability to navigate multidisciplinary challenges, preparing them for real-world engineering environments [5][6]. Similarly, [7] observed that students engaged in lab-based learning develop a stronger capacity to apply theoretical concepts to practical challenges, better preparing them to meet industry demands. The importance of experiential learning in engineering technology is further underscored by [8], which highlights the role of progressive lab activities and a comprehensive final project in bridging the gap between theory and practical applications, thereby enhancing students' preparedness for industry demands while addressing ABET outcomes.

The Signals and Systems course at Northern Kentucky University adopts a structured, lab-centered curriculum designed to achieve these outcomes and performance indicators. By emphasizing hands-on learning, the course bridges the gap between theory and practice, enabling students to apply classroom concepts in real-world contexts. Each lab activity is designed to enhance problem-solving, critical thinking, and technical proficiency while progressively increasing in complexity. The final project integrates these skills, challenging students to design and implement a comprehensive signal processing system that mirrors industry practices.

This paper details the course's lab-centered approach, outlining six laboratory experiments and a final project designed to reinforce theoretical concepts through practical applications. The utilization of the course to assess students' development of skills and competencies necessary for professional engineering roles as well as assessing ABET standards and performance would be very advantageous. By providing a dynamic and engaging learning environment, this approach enhances students' readiness for industry challenges and future technological advancements.

Course Overview

The Signals and Systems course introduces students to the core principles of signal analysis and system modeling, bridging theoretical knowledge with practical applications. This course covers key topics such as continuous-time and discrete-time signals, time-domain and frequency-domain solutions, advanced circuit analysis, Laplace and z-transforms, Fourier analysis, and signal processing techniques.

Through a combination of lectures and lab sessions, students explore concepts like sinusoidal steady-state analysis, phasors, impedance, and the natural and step responses of RC, RL, and RLC circuits. Laboratory activities reinforce theoretical knowledge, offering hands-on experience with real-world tools and techniques, such as designing, analyzing, and building signal processing systems.

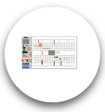
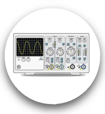
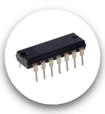
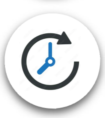
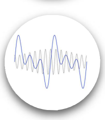
The course concludes with a final project in which students design a Multi-Functional Signal Processing System, integrating their knowledge and teamwork to solve practical engineering challenges. This capstone project aligns with ABET accreditation requirements, emphasizing the application of engineering technology principles in collaborative and practical settings.

By the end of the semester, students will have a robust understanding of signals and systems, along with the analytical and technical skills essential for pursuing advanced studies, succeeding in engineering careers, and addressing real-world challenges.

Key Learning Objectives of the Lab Activities and ABET Alignment

Each lab activity in the Signals and Systems course is carefully structured to enhance students' understanding of foundational concepts in signal analysis and system design, while aligning with the specific learning outcomes required by ABET accreditation for Engineering Technology programs. These labs bridge theoretical knowledge with practical, hands-on applications, enabling students to analyze, design, and implement signal processing systems. The lab activities highlight critical ABET competencies, as outlined in Table 1. By emphasizing the application of mathematics, science, and engineering principles, as well as teamwork, problem-solving, and communication skills, the lab activities prepare students with the technical expertise needed to address real-world challenges in fields such as communications, control systems, and signal processing. The knowledge and skills gained through these activities culminate in a final project that integrates and applies all course concepts.

Table 1. Key Learning Objectives of the Lab Activities

	*Lab 1: Fundamentals of DC and AC Circuit Design* Learning Objectives: Review Priciples of Circuit Design, Analysis, Simulation, and Construction
	*Lab 2: Passive Filters and Frequency Response Analysis* Learning Objectives: Understand the Principles and Applications of Electrical Filters
	*Lab 3: Operational Amplifiers in Circuit Design* Learning Objectives: Explore Operational Amplifier Configurations and their Applications
	*Lab 4: Audio Signal Visualization and VU Meter Design* Learning Objectives: Study Methods for Visualizing and Interpreting Signal Behavior
	*Lab 5: Audio Amplification and System Optimization* Learning Objectives: Gain Insights into Audio Signal Amplification and System Design
	*Lab 6: Timing Circuits and Control Applications* Learning Objectives: Investigate Timing and Control Circuit Applications
	*Final Project: Integrated Signal Processing System Development* Learning Objectives: Apply Course Concepts to Design and Implement a Complete Engineering System

- **Fundamentals of DC and AC Circuit Design:** This lab is designed as a comprehensive review to refresh students' understanding of fundamental electronics concepts and to reacquaint them with essential laboratory tools. Students revisit the use of breadboards, multimeters, signal generators, and oscilloscopes, focusing on their application in circuit design and analysis. Key components such as circuit construction techniques, basic electrical concepts, and safety procedures are reviewed.

Additionally, the lab provides students with a hands-on opportunity to revisit the practical implementation of basic circuit components, such as resistors, capacitors, inductors, and diodes. Emphasis is placed on understanding the behavior of these components in various configurations, as well as troubleshooting common errors in circuit design. The objective is to ensure that students are proficient and comfortable with these tools, as they are critical for building and testing circuits in subsequent labs. By refreshing these foundational skills, this lab prepares students to engage with more advanced circuit design and analysis tasks later in the course.

ABET Outcome Applications: Develops the ability to apply mathematical and engineering techniques to analyze basic circuits and use modern tools for engineering practice. Enhances problem-solving and communication skills in reporting results.

- **Passive Filters and Frequency Response Analysis:** This lab introduces students to the design and analysis of passive filters, including high-pass and low-pass filters, using resistors, inductors, and capacitors (RLC components). Students explore the frequency response of these filters, measuring and interpreting amplitude and phase shifts using oscilloscopes and function generators. In addition to understanding the theoretical principles of filtering, students gain practical experience in selecting and combining components to achieve specific filtering goals, such as noise reduction or signal conditioning. This lab also emphasizes the importance of analyzing real-world applications of filters in audio processing, telecommunications, and control systems. The key concepts include:
  - *Frequency Response Analysis*: Students learn to analyze and interpret the behavior of circuits across various frequencies, focusing on cutoff frequencies and signal attenuation.
  - *Filter Design Applications*: By experimenting with high-pass and low-pass filters, students gain practical insights into real-world applications such as audio processing and noise reduction.

This lab builds a foundation for understanding signal manipulation and prepares students for advanced signal processing tasks.

ABET Outcome Applications: Reinforces knowledge of engineering principles to design systems meeting specified needs and conduct experiments for performance evaluation. Promotes technical communication and interpretation of data.

- **Operational Amplifiers in Circuit Design:** In this lab, students design and analyze circuits using operational amplifiers in inverting, non-inverting, and integrator configurations. Through hands-on activities, students experiment with the behavior and applications of op-amps, developing a practical understanding of their operation and significance in circuit design. They also explore the impact of component selection, such as resistor and capacitor values, on circuit performance, gaining insights into tuning and optimizing op-amp circuits for specific applications. This lab bridges theoretical concepts with real-world applications, preparing students to utilize op-amps in advanced systems such as signal conditioning, filtering, and amplification. Key concepts covered include:
  - *Signal Amplification*: Understanding how op-amps amplify signals in different configurations.
  - *Feedback Mechanisms*: Exploring how feedback circuits control the behavior of op-amps for specific applications.

This lab provides students with the skills to apply op-amps effectively in complex circuits and systems.

ABET Outcome Applications: Enhances the ability to apply knowledge of mathematics and engineering techniques to system design. Builds problem-solving skills through the use of modern engineering tools and effective teamwork.

- **Audio Signal Visualization and VU Meter Design:** This lab focuses on designing an LED-based Volume Unit (VU) meter for audio signal visualization. Students use the LM3915 IC to create a functional and visually engaging circuit, gaining experience in audio signal processing and interpretation. In addition to understanding how the VU meter translates audio signal levels into visual indicators, students also explore the principles of logarithmic scaling and how it enhances the usability of the meter in real-world applications. This lab encourages creativity in circuit design while reinforcing the practical integration of ICs and LEDs in audio systems. The objectives include:

- *Signal Visualization*: Helping students understand how to represent audio signal levels in a real-time visual format.
- *Circuit Design Integration*: Teaching students to incorporate ICs and LEDs into functional systems.

This lab bridges theoretical knowledge and real-world applications, preparing students for more complex audio processing systems.

ABET Outcome Applications: Integrates skills in designing systems for broadly-defined problems, applying modern engineering tools, and analyzing results to meet user needs. Supports effective communication through design reporting.

- **Audio Amplification and System Optimization:** In this lab, students design, build, and test a single-stage audio signal amplifier using operational amplifiers. The focus is on creating a functional, portable amplifier with adjustable gain control. Students also explore the impact of component choices, such as resistor and capacitor values, on the amplifier's performance, ensuring the system achieves optimal signal quality and minimal distortion. This lab emphasizes practical skills in assembling and troubleshooting audio systems, while introducing real-world considerations such as power efficiency, noise reduction, and user adaptability in audio circuit design. Key concepts include:
  - *Amplification Techniques*: Understanding how op-amps can boost audio signals.
  - *System Optimization*: Exploring methods to achieve efficient and high-quality signal amplification.

This lab helps students develop practical skills in audio system design and performance optimization.

ABET Outcome Applications: Develops the ability to design and implement systems that meet specified needs, perform experiments, and evaluate performance. Encourages teamwork and communication in technical settings.

- **Timing Circuits and Control Applications:** This lab introduces students to the design of timing and control circuits using the 555 timer IC. Applications include creating auto-shutoff circuits (monostable mode) and flashing LED indicators (astable mode). Students learn to calculate and adjust the timing parameters by selecting appropriate resistor and capacitor values, enabling precise control over the circuit's behavior. By experimenting with these two modes, students gain insights into the versatility of the 555 timer for generating single pulses or continuous waveforms. Additionally, the lab explores practical implementations of timing circuits in automation and user-interface systems, such as interval timers and signal generators. The two primary focus areas are:
  - *Timing Control*: Understanding how RC networks control timing in circuits.
  - *Repetitive Signal Generation*: Learning to create square waveforms and apply them in control applications.

This lab enhances students' understanding of control systems and prepares them for advanced applications in automation and timing.

ABET Outcome Applications: Prepares students to conduct experiments and analyze results, emphasizing innovative applications of standard engineering principles to solve practical problems.

- **Integrated Signal Processing System Development:** The final project synthesizes all the knowledge and skills gained throughout the course. Students design, build, and test a multi-functional dual-channel audio signal processing and visualization system that incorporates key concepts from various labs. The system includes audio signal amplification, real-time visualization through an LED-based Volume Unit (VU) meter, and an optional timing feature using a 555 timer IC for dynamic effects such as flashing LEDs or buzzers when a signal exceeds a threshold.

To ensure portability and robustness, students are required to solder the system onto a PCB or protoboard, eliminating the use of breadboards. This project challenges students to integrate amplification, visualization, and timing functionalities into a cohesive and practical product. Additionally, students document their design process, including circuit design, calculations, experimental results, and implementation challenges, culminating in a professional presentation to demonstrate the system's features and real-world applications. The project objectives include:

- *System Integration*: Combining multiple circuit functionalities into a cohesive design.
- *Real-World Application*: Applying concepts to design a practical, portable system for audio signal processing.

This project challenges students to think critically, solve complex problems, and demonstrate teamwork and technical communication skills.

ABET Outcome Applications: Synthesizes the ability to solve broadly-defined engineering problems through design, analysis, and teamwork. Promotes professional communication through comprehensive reporting and presentation.

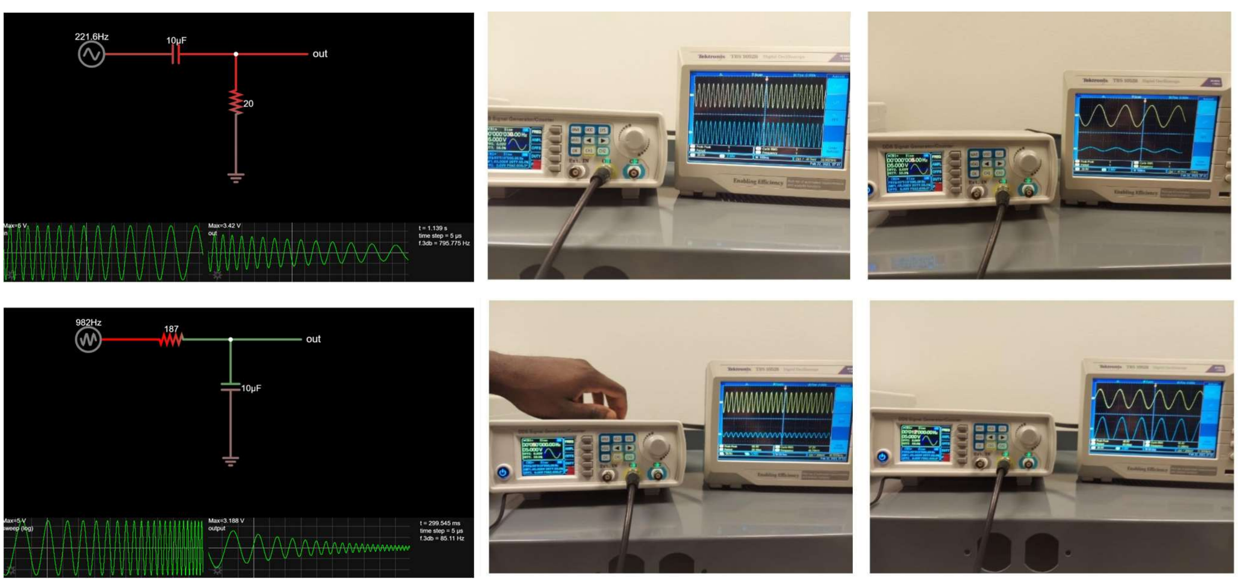


Figure 1. High Pass (Top) and Low Pass (Bottom) Passive Filters Simulations and Lab Results

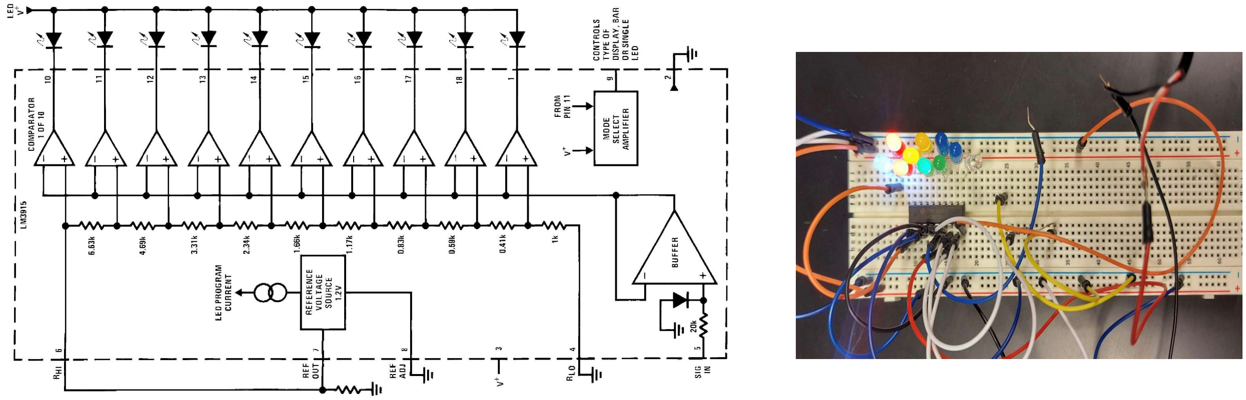


Figure 2. Circuit Diagram and a Sample of the Audio Signal Volume Unit Meter

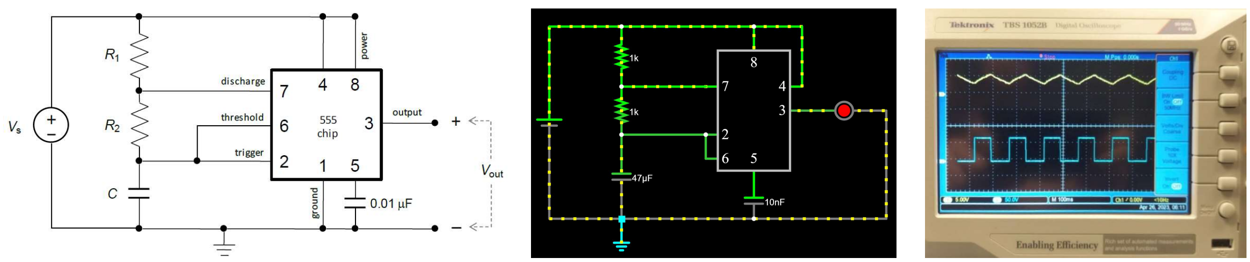


Figure 3. Circuit Diagrams, Simulations, and Output of the Astable Timing Circuit

Engagement Through Experiential Learning

The experiential learning approach of the Signals and Systems course is closely aligned with ABET Criterion 3: Student Outcomes and the program's educational objectives. By engaging students in hands-on, experiential learning, the course ensures they develop critical competencies such as applying engineering knowledge, conducting experiments, and designing systems to meet specified needs. These activities develop problem-solving, teamwork, and technical communication skills, all of which are essential for success in professional engineering roles.

The hands-on learning framework has consistently received positive feedback from students across multiple semesters. The hands-on nature of the labs was frequently highlighted as a key factor in reinforcing theoretical concepts and deepening students' understanding of practical applications. Students emphasized the value of real-world scenarios presented in labs, which helped bridge the gap between theory and practice. Many students expressed that the labs provided a tangible representation of course content, making complex concepts more accessible and engaging.

Moreover, students praised the labs for creating an engaging platform to explore and apply core engineering principles in action. While the lab activities were well-received, feedback also suggested that some students found writing detailed lab reports less effective for learning and more reflective in nature. This observation provides an opportunity to refine assessment methods for future iterations of the course. This feedback demonstrates the effectiveness of the lab-centered approach in enhancing engagement and meeting ABET outcomes, while also identifying areas for continuous improvement, such as balancing hands-on activities with report-writing expectations.

Adaptability Across STEM and Engineering Education

The lab-centered approach used in this Signals and Systems course offers a highly adaptable framework that can be seamlessly applied to a wide range of engineering, technology, and STEM programs. Its modular structure allows for customization to suit varying course objectives, student proficiency levels, and program-specific requirements. For instance, foundational courses could simplify the labs to focus on basic concepts like circuit analysis, instrumentation, and signal properties. In contrast, advanced courses could incorporate more sophisticated designs, such as real-time signal processing, adaptive filtering, or the integration of advanced technologies like microcontrollers, field-programmable gate arrays (FPGAs), and AI-based systems.

This adaptability ensures that the course remains relevant across diverse disciplines, including electrical engineering, computer engineering, biomedical engineering, and even interdisciplinary STEM programs. Educators can modify the final project to align with emerging trends, such as Internet of Things (IoT) applications, energy-efficient signal processing, or AI-driven automation. This flexibility allows students to engage with cutting-edge technologies while addressing real-world engineering challenges.

Furthermore, the approach supports the development of ABET-aligned learning outcomes, such as the ability to design systems that meet specific needs, apply engineering principles, and work effectively in teams. By exposing students to modern tools and methodologies, this adaptable framework equips them with the technical expertise and problem-solving skills necessary for success in diverse engineering fields.

Beyond individual courses, this model can serve as a template for multidisciplinary programs or capstone projects, encouraging collaboration across departments and promoting innovation. Its emphasis on hands-on learning, combined with theoretical rigor, provides students with a strong foundation to excel in academia or industry, bridging the gap between classroom concepts and practical applications.

Conclusion

The lab-centered framework implemented in the Signals and Systems course provides a dynamic and effective method for bridging the gap between theoretical knowledge and practical application. By aligning with ABET criteria and emphasizing hands-on learning, the course develops critical skills such as problem-solving, teamwork, and technical proficiency, which are essential for success in engineering roles. The structured progression of lab activities, leading to a comprehensive final project, mirrors the complexities of real-world engineering tasks and ensures students are well-prepared for industry demands. This approach not only enhances student engagement and motivation but also addresses key performance indicators for engineering technology programs. The integration of both simulation-based and hands-on elements allows students to develop a deeper conceptual understanding while building practical competencies. The feedback from students further validates the effectiveness of this method in achieving educational outcomes and highlights areas for continuous improvement, such as balancing design complexity with accessibility. By providing a strong foundation in both theory and practice, this lab-centered approach not only prepares students for professional success but also promotes a culture of innovation and lifelong learning in engineering education.

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