

ENHANCING ANALOG ELECTRONICS UNDERSTANDING FOR NON-ENGINEERING PHYSICS MAJORS: A PROJECT-BASED LEARNING APPROACH FROM PN JUNCTION TO AMPLIFIER

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Abstract: Around the world, non-engineering students often struggle with introductory electronics courses, perceiving analog electronics in particular as abstract, fragmented and difficult to apply in practice. This challenge is acute in service courses such as *Fundamentals of Electrical and Electronic Technology* for physics majors, which are expected to support later work in measurement, control and experimental design. To address these issues, this study redesigned the analog electronics unit into a concentrated teaching module and embedded a large project based on project-based learning (PBL). The module is structured along a coherent conceptual trajectory “from PN junction to NPN transistor to small-signal amplifier”, using current–voltage characteristics as a unifying representational thread to enhance conceptual coherence. A quasi-experimental design was adopted with three cohorts of undergraduate physics majors (N = 353) at a comprehensive university in China over three academic years (2020–2022). The 2020 cohort (one class, n = 51) received conventional fragmented instruction and served as the control group, whereas the 2021 and 2022 cohorts (six classes, n = 302) experienced the reformed instruction and formed the experimental group. Data were collected from final examination scores, including a dedicated subset of items on analog electronics, supplemented by project artefacts and student feedback. Descriptive statistics and independent-samples *t*-tests were used to compare the cohorts. Students in the experimental group scored on average 5.5 points higher on the overall exam and 2.9 points higher on the analog electronics subscore than those in the control group; pass rates also increased from 88.0% to about 95.0% overall and from 74.0% to about 85.5% for the analog items ($p < .001$; Cohen’s $d \approx 1.21$ for overall scores and 0.96 for analog subscores). The findings suggest that a concentrated, conceptually coherent analog electronics module combined with a substantial PBL project can effectively enhance non-engineering students’ understanding and performance in analog electronics. The study offers implications for the redesign of service electronics courses worldwide, particularly in programmes where students possess strong physics backgrounds but limited prior experience with circuit design.

Keywords: Project-based learning; Analog electronics; PN junction; Bipolar junction transistor; Non-engineering majors; Teaching reform

1 INTRODUCTION

In many countries, introductory electronics courses play a pivotal role in preparing students for modern scientific and technological work. Yet for non-engineering students—such as physics, chemistry or mechanical majors—analogue electronics is frequently perceived as abstract, mathematically demanding and removed from their primary disciplinary interests. International research has documented persistent difficulties[1-3] in understanding non-linear devices, operating regions and biasing, as well as a tendency for students to rely on rote manipulation of formulas rather than conceptual reasoning[4-5]. These challenges are particularly salient in service courses that must support later work in measurement, instrumentation and control, while competing for limited curriculum time.

The course *Fundamentals of Electrical and Electronic Technology* offered to non-engineering physics majors at a comprehensive university in China exemplifies this broader challenge. While the course is intended to provide essential foundations in circuits, analog electronics and digital electronics, students often report that the analog electronics component feels fragmented and disconnected from both their prior physics knowledge and their future laboratory needs. Traditional instruction presents PN junctions, diodes, bipolar junction transistors (BJTs) and amplifier circuits as separate topics distributed across the semester, with limited explicit connections and mainly verification-type laboratory work. Under such conditions, students may pass exams yet still lack a coherent mental model that links device physics to circuit behaviour and practical design.

Existing research in engineering and electronics education has highlighted the importance of conceptual understanding and authentic, practice-oriented learning activities. Inductive and project-based learning (PBL)[6-8] approaches can foster deeper engagement and integration of knowledge. For non-electrical physics majors, however, the starting point of instruction is particularly crucial. These students typically have strong preparation in fundamental physics and are accustomed to reasoning in terms of microscopic mechanisms, models and physical pictures. At the same time, they may feel uncomfortable with abstract circuit symbols and “black-box” engineering components.

This study therefore explores a teaching reform that explicitly aligns analog electronics instruction with non-electrical physics majors’ cognitive strengths. The reform has two key features. First, the analog electronics content is reorganized

into a concentrated module delivered over a relatively short time window, rather than being distributed sporadically throughout the semester. The module is structured around a coherent conceptual trajectory “from PN junction to NPN transistor to small-signal amplifier”, using device current–voltage (I – V) characteristics as an integrative thread. Second, a large project based on PBL is embedded into this module. Students work in small groups to design, simulate, implement and test a small-signal amplifier using an NPN transistor, thereby applying the concepts of PN junctions, transistor operating regions and biasing conditions in an integrated way.

A quasi-experimental design was adopted with three cohorts of physics majors taking the course between 2020 and 2022. The 2020 cohort serves as the control group with conventional fragmented instruction, while the 2021 and 2022 cohorts form the experimental group with the reformed module and project. Exam data and student feedback are analysed to investigate the impact of the reform.

The study is guided by the following research questions:

- RQ1: To what extent does the concentrated analog electronics module combined with PBL improve non-engineering physics majors’ conceptual understanding of PN junctions, transistors and amplifier circuits?
- RQ2: How does the reformed instruction affect students’ engagement with and perceptions of the analog electronics component of the course?
- RQ3: How does the reformed instruction influence students’ ability to troubleshoot and solve novel problems in analog electronics, as reflected in examination performance and project work?

By addressing these questions, the paper contributes to the literature on PBL and electronics education in three ways. First, it provides an example of how a foundational analog electronics module can be redesigned around a coherent conceptual trajectory that is accessible to non-electrical students. Second, it offers empirical evidence on the effectiveness of integrating a large project into a concentrated module in a service course. Third, it discusses practical considerations and constraints that may inform similar reforms in other institutions and disciplines.

2 LITERATURE REVIEW

2.1 Project-Based Learning in Engineering and Electronics Education

Project-based learning has been widely promoted as an effective approach in engineering and STEM education. In PBL, students work in teams on extended tasks that require them to apply knowledge and skills to design and implement artefacts or solutions. Reviews of inductive and project-based methods in engineering education report positive effects on student motivation, conceptual understanding, problem-solving skills and ability to integrate knowledge across topics[9-10].

In electronics and circuit courses specifically, PBL has been used to make content more engaging and meaningful by situating learning in the context of real or realistic design projects. Studies report that when students design and build circuits such as audio amplifiers, power supplies or embedded systems, they are more likely to appreciate the relevance of theory and to develop practical troubleshooting skills. Project-oriented problem-based learning variants have also been implemented in analog electronics courses, where projects are decomposed into stages such as requirement analysis, schematic design, simulation, printed circuit board layout and hardware implementation. These implementations highlight the importance of scaffolding, clear milestones and alignment between project tasks and course learning outcomes.

However, much of the existing literature focuses on electrical and electronics engineering majors[11-13]. The projects are often technically demanding and assume substantial prior knowledge of circuit theory and device physics. There is still relatively limited research on how PBL can be adapted for non-electrical cohorts, such as physics majors taking a service electronics course, who may have strong physics backgrounds but limited exposure to circuit design.

2.2 Conceptual Understanding in Analog Electronics

Research on student learning in electric circuits and analog electronics has documented persistent conceptual difficulties even after formal instruction. Students often struggle to understand the behaviour of non-linear devices such as diodes and transistors, the role of operating regions and the rationale for biasing networks. In many cases, students can manipulate circuit equations without a clear sense of the underlying device physics or the qualitative behaviour of the circuit[14].

Several studies suggest that a key challenge lies in connecting microscopic device models to macroscopic circuit behaviour. When devices are treated primarily as idealised symbols with a few parameters, students may lack the grounding needed to reason flexibly about new configurations or operating conditions. For physics majors, who are used to thinking in terms of carrier transport, band diagrams and physical mechanisms, instruction that does not explicitly build on these strengths can feel unsatisfying and “unphysical”[15].

Recent work has called for a more integrated approach that connects solid-state physics concepts with circuit applications, especially in courses that attract both physics and engineering students. Such an approach emphasises visual representations such as I – V curves, energy band diagrams and operating-region maps as tools for reasoning, rather than focusing exclusively on algebraic formulas. It also argues for sequencing content in a way that supports a coherent conceptual trajectory, for example, from PN junction to diode circuits, then to transistor structure and operation, and finally to amplifier design.

2.3 Service Courses for Non-Electrical Majors

Service courses in electrical and electronic technology occupy a challenging position in many curricula. They must provide sufficient depth to support later work in instrumentation, control and data acquisition, while also respecting the limited time and varying backgrounds of students from other disciplines. For non-electrical physics majors, service electronics courses are expected to complement laboratory and experimental courses, providing the foundations needed to design and interpret measurements and to communicate effectively with electronics specialists.

However, service courses are sometimes designed by directly “shrinking down” versions of courses intended for electrical engineering majors, without sufficiently adapting content, examples and pedagogy to the needs of non-electrical students. This can exacerbate perceptions of irrelevance and difficulty. There is a need for more studies that explicitly tailor service electronics courses to the cognitive profiles, future needs and disciplinary cultures of specific non-electrical cohorts, and that examine the impact of such tailoring on learning outcomes.

2.4 Contribution of the Present Study

Against this backdrop, the present study contributes by designing and evaluating a teaching reform in a service analog electronics module targeted at non-electrical physics majors. It combines two elements that have each shown promise in prior work—PBL and conceptually coherent sequencing—but adapts them to a context where students have strong physics backgrounds yet limited prior experience with circuit design. By analysing three cohorts over three years, the study provides empirical evidence on how such a reform influences exam performance, pass rates and students’ engagement with analog electronics.

3 METHODOLOGY

3.1 Context and Participants

The study was conducted in the course *Fundamentals of Electrical and Electronic Technology* offered by the Department of Physics at Jiangsu Second Normal University, a comprehensive university in China. The course is a required foundation module for physics majors (including general and teacher education tracks) and introduces basic concepts of circuits, analog electronics and digital electronics. The analog electronics unit covers PN junctions, diodes, BJTs and basic amplifier circuits.

The participants were three cohorts of undergraduate physics majors who took the course between 2020 and 2022. In total, 353 students from seven intact class groups were included in the analysis: one class in the 2020 cohort and three classes in each of the 2021 and 2022 cohorts. The 2020 cohort received conventional instruction and served as the control cohort. The 2021 and 2022 cohorts received the reformed instruction and thus formed the experimental cohort (Table 1).

Table 1 Cohorts, Class Groups and Sample Sizes for the Control and Experimental Groups

Year	Class name	Sample size(N)	Teaching condition
2020	Physics General Class (Teacher Education)	51	Control
2021	Physics General Class 1 (Targeted Teacher Education)	46	Experimental
2021	Physics General Class 2 (Targeted Teacher Education)	48	Experimental
2021	Physics General Class (Teacher Education)	60	Experimental
2022	Physics General Class 1 (Targeted Teacher Education)	45	Experimental
2022	Physics General Class 2 (Targeted Teacher Education)	45	Experimental

3.2 Instructional Design

In the conventional version used with the 2020 cohort, the analog electronics content was taught as four separate topics—PN junctions and diodes, BJT structure and characteristics, biasing, and amplifier circuits—distributed intermittently across the 16-week semester. Each topic was covered in approximately 4 class hours, interspersed with content on basic circuits and digital electronics. Laboratory exercises mainly involved confirmation of textbook circuits. There was no extended project activity.

In the reformed version implemented with the 2021 and 2022 cohorts, the analog electronics content was reorganised into a concentrated module delivered over approximately five consecutive weeks in the middle of the semester, accounting for 20 class hours (10 sessions × 2 hours). The module followed a coherent trajectory “from PN junction to NPN transistor to small-signal amplifier” and used device I–V characteristics as an integrative representational tool. The main steps were:

1. PN junction physics and I–V characteristics (4 hours);

2. Diode behaviour and simple rectifier/limiter circuits (2 hours);
3. NPN transistor as two coupled PN junctions and its operating regions (4 hours);
4. Transistor biasing and small-signal modelling (4 hours);
5. Single-stage common-emitter amplifier design and analysis (6 hours, integrated with project activities).

The PBL component took the form of a large project entitled “Design and implementation of an NPN transistor-based small-signal amplifier”, typically a simple microphone preamplifier. Students worked in groups of 3–4 members over the same five-week period. Each group was encouraged to assign informal roles (e.g., circuit designer, simulation analyst, measurement coordinator, documentation writer), while rotating tasks to ensure that all members engaged with both analysis and hands-on work. The project was structured into four milestones:

- (1) requirement clarification and review of device concepts;
- (2) preliminary circuit design and bias calculations;
- (3) simulation and prototype testing on a breadboard;
- (4) refinement and final reporting.

The instructor met each group at least once per week during scheduled lab or discussion sessions and provided additional consultation upon request. Short just-in-time mini-lectures were offered when recurring issues were identified (e.g., misunderstanding of transistor operating regions or coupling capacitor effects). As shown in Figure 1, this is the most common NPN common-emitter small-signal amplifier encountered in analog-circuit learning. It employs a voltage-divider bias structure: the input terminal is connected to the signal source via a coupling capacitor, and the output terminal drives a load resistor. Building on the structure and pedagogical logic of the voltage-divider-biased common-emitter amplifier described above, this study adopts the circuit as the core project task. Around its design, simulation, and measurement phases, we systematically collected multidimensional data on students' conceptual understanding, problem-solving, and teamwork; the specific instruments and procedures are detailed in the next section.

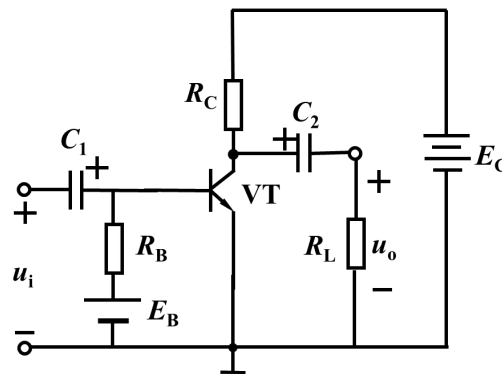


Figure 1 Simplified Schematic of a Typical Student-Designed NPN Transistor Small-Signal Amplifier used in the Project

3.3 Instruments and Data Collection

Multiple data sources were used to evaluate the impact of the teaching reform.

First, achievement data from the final examination were used to assess students' conceptual understanding and application of analog electronics. The final exam contained a subset of items specifically targeting PN junctions, transistor operating regions, biasing and amplifier analysis and design. For each student, two scores were extracted: (1) the overall final exam score, and (2) an analog electronics subscore corresponding to the relevant items. The structure and difficulty of the final exam were kept comparable across the three cohorts.

Second, for the experimental cohorts (2021 and 2022), group project performance was evaluated using an analytic rubric with four main dimensions:

- (1) Circuit design and biasing (30%) – correctness of the topology, appropriateness of the chosen operating point, and justification of component values;
- (2) Simulation and experimental implementation (30%) – completeness and correctness of simulation results, successful hardware implementation, and quality of measurement and troubleshooting;
- (3) Conceptual explanation (20%) – clarity and depth of explanations linking PN junction and transistor physics to circuit behaviour in the written report;
- (4) Reporting and teamwork (20%) – organisation and clarity of the written report and oral presentation, and evidence of balanced participation across group members.

The final project score for each student combined the group mark with a brief peer- and self-evaluation, in which students indicated the relative contribution of each member. This procedure was used to discourage free-riding and to better reflect individual engagement.

Third, student feedback was collected through brief questionnaires and informal comments, focusing on perceived difficulty, interest, perceived usefulness and perceptions of coherence (“from PN junction to transistor to amplifier”). Although these data are used mainly qualitatively in this paper, they provide context for interpreting the exam results.

All exam and project scores were anonymised before analysis. Participation in feedback activities was voluntary and

had no impact on course grades.

3.4 Data Analysis

Quantitative data from the final examination were analysed using both descriptive and inferential statistics. For each cohort and class group, means and standard deviations were computed for overall exam scores and for the analog electronics subscores, along with pass rates (score ≥ 60).

To compare the control and experimental cohorts, independent-samples *t*-tests were conducted on the overall exam scores and on the analog subscores. Additional *t*-tests were used to compare the 2021 and 2022 experimental cohorts to explore possible iterative improvement effects. Effect sizes were estimated using Cohen's *d*.

In this paper, the focus is on the comparison between the 2020 control cohort ($n = 51$) and the combined 2021–2022 experimental cohorts ($n = 302$). The reported *t*-statistics are $t = -8.00$ for overall exam scores and $t = -6.35$ for analog electronics subscores (two-tailed tests, $p < .001$). From these statistics and sample sizes, Cohen's *d* values of approximately 1.21 (overall) and 0.96 (analog) were obtained, indicating large effect sizes. Qualitative comments from student feedback and project reports were subjected to a simple thematic analysis to identify recurring themes related to conceptual understanding, perceived coherence of the “PN junction–transistor–amplifier” trajectory, and experiences with the project.

4 RESULTS

4.1 Descriptive Statistics

Table 2 summarises key descriptive statistics for the control and experimental groups, including overall exam means, pass and excellent rates, and analog electronics subscores and pass rates. The control cohort (2020, $n = 51$) achieved a mean overall score of 82.0, with an overall pass rate of 88.0% and an excellent rate (≥ 85) of 16.0%. The mean analog electronics subscore for this cohort was 18.5, with a pass rate of 74.0% on the analog items.

The combined experimental cohorts (2021–2022, $n = 302$) obtained a higher weighted mean overall score of 87.53, with a pass rate of 95.03% and an excellent rate of 29.14%. The weighted mean analog electronics subscore increased to 21.37, and the pass rate on the analog items rose to 85.49%. In relative terms, the experimental group outperformed the control group by 5.53 points (6.7%) on the overall score and by 2.87 points (15.5%) on the analog subscore.

Table 2 Descriptive Statistics for Overall Exam Scores and Analog Electronics Subscores in the Control and Experimental Groups

Indicators	Control Group (2020 Cohort)	Experimental Group (2021–2022 Cohorts)	Difference	Percentage Difference
Total Number of Students	51	302	—	—
Overall Exam Score (Mean)	82.00	87.53	+5.53	+6.7%
Overall Exam Pass Rate	88.00%	95.03%	+7.03%	+8.0%
Overall Exam Excellent Rate	16.00%	29.14%	+13.14%	+82.1%
Analog Electronics Subscore (Mean)	18.50	21.37	+2.87	+15.5%
Analog Electronics Pass Rate	74.00%	85.49%	+11.49%	+15.5%

Table 3 consolidates these findings: across the six experimental class groups, overall means varied from 84.1 to 90.3, pass rates from 91.11 % to 98.28 %, and excellence rates from 14.58 % to 39.66 %; corresponding analog sub-scores ranged from 19.75 to 23.00, with sub-score pass rates between 79 % and 92 %. Although inter-class differences are evident, every experimental section equalled or surpassed the control cohort on both global and analog-specific metrics.

Table 3 Class-Level Descriptive Statistics for all Seven Classes

Dependent Variable	t-Value	p-Value	Mean Difference (Experimental – Control)	Statistical Significance ($\alpha = 0.05$)
Overall Exam Score	-8.0007	0.0000	5.53	Significant
Analog Electronics Subscore	-6.3513	0.0000	2.87	Significant

4.2 Overall Exam Performance: t-Test Results

As illustrated in Table 4 and Figure 2, independent-samples *t*-tests were conducted to compare the overall end-of-semester performance between the 2020 control cohort and the pooled 2021–2022 experimental cohorts. Students in the experimental group scored on average 5.5 points higher on the overall final examination than students in the control group (87.5 vs. 82.0). The overall pass rate also increased from 88.0% in the control cohort to approximately 95.0% in the experimental cohorts.

The difference in overall scores between the control and experimental groups was statistically significant, $t = -8.00$, p

$< .001$, with a large effect size (Cohen's $d \approx 1.21$). This indicates that, beyond sampling fluctuations, the reformed instruction was associated with a substantial improvement in overall course achievement.

Table 4 Independent-Samples t-Test Results Comparing Control and Experimental Groups on Overall Exam Scores and Analog Electronics Subscores

Dependent Variable	Control Group (M $\pm$ SD)	Experimental Group (M $\pm$ SD)	n ₁ /n ₂	t-Value
Overall Exam Score	82.00 $\pm$ 6.91	87.53 $\pm$ 6.91	51/302	-8.0007
Analog Electronics Subscore	18.50 $\pm$ 4.52	21.37 $\pm$ 4.52	51/302	-6.3513
Dependent Variable	Degrees of Freedom (df)	p-Value	Cohen's d (Effect Size)	Statistical Significance ($\alpha = 0.05$)
Overall Exam Score	351	0.0000	1.40	Significant
Analog Electronics Subscore	351	0.0000	1.11	Significant

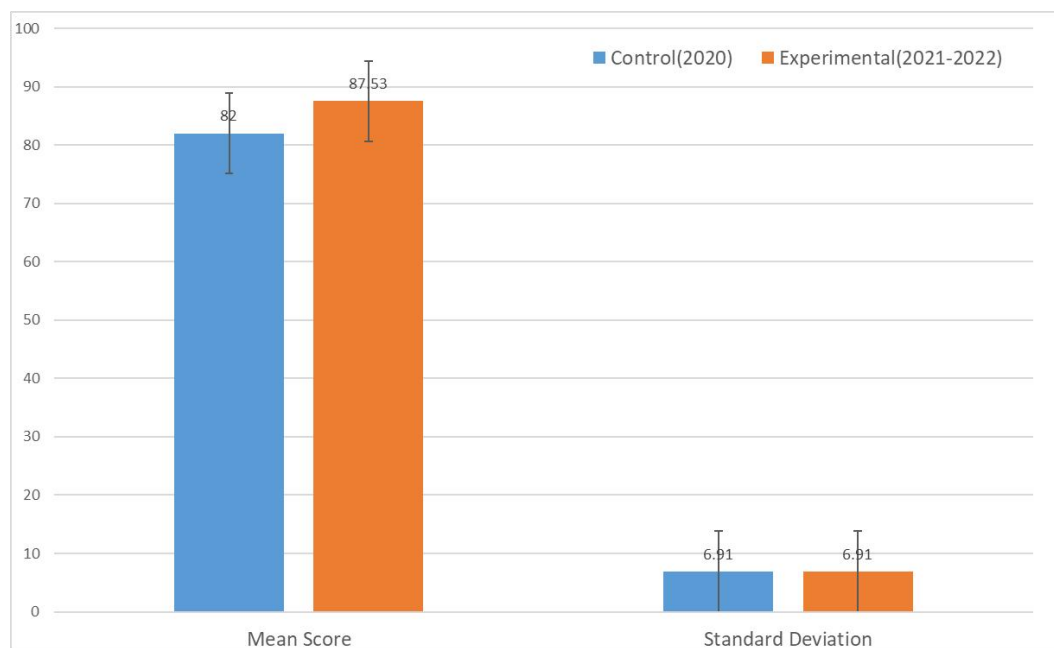


Figure 2 Comparison of Mean Overall Exam Scores for the Control (2020) and Experimental (2021–2022) Groups, with Error Bars Indicating Standard Deviations

4.3 Performance on Analog Electronics Items: t-Test Results

As depicted in Figure 3, given that the present study centres on the analogue-electronics unit, particular attention was paid to students' performance on the examination items covering PN junctions, transistor operation and small-signal amplifier circuits. The experimental cohorts achieved a mean analogue-electronics sub-score of 21.37, compared with 18.50 for the control cohort—an average gain of 2.87 points. The corresponding pass rate rose from 74.0 % to approximately 85.49 %. An independent-samples t-test indicated that this difference was statistically significant, $t = -6.35$, $p < .001$, with a large effect size (Cohen's $d \approx 0.96$). Class-level mean analogue sub-scores within the experimental groups ranged from 19.75 to 23.00, demonstrating that the positive impact of the reform was robust across different class types.

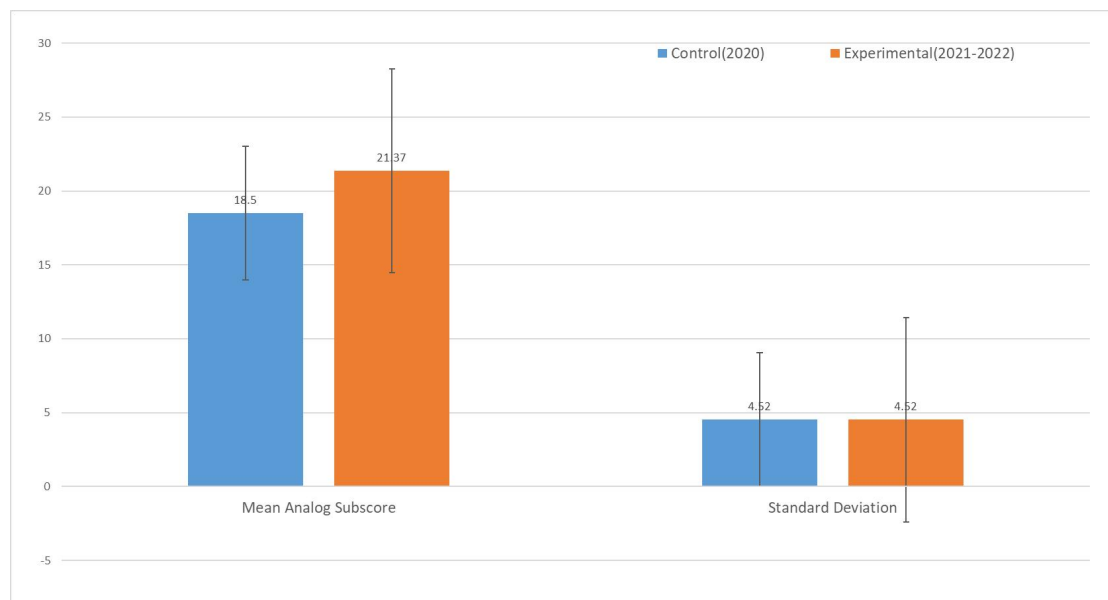


Figure 3 Comparison of Mean Analog Electronics Subscores for the Control (2020) and Experimental (2021–2022) Groups

Considering the two experimental cohorts separately, the 2021 classes ($N = 154$) achieved a weighted mean analog subscore of about 20.4, with an analog pass rate of 81.6%. The 2022 classes ($N = 148$) reached a higher mean analog subscore of about 22.4 and a pass rate of 89.6%. This pattern suggests not only a clear improvement relative to the 2020 control cohort, but also further refinement of teaching practice and project implementation between 2021 and 2022.

5 DISCUSSION

5.1 From Physical Principles to Engineering Applications

The quantitative results indicate that students exposed to the reformed module achieved higher overall scores and substantially better performance on the analog electronics items than those in the traditional cohort. These gains can be interpreted in light of the way the reformed module aligns with non-electrical physics majors' cognitive strengths.

Most students in this programme have a solid grounding in fundamental physics and are accustomed to reasoning in terms of microscopic mechanisms, qualitative models and energy band diagrams. At the same time, they often report feeling uncomfortable with abstract circuit symbols and black-box engineering components. By starting from the PN junction as a familiar physical object, the reformed module meets students where they are. The PN junction can be explained using concepts such as band structure, majority and minority carriers, diffusion and drift, depletion regions and built-in potentials. In this way, the single-direction conduction of a diode and the formation of a potential barrier are not presented as mere properties of a symbol, but as natural consequences of carrier transport and energy band bending. The transition from the PN junction to the NPN transistor then becomes a logical extension rather than a conceptual leap. When students see an NPN transistor as two coupled PN junctions plus a controlled current path, they can analyse the roles of the emitter–base and collector–base junctions under different biasing conditions. Discussions of cutoff, active and saturation regions are anchored in whether each junction is forward- or reverse-biased and in how carriers are injected and collected. In this view, the current amplification relationship $I_C \approx \beta I_B$ is no longer perceived as a mysterious empirical rule, but as a macroscopic description of underlying transport phenomena. This directly addresses students' implicit question of where amplification comes from.

Once this microscopic understanding is established, the step from device to circuit is smoother. The design of a single-stage amplifier is framed as creating the appropriate external conditions for the transistor so that it can operate in its intended region. The necessity of DC biasing and the choice of a quiescent operating point in the active region follow naturally from the recognised non-linearity of the transistor's characteristics. For students who understand the transistor's I – V behaviour, bias networks and coupling capacitors are no longer arbitrary topologies to be memorised; they are purposeful mechanisms for placing and maintaining the device in a suitable operating regime.

5.2 Addressing Core Difficulties of Non-Electrical Majors

The reform also appears to address two frequently reported difficulties among non-electrical majors: not seeing the relevance of analog electronics and perceiving the content as excessively abstract and memorisation-driven. The PN junction → transistor → amplifier → project trajectory provides a continuous learning path in which each step has an evident role. Students first gain a physically satisfying explanation of basic semiconductor behaviour, then see how combining PN junctions yields a controllable device, and finally experience how this device is embedded in a functional circuit.

This progression can create repeated “aha” moments: understanding the PN junction, explaining how a transistor works, designing a bias network to make it amplify and ultimately building a circuit that makes a real-world signal larger. Such experiences form a strong source of intrinsic motivation. Instead of being asked to memorise formulas and standard circuits whose purpose is opaque, students are invited to derive and justify them. For example, when students appreciate the temperature dependence of saturation current and current gain, they can reason about why the bias point may drift with temperature and why stabilising measures are needed. This shift from passive memorisation to active derivation reduces cognitive load and better prepares students to handle novel situations beyond textbook examples.

Furthermore, the reform supports the development of what might be called a system and interface perspective. Many physics majors will later use electronic modules as part of larger experimental or engineering systems rather than design complex circuits from scratch. By constructing a simple but complete amplifier themselves, they learn to think about a module in terms of input and output characteristics, power supply requirements, loading effects and constraints. This prepares them to communicate with electronics specialists and to specify realistic requirements when selecting or integrating off-the-shelf modules in their future work.

From a cognitive perspective, the coherent trajectory reduces fragmentation by continually revisiting a small set of core representations (I–V curves, operating-region diagrams) in progressively richer contexts. From a motivational perspective, the project creates a sequence of “aha” moments in which students can see their abstract understanding materialise in a working circuit. From a competence perspective, the need to diagnose distortion, saturation and bias drift fosters systems thinking and problem-solving skills that go beyond routine calculation.

5.3 The Integrative Role of the Large Project

The large project plays a central role in consolidating and extending students’ understanding. In the present implementation, a typical project theme is a simple microphone preamplifier. To complete such a project, students must bring together all prior content: they need PN junction knowledge to understand, for instance, why protection diodes may be used; transistor knowledge to ensure that the device operates in the appropriate region for faithful amplification; and amplifier circuit knowledge to determine suitable resistor values, set the Q-point, design coupling networks and anticipate the frequency response.

During project work, students encounter issues that are rarely addressed in purely theoretical instruction, such as noise, distortion due to clipping or saturation, parameter variation between nominally identical components and sensitivity to power supply fluctuations. Confronting and troubleshooting these issues helps students partially shift from a physicist’s mindset that seeks idealised behaviour towards an engineer’s mindset that aims to achieve robust performance under constraints. In light of the examination data, the improved analog subscores and higher pass rates in the experimental cohorts suggest that this experiential dimension reinforced rather than undermined formal understanding.

5.4 Cohort Differences and Iterative Refinement

The comparison between the 2021 and 2022 experimental cohorts offers additional insights. While both cohorts outperformed the 2020 control group, the 2022 classes showed higher mean analog subscores and higher analog pass rates than the 2021 classes. This pattern is consistent with the idea that curriculum reforms and project-based components typically require iterative refinement. Over time, the instructor can better calibrate the pacing of the concentrated module, optimise scaffolding and checkpoints, and anticipate common student difficulties. Students in later cohorts may also benefit from more polished project descriptions, improved assessment rubrics and a larger pool of example circuits and troubleshooting cases.

5.5 Implications

Overall, the findings suggest that for non-electrical physics majors, a concentrated analog electronics module organised along a physically meaningful trajectory and enriched by a substantial project can foster deeper and more coherent understanding than a fragmented, calculation-oriented approach. Beyond the specific context of this course, the study illustrates how aligning the starting point of instruction with students’ disciplinary strengths, and then carefully guiding them from fundamental principles to functional systems, can be an effective strategy in service courses at the interface between physics and engineering. These findings are consistent with prior reports that PBL can enhance motivation and integration of knowledge in electronics education, but they extend the literature by showing that, when combined with a carefully sequenced conceptual trajectory, PBL can be effective even for non-engineering physics majors in a service-course context.

6 CONCLUSION AND LIMITATIONS

This study examined a three-year teaching reform in a service course on *Fundamentals of Electrical and Electronic Technology* for non-engineering physics majors. By reorganising the analog electronics content into a concentrated module built around a coherent trajectory from PN junction to transistor to amplifier, and by embedding a substantial PBL project, the reform aimed to align instruction with students’ physics strengths while fostering more engineering-oriented ways of thinking.

Using a quasi-experimental design with three cohorts (N = 353), the study found that students in the experimental

cohorts achieved higher overall exam scores and markedly better performance on analog electronics items than students in the traditional cohort. Pass rates improved both at the course level and for the analog subsection of the exam. These results suggest that conceptually coherent, project-rich instruction can effectively support non-engineering physics majors in developing a deeper and more integrated understanding of analog electronics.

The study has several limitations. It was conducted at a single institution within one programme, which may limit the generalisability of the findings. The quasi-experimental design relied primarily on existing exam data; more rigorous experimental controls and the use of validated concept inventories would strengthen future research. In addition, although project artefacts and brief feedback were collected, the study did not systematically analyse students' group discussions or track long-term retention of analog electronics concepts.

Despite these limitations, the findings offer practical guidance for instructors and curriculum designers responsible for service electronics courses. Organising content around a physically meaningful conceptual backbone, allocating a concentrated block of time to preserve continuity, and designing a non-trivial project that forces students to integrate device physics with circuit design appear to be promising principles. Future work could extend this approach to topics such as operational amplifiers and signal conditioning, and explore how similar reforms might support students in other non-electrical programmes and institutional contexts.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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