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Comparative Study of Digital Electronics Learning: Using PCB versus Traditional Methods in an Experiment-Centered Pedagogy (ECP) Approach for Engineering Students

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Now, as a graduate student majoring in Advanced Computing, Ejiga is not only expanding his academic horizons but also actively contributing to the evolving landscape of engineering education. His role in the pedagogy project reflects a keen interest in developing educational strategies that are more interactive and hands-on, a testament to his dedication to enhancing learning experiences in engineering. Ejiga's background in computer science, combined with his current focus on advanced computing, positions him uniquely to contribute significantly to both his department and the broader academic community.

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Dr. Mahmudur Rahman received his PhD in Computer Science in 2008 from Concordia University, Montreal, Canada with an emphasis on Medical informatics and Image Retrieval. Prior to joining as an Assistant Professor at Morgan State University in 2014, Dr. Rahman extensively conducted research at the National Institutes of Health (NIH), USA for almost six years as a Research Scientist. He significantly contributed to research and development of the image processing, classification, and retrieval methods extensively used in the NLM's Open-i Search Engine for biomedical literature. Dr. Rahman has good expertise in the fields of Computer Vision, Image Processing, Information Retrieval, Machine Learning, and Data Mining and their application to retrieval of biomedical images from large collections. Since joining Morgan, Dr. Rahman also has been actively involved in basic educational and instructional research by infusing several interactive and active learning techniques in classroom to teach introductory programming courses with a goal to improve the retention rate in the CS department. Dr. Rahman has published a book, two book chapters and around seventy articles in peer-reviewed journals and conference proceedings, such as IEEE Transaction on Information Technology in Biomedicine, Computerized Medical Imaging and Graphics, etc. and presented his works in numerous conferences and workshops, such as ICPR, CBMS, CLEF, CIVR, HISB, SPIE, BIBE, IEEE FIE, etc. His current research is focusing on Crowdsourcing and Deep learning techniques and their application in medical fields, especially for retrieval and diagnostic purposes.

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Abstract

In the dynamic landscape of engineering education, the significance of hands-on experimentation in Digital Electronics, including Computer Architecture and Digital Logic, cannot be understated. The core inquiry of this study is determining whether the integration of standalone printed circuit board (PCB) hardware augments conceptual understanding and engagement compared to conventional electronic instrument-based methods. Although both methods use the experiment-centered pedagogy (ECP) framework, the objective is to identify which method provides enhanced comprehension of core concepts and practical applications. Using a quantitative method anchored in pragmatic research philosophy, the efficacy of learning outcomes and practical applications were scrutinized. One semester leveraged PCB tools, while the previous semester utilized conventional techniques. Feedback was garnered from educators and students, with SPSS facilitating statistical analysis. Additionally, Bidirectional Encoder Representations from Transformers (BERT) were utilized for sentiment analysis. The comparative study highlights the superiority of the PCB method over traditional approaches in digital electronics education for engineering students. Key findings include a 23% higher initial comprehension score (83% for PCB vs. 60% for traditional in pre-test)and a slight edge in retention and understanding (80% for PCB vs. 76% for traditional in post-test). Active learning and hands-on activities were significantly more prevalent in PCB classes, with a 100% engagement rate in practical group activities compared to none in traditional settings. Sentiment analysis showed a 75% positive response towards the PCB method, indicating a strong preference and perceived effectiveness among students. These results indicate that PCB incorporation augments supported learning and the grasp of core concepts and positively influences student perceptions and conceptions. This proactive engagement pushes learners towards a collaborative learning environment, accentuating group discussions, peer tutoring, and troubleshooting activities. To conclude, traditional methods have their place, but PCB integration in the Digital Electronics curriculum seems paramount in elevating learning efficacy and student engagement, underlining the imperative of hands-on, experiential learning in today’s engineering education framework.

Introduction

STEM occupations employ about 25% of the labor force in the United States [1]. In 2021, 34.9 million (24%) of the 146.4 million people in the workforce between the ages of 18 and 74 worked in STEM fields [1]. With a poor retention rate of 38.3%, African Americans account for only 5% of engineering " 'bachelor's degree holders. Unengaging learning environments have a factor to play in this [2]. The ASEE retention research makes the case that curriculum improvements and firsthand learning in the classroom can raise retention rates [2].

One of the core subjects in most scientific degrees and all electrical engineering programs is digital electronics [3]. Digital electronics forms the foundation of modern technology, enabling the design and function of computers, smartphones, and countless other devices. Issues arising from the complexity of concepts, teaching methods, and course structure contribute to challenges faced by students. Resources and approaches are available to ease learning in this area. The study of digital electronics involves electronic circuits used to process and control digital signals, with a focus on the design process of combinational and sequential logic design, teamwork, communication methods, engineering standards, and technical documentation [4]. Some instructors are experimenting with interactive online textbooks and web-based circuit simulators to enhance the didactic aspects of learning digital electronics [5].

This study compares two methods of teaching digital electronics: the traditional electronic instrument-based method and the standalone printed circuit board (PCB) hardware method. The traditional method of teaching digital electronics in the lab involves building a test circuit and using a generalized electronic instrument. Although the cost of the traditional method has significantly decreased in the past decade by replacing benchtop instruments with all-in-one laptop-controlled data acquisition modules, the cost of the laptop and module remains a few hundred dollars, which is not cost-effective for in-class and at-home use by all students. The traditional method presented in this paper uses the Analog Devices Active Learning Module (ADALM) 100 (m1k) to power the breadboard. The PCB method introduces a compact standalone $5 customized setup that is more portable and easier to set up and use.

Laboratory exercises in traditional engineering education are often well-guided and provided with a comprehensive laboratory manual [6]. The detailed instructions included in formative laboratory assessments represent teacher-centered instructivist techniques, in which students follow directions while the teacher acts as a guide [7] [8]. According to the constructivist viewpoint, students create their own knowledge while the teacher supplies guidance and learning opportunities to encourage participation and learning [7]. Hence, these factors contribute to the challenges students face in comprehending and applying theoretical knowledge in digital electronics and computer architecture. To overcome this challenge, the paper introduces the concept of Experiment Centric Pedagogy (ECP). It gives details of the implementation of ECP in a Digital Electronic classroom at a Historically Black College / University (HBCU). ECP is a novel pedagogical technique prioritizing practical, firsthand learning to augment student comprehension. To improve student learning results in engineering courses, faculty members decided that it is necessary to increase the sustainability of ECP [2].

Over the years, different forms of learning pedagogies have been used to enhance learning experience in classrooms worldwide. Active learning, experiment-based learning, and problem-based learning (PBL) are notable techniques used. One popular teaching strategy used in information literacy training is active learning [9]. The active learning strategy is increasingly recognized as a well-liked means of transforming traditional teacher-centered classroom environments into contemporary student-centered learning environments [10]. Students' activities to build knowledge and comprehension are usually referred to ascactive learning [11]. Research has been conducted using active learning techniques as seen in [12], [13], [9], [14], [15] and [16]. Research has shown motivation and active learning boosts student engagement (Figure 1).

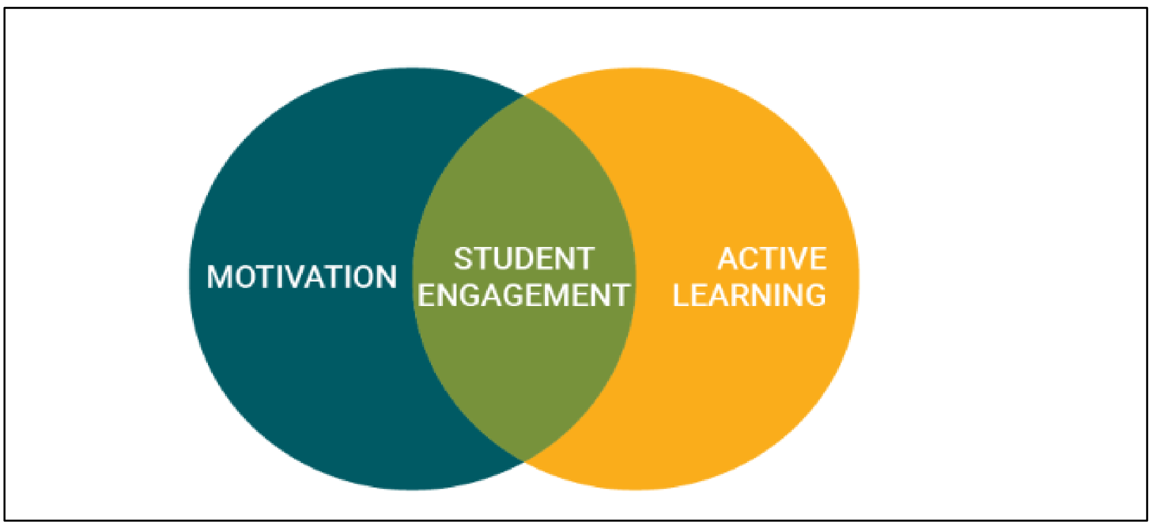

Figure 1: Student engagement [16]

The integration of theoretical learning and practical experimentation is known as experiment-based learning. Through practical experiments, experiment-based learning allows students to participate in scientific inquiry and discovery, promoting a greater comprehension of the scientific process and its tenets in everyday situations. Durre et al. [17] used 3D printers to propose a changeable mechanical logic gate system for experiment-based learning. Precup et. al [18] proposed teaching advanced control engineering using an experiment-based method that focuses on real-time laboratory experiments, controlled plant analysis, control structures, algorithms, and assessment. Another experiment-based research can be seen in [19] and [20].

In PBL, learning aims are defined by the students' using triggers from a problem scenario [21]. Alama et. al [22] investigated how academic libraries might implement a user-centered learning method using PBL in Learning Commons (LC) locations outside the classroom. Ge et al. [23] investigated the application of PBL to online English instruction in Guiyang, China, and Tanjung et al. [24] examined how the technological, pedagogical, and content knowledge (TPACK) approach combined with the PBL model affects the historical learning outcomes of high school students at Sultan Iskandar Muda in Medan. Using a sample of XI students from Social Sciences 1 and IPS 3 as the experiment and control classes, the study used a quasi-experiment method. There are pre-test and post-test phases to the study, and there are 25 valid test questions. The control class scored 68.4, while the experiment class received an average of 80.3. The study shows that the PBL model impacts historical learning outcomes by rejecting the hypothesis of H_0 and accepting the hypothesis of H_a.

Experiment centered pedagogy, which aims to provide educators with the ability to scientifically investigate '"students' mental and cognitive processes to support their teaching approaches, is in line with the way that educational practices are developing [25]. By exposing students to practical, real-world experiences and laboratory tasks, the application of ECP fosters a greater comprehension of academic topics through firsthand learning. Studies have also shown how ECP can enhance engineering '"students' educational experiences [26], especially in classes like Digital Electronics. The goal of ECP is to increase '"students' comprehension and interest in the course material using a firsthand approach. This method prioritizes practical, firsthand experience over traditional lecture-based learning. It aims to link theory and practice, boost engagement, boost critical thinking and problem-solving abilities, and prepare for applications in the real world.

The literature reveals a transformative shift towards experiment-based learning pedagogies to enhance engagement and comprehension in STEM fields, particularly digital electronics education. Despite these advancements, a gap persists in effectively integrating practical, hands-on experiences with theoretical learning. Closing this gap is especially important for increasing engagement with students from underrepresented groups. Therefore, the need for innovative approaches like ECP to bridge this divide is clear. Hence, this study aims to find whether, in comparison to the traditional approach, the integration of PCB hardware enhances conceptual understanding and engagement. The goal is to decide which approach yields an improved understanding of fundamental ideas and real-world applications using the ECP paradigm. A quantitative approach based on pragmatic research philosophy examined the effectiveness of learning outcomes and real-world applications. In one semester, PCBs were used, while traditional methods were employed in the previous semester.

Research Objectives

Th'study aims to investigate whether, in comparison to conventional teaching techniques, the incorporation of PCBs in digital electronics education improvesstudents' conceptual understanding and engagement. The research objectives include:

1. To enhance '"' understanding and engagement in Digital Electronics, specifically in the Computer Architecture and Digital Logic course, through integrating PCB tools within the curriculum.
2. To achieve a significant improvement in '"students' perception and conceptual understanding, as evidenced by statistical analysis using SPSS and sentiment analysis with BERT, in addition to a boost in active learning attributes and an enhancement in core concept comprehension.
3. To utilize the ECP framework to systematically compare the efficacy of PCB-integrated learning against conventional methods over consecutive semesters, gather feedback from educators and students to inform improvements.
4. To ensure the objectives align with the broader goal of advancing engineering education by incorporating hands-on experimentation, fostering a more engaging and effective learning environment that encourages collaborative learning, peer tutoring, and practical application of theoretical knowledge.
5. To complete the comparative study and implement PCB-integrated learning methods in the Digital Electronics curriculum within one academic year, ensuring timely evaluation and adaptation based on the gathered feedback and analysis outcomes.

Theoretical Framework

A theoretical framework is essential for determining the caliber and range of studies in research. It offers a methodical perspective on phenomena, elucidating and forecasting them [27]. The TPACK theoretical framework defines technology in education as much more than specialized hardware or software skills [28]. The three broad knowledge bases of technology, pedagogy, and content and the relationships between and among these knowledge bases define what teachers need to know according to the TPACK framework. The TPACK framework finds a unifying structure that respects this complexity and recommends suitable technology integration. Technology knowledge is incorporated into content and pedagogical knowledge, expanding upon " 'Shulman's concept of Pedagogical Content Knowledge (PCK) [28]. In the 1980s, Shulman established PCK, which is the synthesis or mingling of subject topic knowledge and pedagogy [29]. Scholars investigating content, theory, and technology connections have been involved in TPACK for a while. Technologies knowledge (TK), content knowledge (CK), pedagogical knowledge (PK), pedagogical content knowledge (PCK), technological content knowledge (TCK), technological pedagogical knowledge (TPK), and technological pedagogical and content knowledge (TPACK) are the seven components that make up the framework (Figure 2). TK stands for knowledge of diverse technologies; CK for content to be taught; PK for teaching methods and procedures; PCK for the teaching process; TCK for the understanding of how technology can generate new representations for content; and TPK for the understanding of how diverse technologies can be employed in teaching.

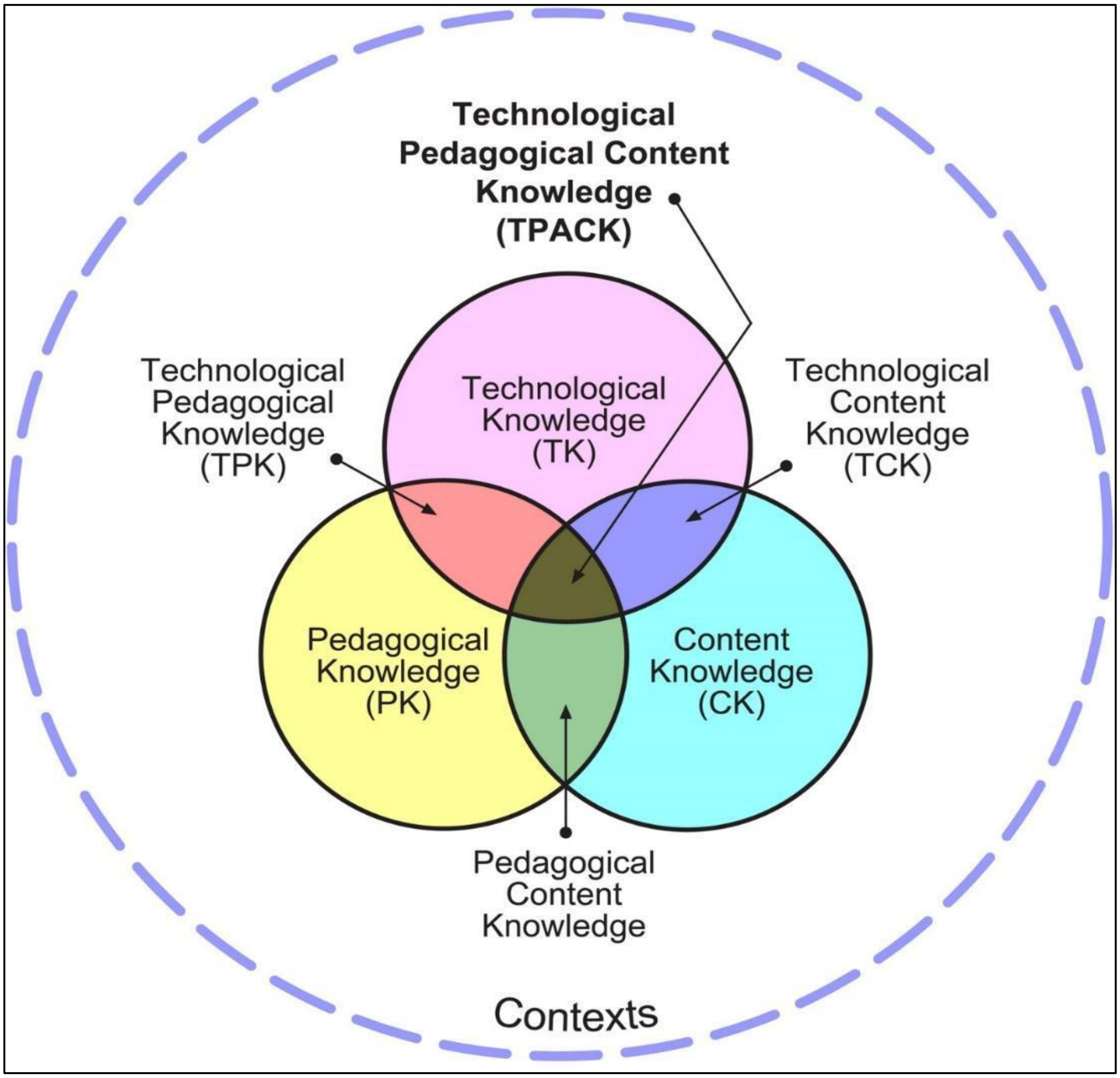

Figure 2: Technological pedagogical and content knowledge [30]

The TPACK framework, integrating technology, pedagogy, and content knowledge, can be effectively utilized in this research. TPACK emphasizes the synergistic relationship between these three domains in educational settings. This study represents technology using standalone PCB hardware or electronic instrument-based hardware, pedagogy by the experiment-centered approach, and content knowledge in digital electronics. TPACK can guide the analysis of how these elements interact to enhance learning outcomes, engagement, and conceptual understanding, thereby offering a comprehensive view of the educational impact of integrating PCB in engineering education.

Electronic instrument-based hardware:

The traditional approach for integrating TPACK into the Computer Architecture and Digital Logic course uses ADALM1000. ADALM is a USB-powered data acquisition module that uses a software interface to set and measure voltage levels. The ADALM is widely used in introductory electronics lab courses because it provides the functionality of common benchtop equipment, e.g., a DC power supply, function generator, oscilloscope, and electrical spectrum analyzer, at a fraction of the size and cost. One downside of this generalizability is the complexity of configuring both the software and hardware (i.e., circuit layout) for a specific hands-on activity. A second downside is the size and cost of the ADALM and the control laptop. For the digital logic activities of the course, only the DC power supply functionality of the ADALM1000 is needed.

Specialized standalone PCB hardware:

Since 2010, high school girls across the US have been building an LED calculator circuit as a core PBL activity during a week-long summer engineering camp at the University of Illinois Urbana-Champaign [31]. Campers first learn about digital logic, digital circuits, truth tables, and Boolean arithmetic. Then, they designed a circuit layout for a 2-bit by 2-bit binary adder with LED display. Finally, they build the circuit that computes sums as large as 3 + 3 and displays the results in binary using LEDs. They lay out components and jumper wires on a protoboard to connect a 9V battery source to a 5V regulator to a set of toggle switches, logic gates to several LEDs that are connected in series with current limiting resistors. Overall, as shown in Figure 3a, the circuit is quite complicated. A significant portion of the activity time is spent debugging incorrect wiring conditions and only about 60% of the 165 girls who attempted to build this version of the circuit were successful.

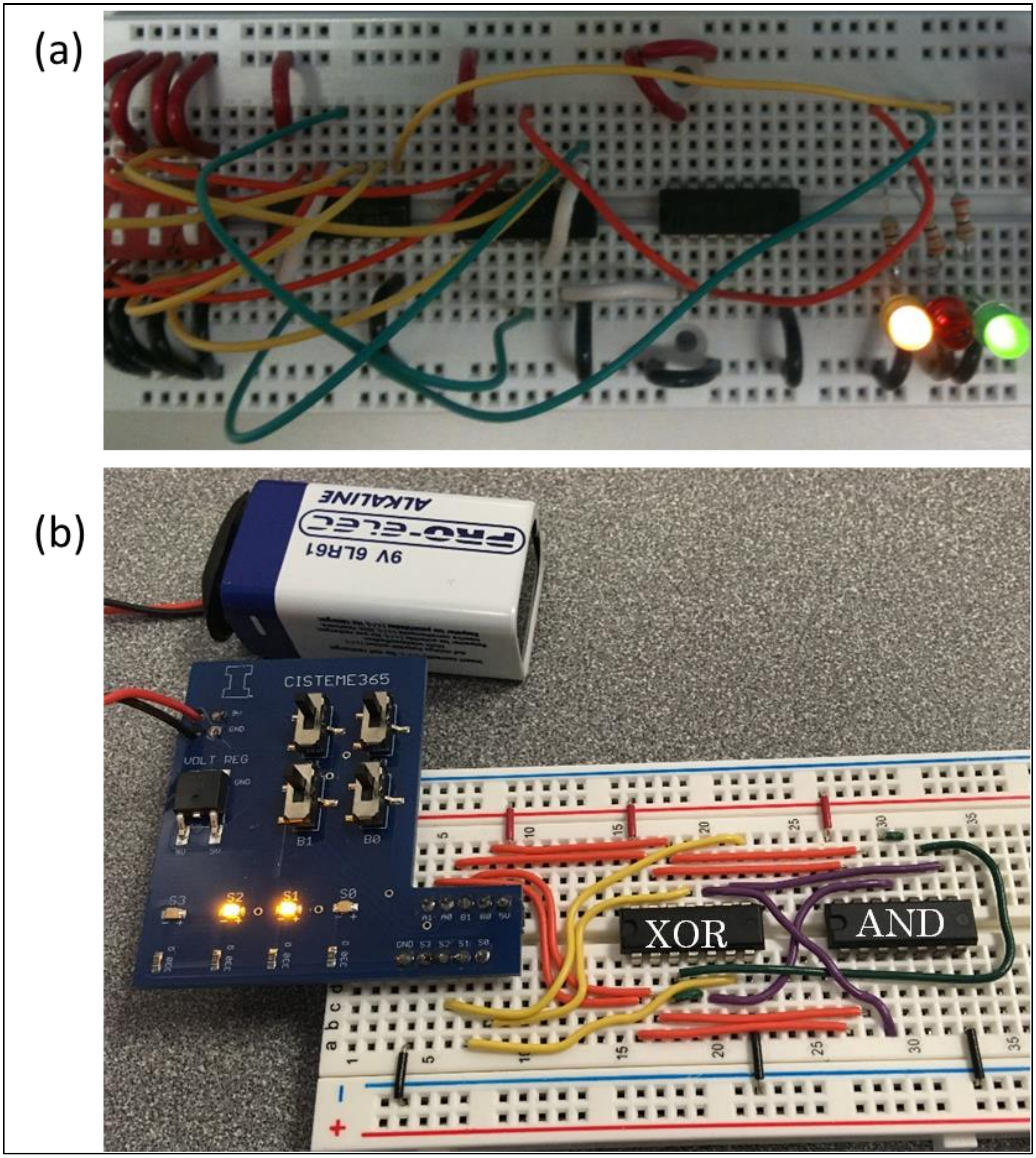

Figure 3: LED calculator circuit using (a) discrete components and (b) an input/output PCB [31]

Intellectually challenging PBL projects that maintain a high success rate are vital for building self-efficacy among students. In the summer 2019, a PCB version of the LED calculator activity was developed that uses surface-mounted components for the 5V regulator, switches, LEDs, and resistors. See Figure 3b. By abstracting away the complex input and output circuitry, campers were able to focus on the wiring connections between the switches, logic gates, and LED outputs, thereby increasing the success rate of building the LED calculator to 100% for the 36 students who participated when the camp was held in summer 2019 and 2023. Campers still gained practical experience laying out a practical circuit on a protoboard but now had sufficient time to explore and experiment with different types of logic gates. Also in the summer 2019, the PCB-based LED calculator project was integrated into the Catalyzing Inclusive STEM Experiences All Year Round (CISTEME365) initiative, a large-scale NSF-funded effort that provides informal hands-on engineering opportunities to pre-college students from low-resourced schools [32],[33]. The PCB approach enabled several hundred students and over 70 teachers, counselors, and other school staff at 24 middle and high schools across Illinois, Texas, and Arizona to develop deep content knowledge and build self-efficacy on digital circuits. The PCB approach was also vital during the COVID pandemic. It enabled students to successfully build digital circuit projects from home when restrictions forced many of the schools' STEM club activities to be held online.

Methodology

Study area and setting:

The research presented in this paper was conducted in a Computer Science class at a Historically Black College/ University (HBCU). The class consists of students who take the courses on-site and online. 24 students participated in the experiment using the traditional method while 46 students used the PCB approach. The students engaging in the class could acquire the kit ahead of time and get access to step-by-step instructions through a YouTube playlist created by the instructor. Every student (who attended physically or virtually) was equally allowed to have individual kits, which they could take home and play around with. Taking kits home was also useful for increasing student motivation because their contact with the tools used were not constrained by class or lab periods only. The aim of these experiments was simply to ensure that the students could have a holistic and analytical understanding of the various basic logic gates.

Study participants:

The set of experiments conducted in this paper is a response to a course titled Computer Systems & Digital Logic (COSC 241) for second year computer science students. Forty-six students were observed during this set of experiments with the CISTEME 365 PCB.

Data collection tool:

1. Signature Assignment: A signature assignment is an assignment that best demonstrates the knowledge or abilities necessary to meet the course objectives. A signature assignment was given to all students at the beginning of the labs. This was conducted using Google Forms.

The signature assignment aimed to evaluate their current knowledge of the basics of digital logic and computer systems before the commencement of the labs. This signature assignment was taken after the end of all the labs as well, to observe if there was a meaningful change in the students' understanding.

The pre-test assessments in both teaching methods are aimed to measure '"students' baseline understanding of digital electronics concepts. In the traditional instrumentation and breadboarding approach, these assessments involve conventional methods such as written tests or quizzes, focusing on theoretical knowledge and problem-solving skills. Conversely, in the PCB-based approach, the pre-test assessments included questions tailored to assess familiarity with PCB design and usage and specific theoretical and problem-solving questions. The goal is to measure the student's level of understanding with regard to digital electronics before the experiment.

The post-test evaluations measure any advancements or modifications in '"' comprehension and utilization of digital electronics concepts after the laboratories are finished. These tests reviewed the same topics covered in the pre-test under the old and new methods. With the use of breadboards and, conventional instrumentation, and PCB approach, this evaluates how successfully the students used their knowledge. This comparison would shed insight into how well each strategy facilitates learning digital electronics-related information and skills.

2. Motivated Strategy Learning Questionnaire (MSLQ): 'MSLQ aims to assess collegestudents' academic motivation and the kinds of learning techniques they employ. The measure consists of 44 items on a 7-point Likert scale [34]. The MSLQ is linked, its documentation is linked, and it is attached. --A pre-test and post-test survey were also issued using the Survey Monkey platform. This was used to conduct the MSLQ. This measured the student's motivation level to use the different ECP instruments (PCB vs Traditional) before and at the end of the experiential learning labs.

3. Classroom Observation Protocol for Undergraduates in STEM (COPUS): Classroom observation protocol for undergraduate students in STEM facilitates the gathering and classification of observational data, usually in large group situations, about what students are doing with what their instructor is doing [35]. This measured the student and instructor activity during the classroom lab session. SPSS was then used to analyze the data derived from this COPUS.

4. Outcome Assessment: A collaborative process of inquiry into the learning outcomes of students, outcomes assessment entails analysis, reflection, and action. Enhancing instructional programs and student learning are the two main objectives of outcomes

assessment. This research compares the outcome assessment data of students using traditional approach and student using PCB approach for learning Digital Electronics.

5. Sentiment Analysis using Student Feedback Form: This instrument was newly introduced in this research to help structure future analyses. It will not be used in the comparison between PCB and the Traditional approach. This research uses BERT, which stands for Bidirectional Encoder Representations from Transformers. BERT is a well-liked language model that increases precision by understanding words in relation to one another [36]. Student learning experiences were evaluated using the BERT model. Textual responses from open-ended questions related to teaching methods, overall learning experience, engagement level, and feedback from lab sessions were listed and prepared for sentiment analysis.

Data analysis method:

Qualitative Analysis-

According to Aspers et. al [37], qualitative research is an iterative process that improves knowledge for the scientific community by identifying new, noteworthy differences that arise from getting closer to the subject being examined. Translating raw data into interpretable and meaningful forms involves various techniques, including searching, analyzing, identifying, coding, mapping, investigating, and characterizing patterns, trends, themes, and categories. This is known as qualitative data analysis [38]. In this research, student feedback data was collected for the purpose of qualitative analysis. Sentiment analysis was carried out using BERT; however, this analysis will not be used in the comparison due to a lack of captured data from past works. It is, however introduced to shape the way non-numeric feedback from students can be analyzed.

Quantitative Analysis-

The primary survey data --is based on MSLQ, and the pre-test and post-test surveys are comprised mostly of close-ended questions that are subjected to quantitative analysis most of the time. Qualitative analysis looks at aspects of the data that ’can’t be measured, while sentiment analysis uses natural language processing to identify the polarity of the data. Qualitative and sentiment analysis are helpful tools in different areas, like education, consumer sentiment, and brand reputation. Qualitative analysis looks at themes, patterns, and meanings in data, whereas sentiment analysis employs machine learning techniques to categorize text data. The quantitative analysis was executed using the Signature assignment, MSLQ data, COPUS data, and Outcome assessment data using SPSS.

Experiment Description:

Traditional Method-

In the traditional approach to teaching digital electronics (Figure 4), the experiment utilizes a hands-on ECP method where students work with essential components such as integrated circuits (ICs), jumper wires, LED lights, a breadboard, and a controller module, specifically the ADALM1000 module. This setup imparts a practical understanding of fundamental logic gates, including NAND, NOR, AND, and Hex gates, and their operations within digital circuits. Digital circuits, unlike their analog counterparts, operate on discrete signals, representing binary levels as logic 1 (high voltage, typically 5V) and logic 0 (low voltage, 0V).

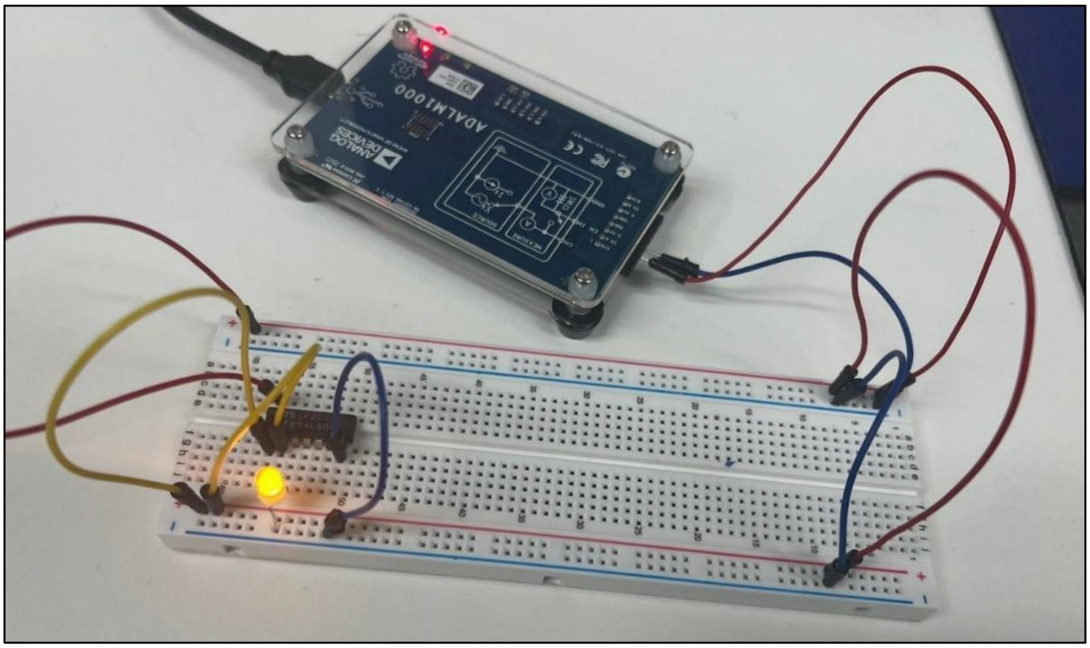

Figure 4: Traditional approach for digital logic exploration

To conduct the experiment, students must follow a set of procedures that begin with integrating ICs onto the breadboard, ensuring correct placement to facilitate the intended circuit configurations. LEDs are connected to the output pins of these ICs to visually indicate the output states, with the longer leg of the LED connected to the positive rail and the shorter leg to the output pin. In this configuration, the LED turns on when the output of the digital logic gate is 0, i.e., low, to affect a NOT gate operation. The breadboard is powered by the ADALM1000 module, with the voltage supplied to the VCC (positive rail) and the ground connected to the GND (negative rail). The experiment stipulates that the operating conditions for the ICs (74XX series) must include a power supply ranging from 4.5V DC to 5.25V DC, with high-level signals recognized at voltages above 2V and low-level signals below 0.8V, ensuring the ICs operate below 70 degrees Celsius.

Through this traditional methodology, students toggle the input pins to achieve desired outputs, thereby gaining firsthand experience in the construction and analysis of digital circuits. This process not only facilitates the application of theoretical knowledge but also enhances the

’”students’ comprehension of the binary logic foundational to digital electronics, aligning with the objective of improving understanding through practical engagement.

PCB Method:

The PCB approach in the experiment signifies a modern, structured methodology for exploring the functionalities of basic logic gates and their applications in digital circuits. Unlike the traditional method, which involves the manual assembly of circuits on a breadboard, the PCB approach employs a CISTEME365 PCB as a foundational platform, providing a more organized and efficient means of connecting various ICs and components. This setup facilitates the construction and analysis of digital circuits, demonstrating logic operations such as AND, OR, NAND, NOR, XOR, and XNOR (Figures 5 and 6).

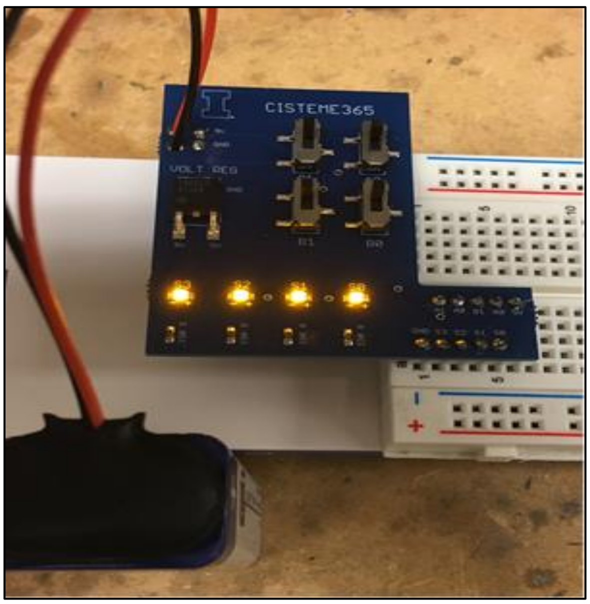

Figure 5: PCB validation

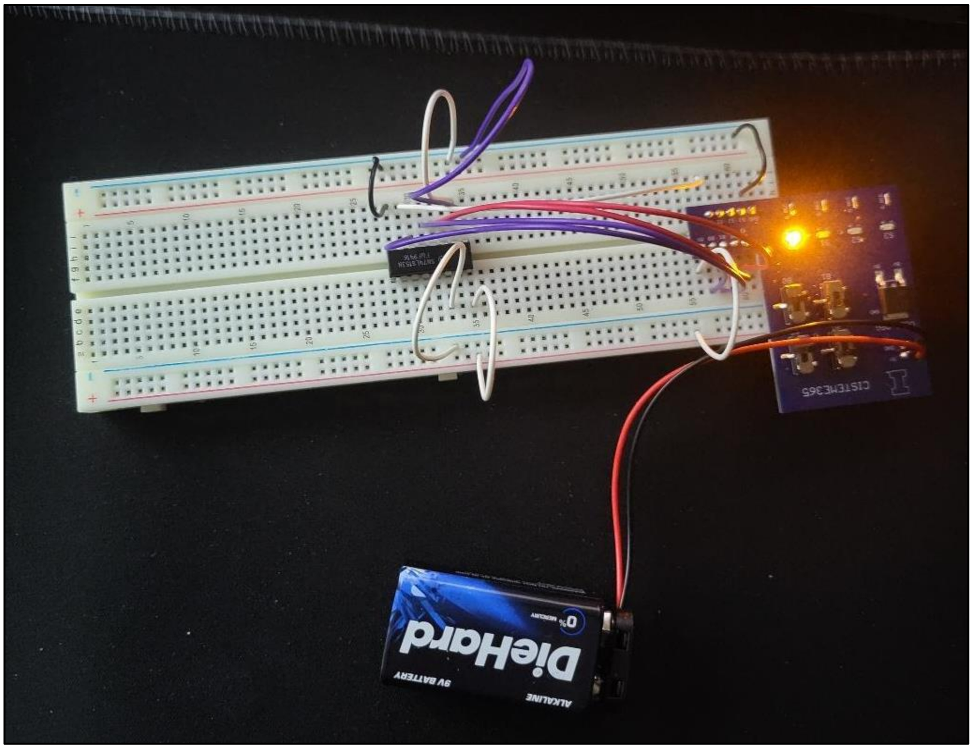

Figure 6: PCB Method for digital logic exploration

The experiment begins with carefully placing the breadboard on the table, followed by positioning the PCB onto the breadboard, ensuring it is centrally located to allow equal access from both sides. As shown in Figure 5, the PCB is first tested to ensure the 9V battery, LEDs, switches, and other PCB components are operational. The outputs of the switches are in the same column of the protoboard as the inputs to the LEDs. Thus, students can check the PCB works by sequentially toggling the switches to turn on and off the LEDs. ICs, including quad 2-input NAND, NOR, AND, OR XOR, and XNOR Gates from Digi Key, are then mounted on the PCB.

An example is shown in Figure 6. Connections are made to establish ground (GND) and power (VCC) lines, with a 9V battery providing the necessary power supply and a surface mount regulator reducing the voltage supplied to the gates and switches to 5V. Inputs and outputs for the logic gates are configured by connecting jumper wires to specific pins, facilitating the demonstration of various logic operations. This PCB-based setup not only streamlines the experimental process but also enhances the learning experience by offering a compact, integrated environment for testing and observing the behavior of digital circuits. Students can use the PCB to interact with the digital logic gates using hardware they interact with daily, i.e., flipping on and off a light switch. This contrasts with the traditional approach in which students must move around wires to achieve the same effect, which is analogous to rewiring the whole house and something they are unfamiliar with. The emphasis on a single, consolidated platform minimizes setup and reconfiguration time and potential errors associated with loose connections in a breadboard setup, making the learning process more engaging and effective. Furthermore, the use of a battery for power and the integration of various logic gates on a single PCB exemplify the real-world application of digital electronics, aligning with the ” ’experiment’s objective to deepen understanding of logic gates and their functions in a practical, hands-on manner. Overall, the PCB approach presents a more accessible, cost-effective, and efficient way to explore digital electronics, catering to the evolving needs of learners and educators in the field.

Result Discussion

Signature Assignment:

The assignment that best demonstrates the knowledge or abilities necessary to meet the course objectives is a“” ““signature assignment”””” or exam. The way signature assignments are incorporated into curricula across the educational route to support students in demonstrating their progress, forming connections across subjects, and applying their knowledge to real-world issues sets them apart from other types of assignments. Figure 7a, shows that the PCB method has superior outcomes in the signature assignment compared to the traditional method for the initially low-performing students.

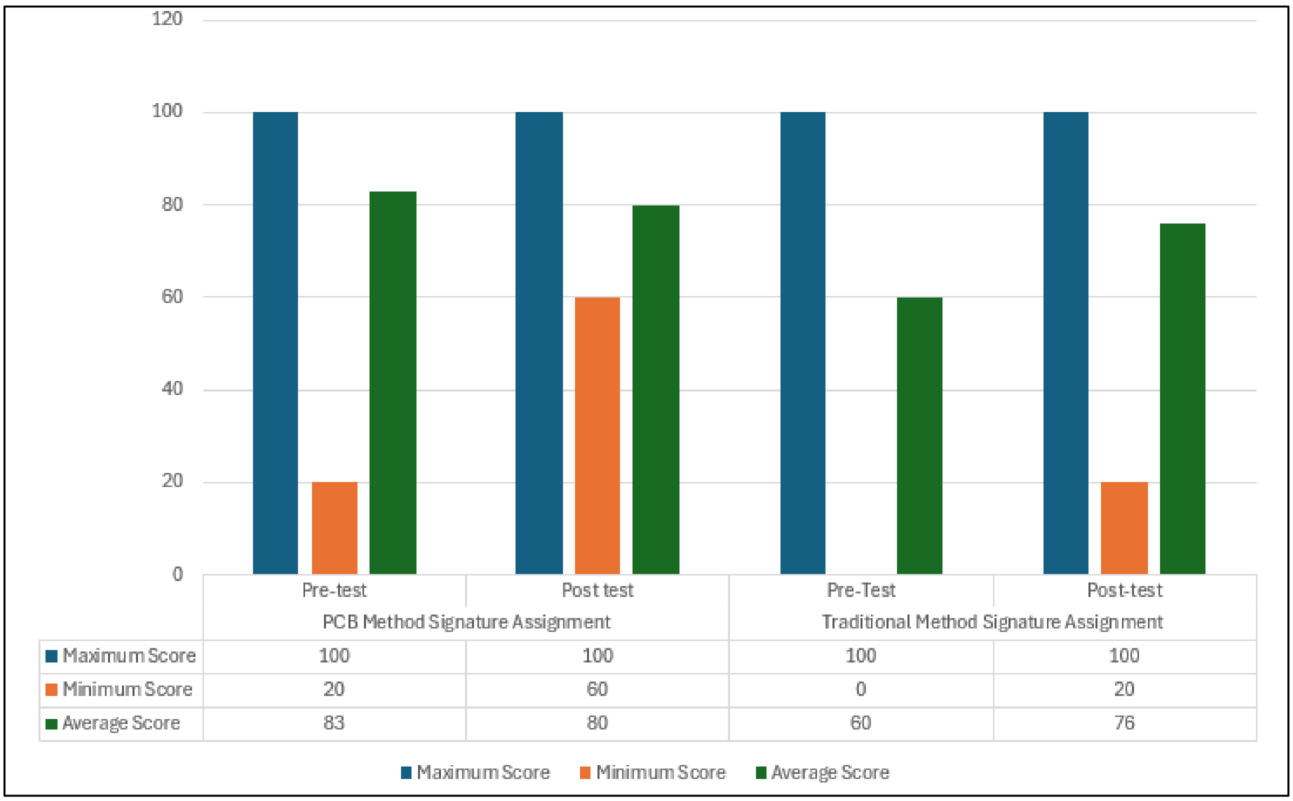

Figure 7a: Signature assignment result comparison.

Notably, the minimum scores for PCB are higher, with the pre-test at 20 versus 0 for Traditional and the post-test at 60 compared to 20, indicating a higher baseline understanding and improvement in the PCB method. The average scores also favor PCB, with an 83% for the pre-test, demonstrating a substantially better initial grasp (23% higher than traditional). The post-test averages are closer, yet PCB still leads with 80 compared to 76, showing a more consistent and retained understanding of the material. This data suggests that the PCB method enhances initial comprehension and leads to better retention and understanding, as evidenced by the higher average and minimum scores. Based on the result comparing the learning gains in terms of maximum and minimum score difference in the pre-test and post-test, the PCB method is essential for students who initially perform low and has a minor effect on students who initially perform high (Figure 7b).

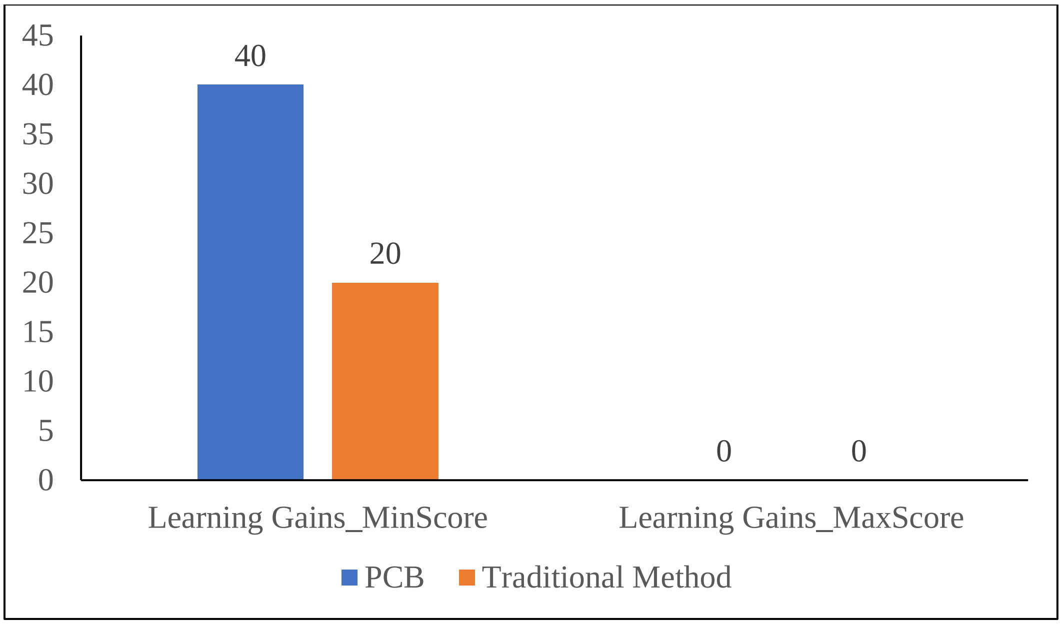

Figure 7b: Learning Gains

Motivated Strategy Learning Questionnaire (MSLQ):

Students' endorsement ratings on statements reflecting general academic occurrences in the context of domains are sought after by the MSLQ self-efficacy components. Three of the original scale's nine components encourage students to assess their own abilities against those of their peers. The two graphs depict post-intervention scores and mean differences in scores, respectively, based on the MSLQ for students taught using traditional and PCB approaches in a digital electronics course.

Figure 8 illustrates that the PCB approach, on average, resulted in higher post-intervention score across most MSLQ constructs. Notably, in 'Metacognition' (MC_POST), students taught with the PCB method scored a mean of 21.9, compared to 21.2 in the traditional approach, indicating a more effective learning outcome in terms of meta-cognition. Similarly, for 'Peer/Learning Collaboration' (PLC_POST), the PCB method scored 15.2 over the traditional method's 14.5, suggesting that the PCB method promotes better collaborative learning practices.

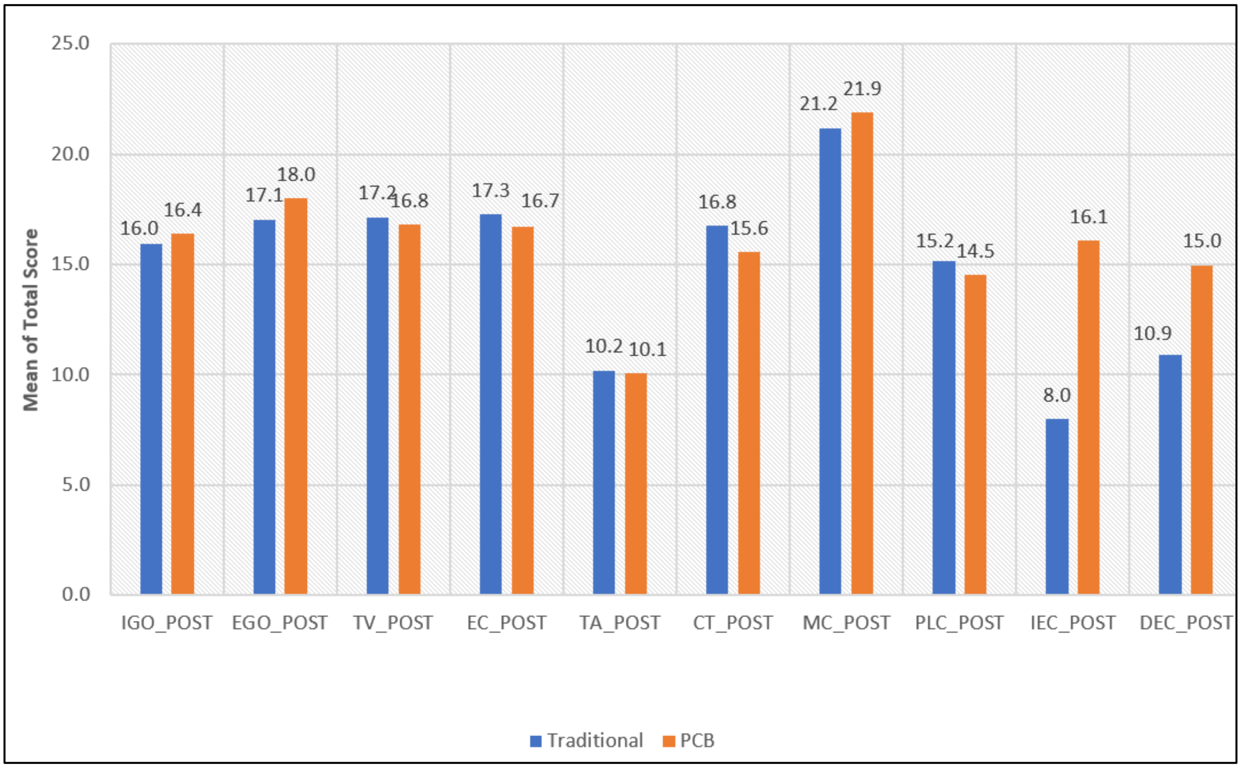

Figure 8: Mean total score of MSLQ post test data.

(IGO-Intrinsic Goal Orientation, TV- Task Value, EC-Expectancy Component, TA-Test Anxiety, CT-Critical Thinking, MC-Metacognition, PLC-Peer Learning/Collaboration, EGO (Extrinsic Goal Orientation, IEC-Interest Epistemic Curiosity Scale, DEC- Deprivation Epistemic Curiosity Scale)

Table 1 shows the mean differences between post and pre-test scores, highlighting improvements or declines in learners' perceptions of motivational and curiosity constructs. The result shows that the decline is due to the traditional method. Thus, the traditional method dampens the learners' curiosity as seen in the IEC and DEC, while PCB has only minimal declines. In the context of engineering education, where hands-on experimentation is crucial, these results suggest that PCB integration can enhance conceptual understanding, curiosity, and engagement. Also, the graph shows that traditional is slightly better for improving critical Thinking (CT), but PCB is better for MC, PLC, IEC, and DEC in terms of mean different scores. The result showed a significant improvement in the learner's peer learning, collaboration, and metacognition. Overall, the data implies that the PCB approach aligns well with the goals of ECP, likely due to its practical nature and connection to their daily lives, which supports active and engaged learning. However, the observed decline in IEC scores indicates that aspects of student curiosity and knowledge-seeking behavior may not be fully addressed by the PCB method alone, and these areas could be opportunities for further pedagogical innovation.

Table 1: Paired Sample t-test result for MSLQ data

Subscales	Traditional		PCB	
	Mean Difference	*p*-value	Mean Difference	*p*-value
IGO	-1.30	0.055	0.59	0.172
EGO	-0.75	0.107	0.81	0.131
TV	-1.05	0.048	0.30	0.330
EC	-0.45	0.259	0.43	0.251
TA	0.25	0.331	0.35	0.222
CT	1.05	0.110	0.73	0.083
MC	-1.60	0.030	1.38	0.044
PLC	-0.20	0.382	1.38	0.016
IEC	-8.50	<.001	-0.36	0.189
DEC	-3.05	0.047	0.03	0.474

(IGO-Intrinsic Goal Orientation, TV- Task Value, EC-Expectancy Component, TA-Test Anxiety, CT-Critical Thinking, MC-Metacognition, PLC-Peer Learning/Collaboration, EGO (Extrinsic Goal Orientation, IEC-Interest Epistemic Curiosity Scale, DEC- Deprivation Epistemic Curiosity Scale)

Classroom Observation Protocol for Undergraduates in STEM (COPUS):

University observation programs needed a protocol to describe the overall condition of teaching; give feedback to instructors who wanted to know how they and their students were spending class time; and determine the needs for faculty professional development. This led to the creation of COPUS. Figure 10 compares the percentage of certain classroom behaviors observed under the traditional and PCB methods, using COPUS. Figure 9 shows that in ‘“‘Listening to ’”Instructor’ (L), the PCB method has a significantly lower percentage (16.95%) compared to the traditional method (45.83%), which may indicate that the PCB method involves less passive listening and potentially more active engagement. A striking result is seen in ‘“‘Other assigned group activity, such as hands-on activities with ECP ’”device’ (OG), where the traditional method registers 0%, while the PCB method students have the device, indicating exclusive engagement in hands-on activities in the PCB method. In ‘“‘Student asks a ’”question’ (SQ), the PCB method has a lower percentage (12.50%) compared to the traditional method (20.34%), which might reflect a difference in how questions are addressed, or the level of inquiry prompted by each method.

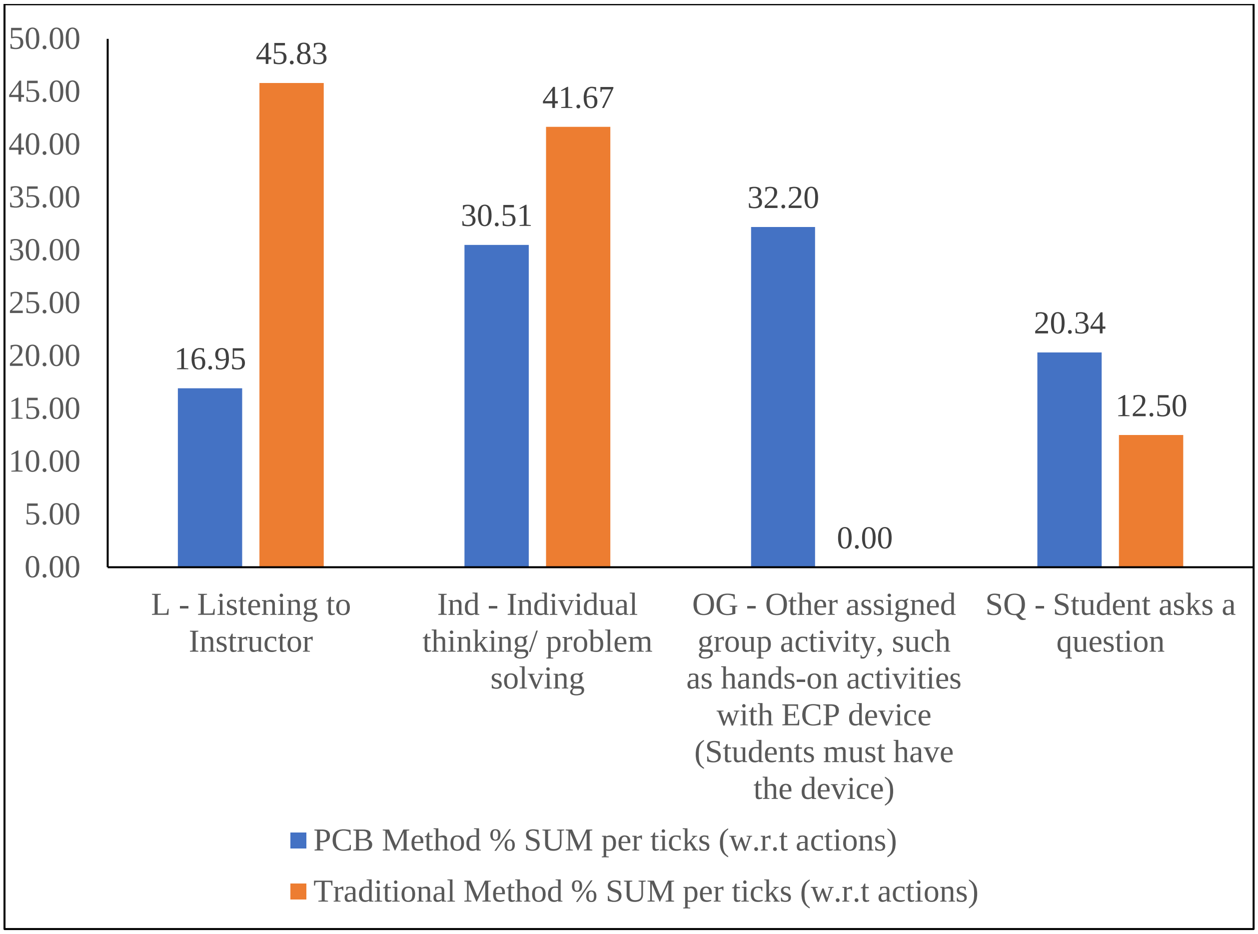

Figure 9: Percentage of time students spend doing different things in class as measured by COPUS.

The PCB method appears to shift classroom dynamics from passive listening towards more hands-on activities, although it may involve less individual problem-solving and student questioning as per the observed behaviors. The figures suggest that PCB encourages active learning, a key component in effective STEM education.

Figure 10 compares classroom activities in terms of what the instructor is doing when observed under the traditional and PCB methods using COPUS. For ‘Lecturing’ (LEC), the PCB method shows significantly lower frequency (9.84%) compared to the Traditional method (37.04%), indicating a shift away from instructor-centered delivery’Real-time writing’ (RtW) is not present in the PCB method, which suggests a move towards more digital methods of engagement. When it comes to ‘Posing Questions to Students’ (PQ), the PCB method (6.56%) is used less than the traditional method (7.41%), although the difference is minimal. A notable distinction is in ‘Listening to and answering student questions with entire class listening’ (AnQ), where the PCB method is significantly lower (11.11%) than the traditional method (22.95%), possibly indicating that the PCB method encourages different forms of interaction. ‘Moving through class guiding ongoing student work during active learning tasks’ (MG) is significantly higher with the PCB method (27.87%) compared to the traditional method (11.11%), suggesting the PCB method promotes more mobility and interaction by the instructor. Lastly, for ‘Showing or conducting a demo, experiment, simulation, video, or animation’ (D/V), both methods register the same frequency (11.11%).

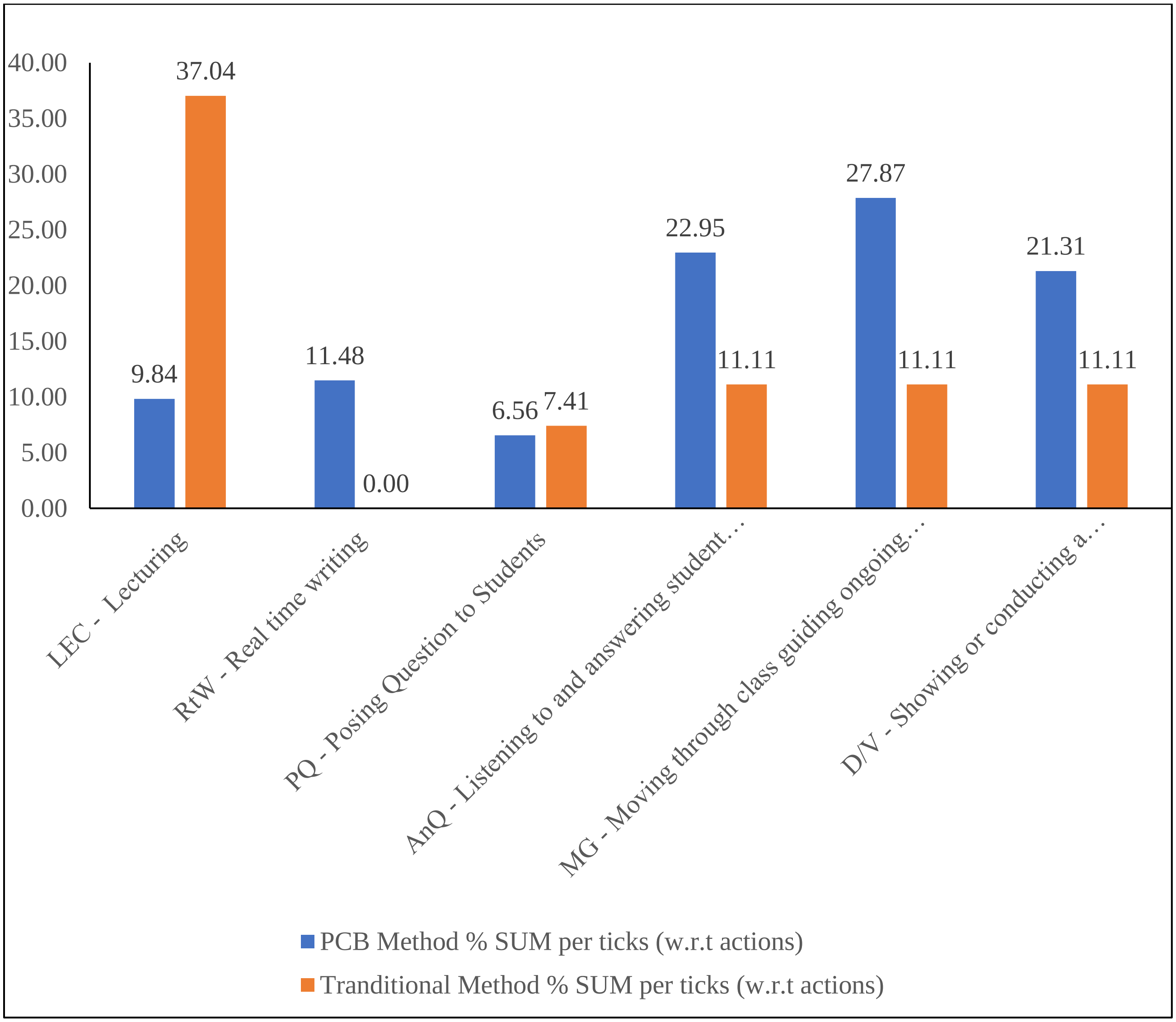

Figure 10: Percentage of time the instructor spends doing different things in class as measured by COPUS.

This data suggests that while the PCB method involves less lecturing and more active guidance, it employs demonstrations as much as the traditional method. The PCB method seems to foster a more interactive and less lecture-centric learning environment.

Outcome Assessment Comparison:

As shown in Figure 11, the PCB method displays variation in students' ability to perform different learning objectives, with exemplary performance ranging from 83.72% to 97.67%. As shown in Figure 12, the traditional method shows uniform excellence with exemplary performances at 100% for most criteria, slightly lower at 75% for recognizing precision, error analysis, drawing conclusions, and offering recommendations, with a consistent target of 25%. This indicates that while traditional Methods maintain a consistently high standard, PCB methods have a broader range of outcomes, suggesting more variability in performance.

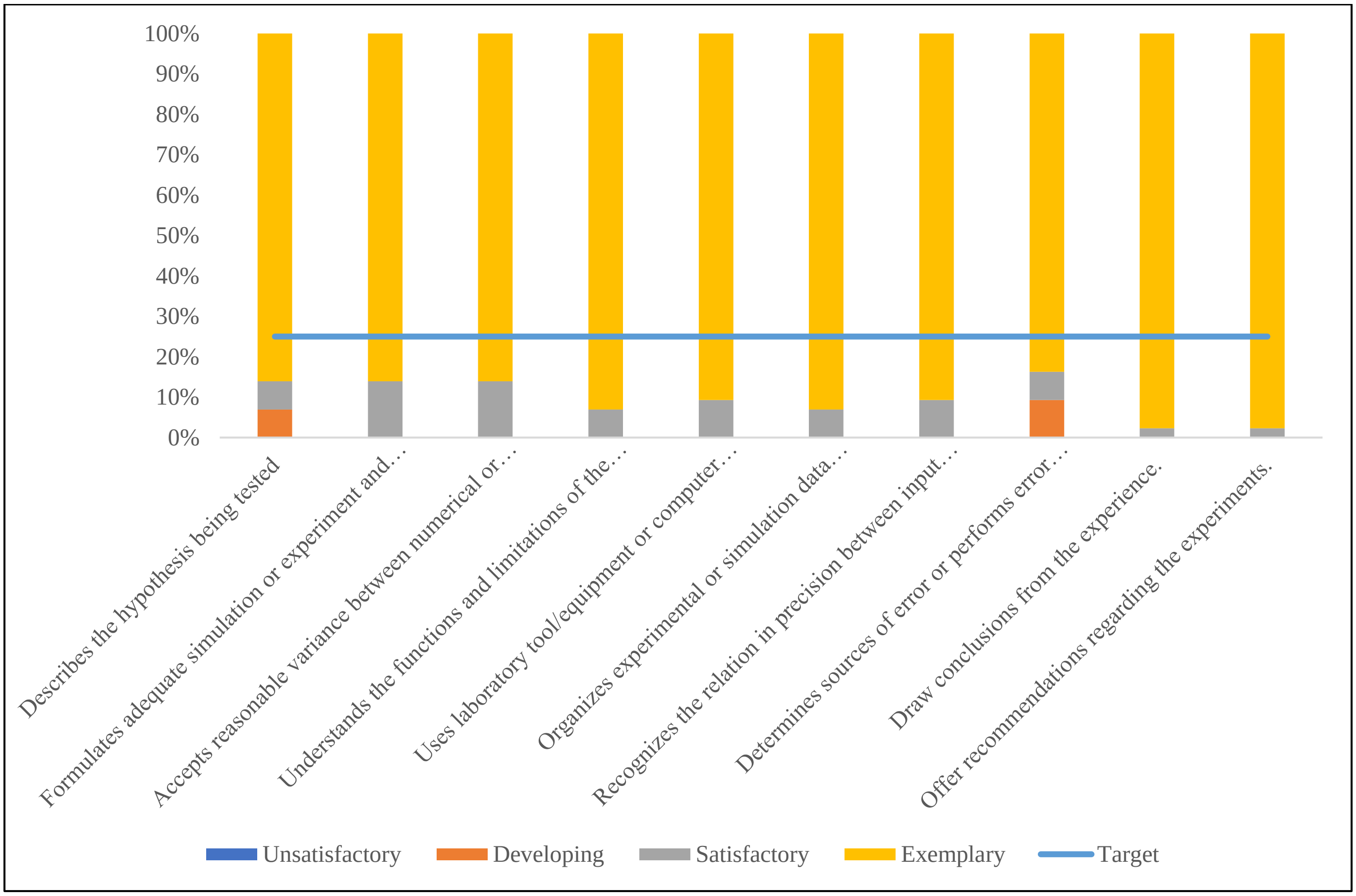

Figure 11: Outcome assessment of students taught using the PCB Method.

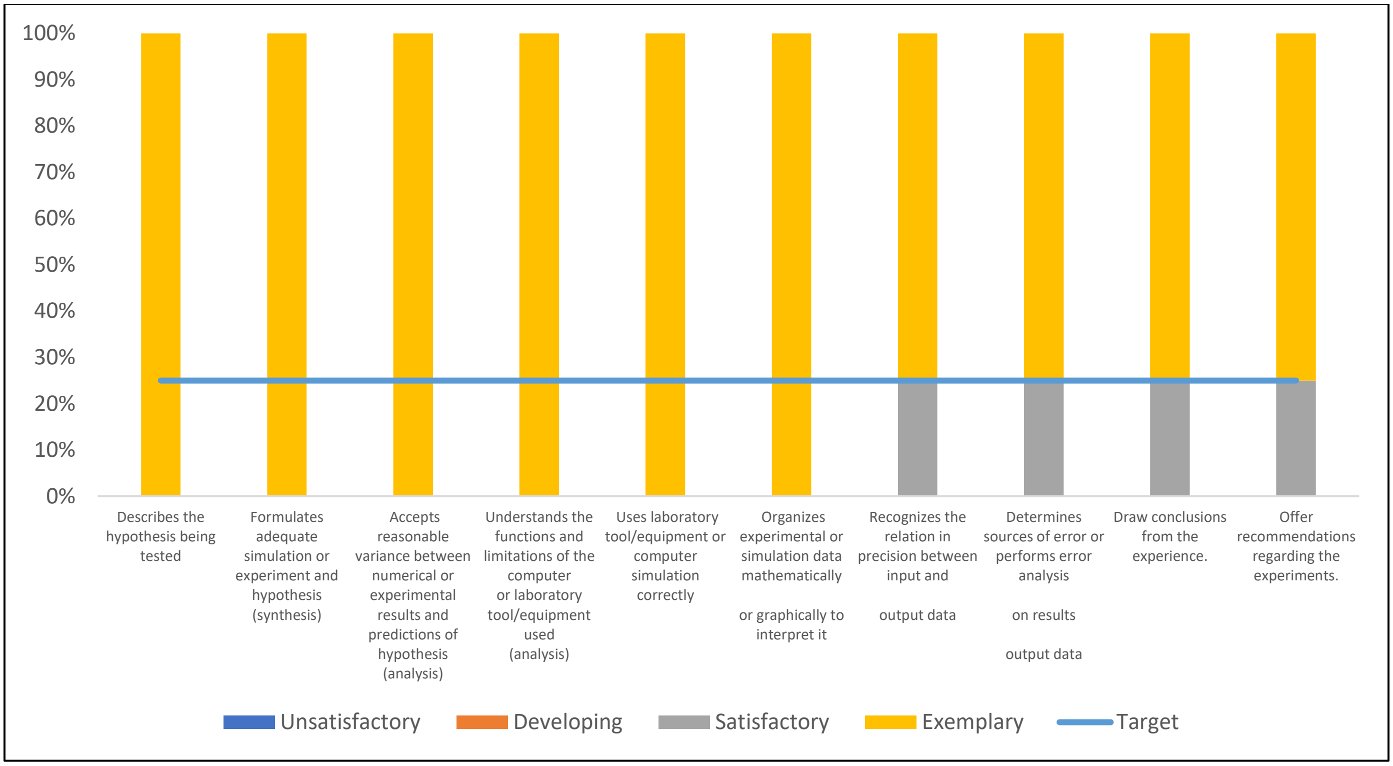

Figure 12: Outcome assessment of students taught using the traditional Method.

Sentiment Analysis using BERT (bidirectional encoder representations from transformers) model:

In the comparative study of digital electronics learning, using PCB versus traditional methods within an ECP approach for engineering students, sentiment analysis using BERT reveals a positive inclination towards PCB integration. Figure 13 illustrates sentiment comparison across various features such as teaching methods, learning experience, engagement level, and feedback. The overwhelming green bars denote a high proportion of positive sentiment, with both teaching methods and learning experience receiving a 75% positive response, while engagement level and feedback were favorably perceived at 66.7%.

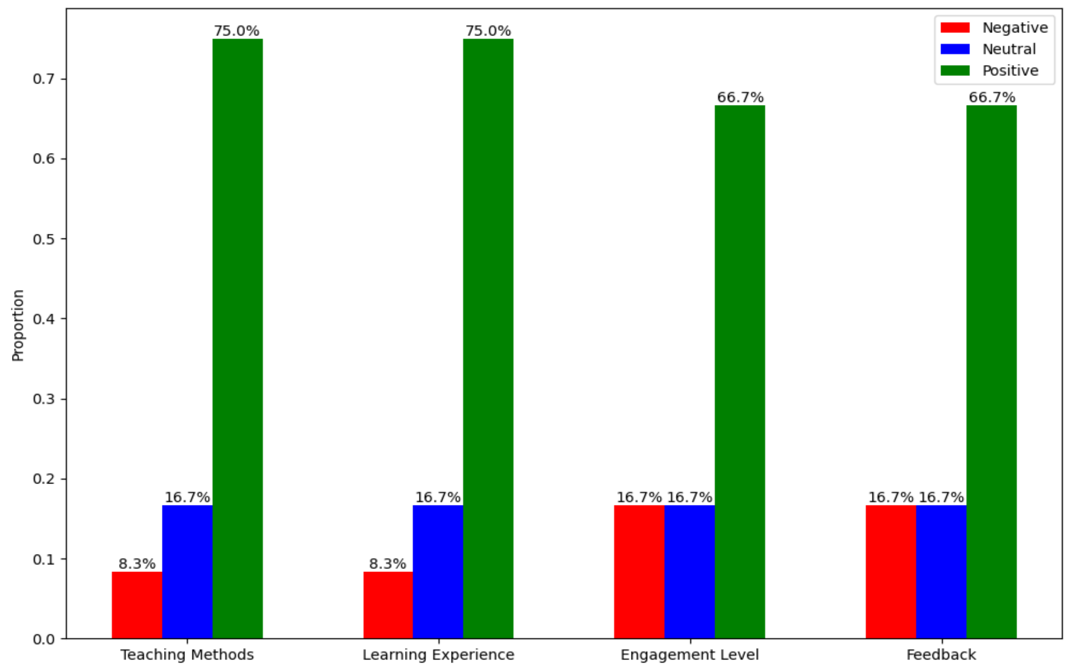

Figure 13: Sentiment comparison across different features for the PCB method

The word cloud reinforces this positive sentiment, with prominent words like “helpful”, “good”, “engaged,” and “great” indicating a positive reception among students (Figure 14). Words like “real,” "hands," and "application" suggest a connection with the tangible aspects of learning through PCB integration, which have contributed to the enhanced perception and conception reported.

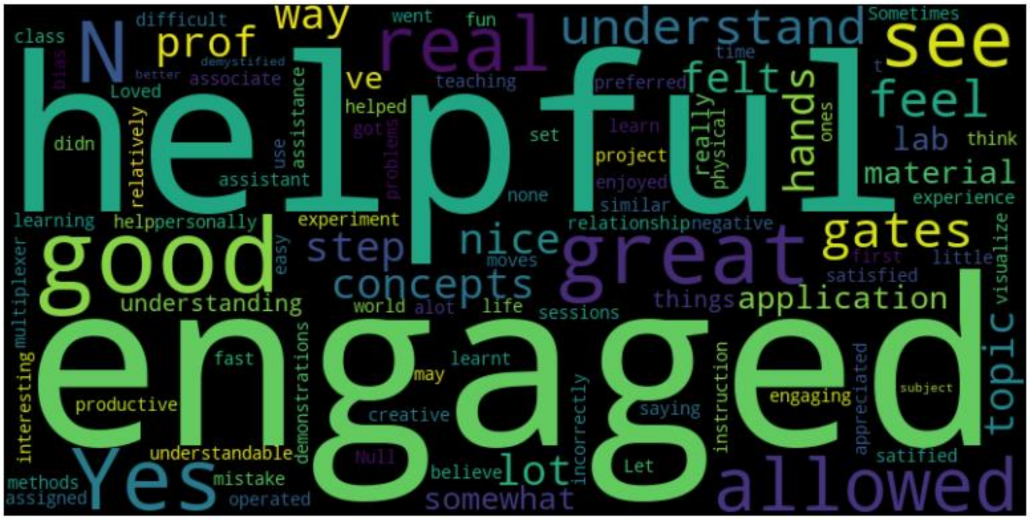

Figure 14: Word Cloud

Figure 15, highlighting top keywords in the bag of words, aligns with the positive sentiment, with "engaged" appearing most frequently, followed by other affirmative terms such as "helpful," "allowed," and "great."

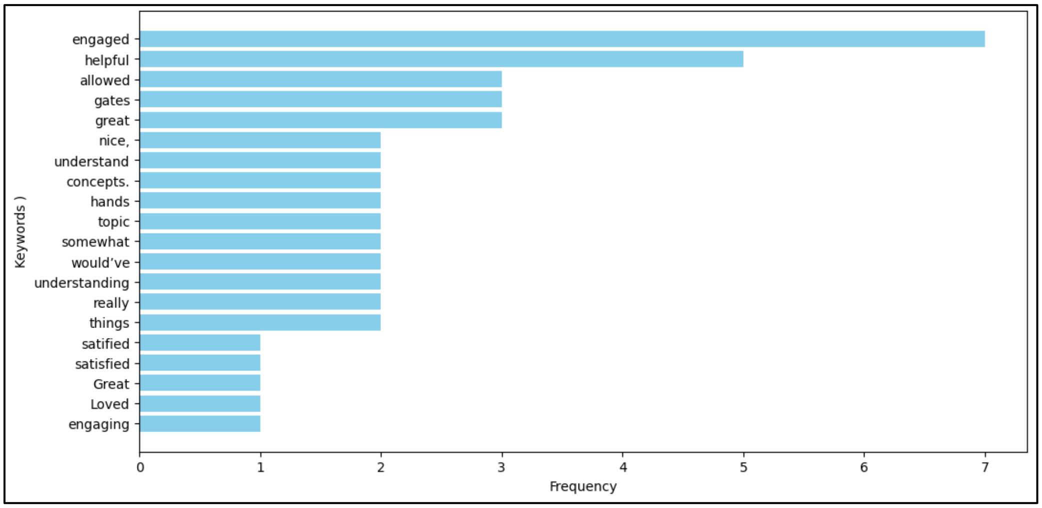

Figure 15: Top keywords from student feedback

The histograms on the distribution of satisfaction, support, relevance, and peer interaction all skew towards the higher end of the scale, suggesting that students found the PCB-integrated learning experience to be more satisfactory, supportive, relevant, and interactive compared to traditional methods. Figure 16 shows the PCB method's overall satisfaction, peer interaction, support, and relevance.

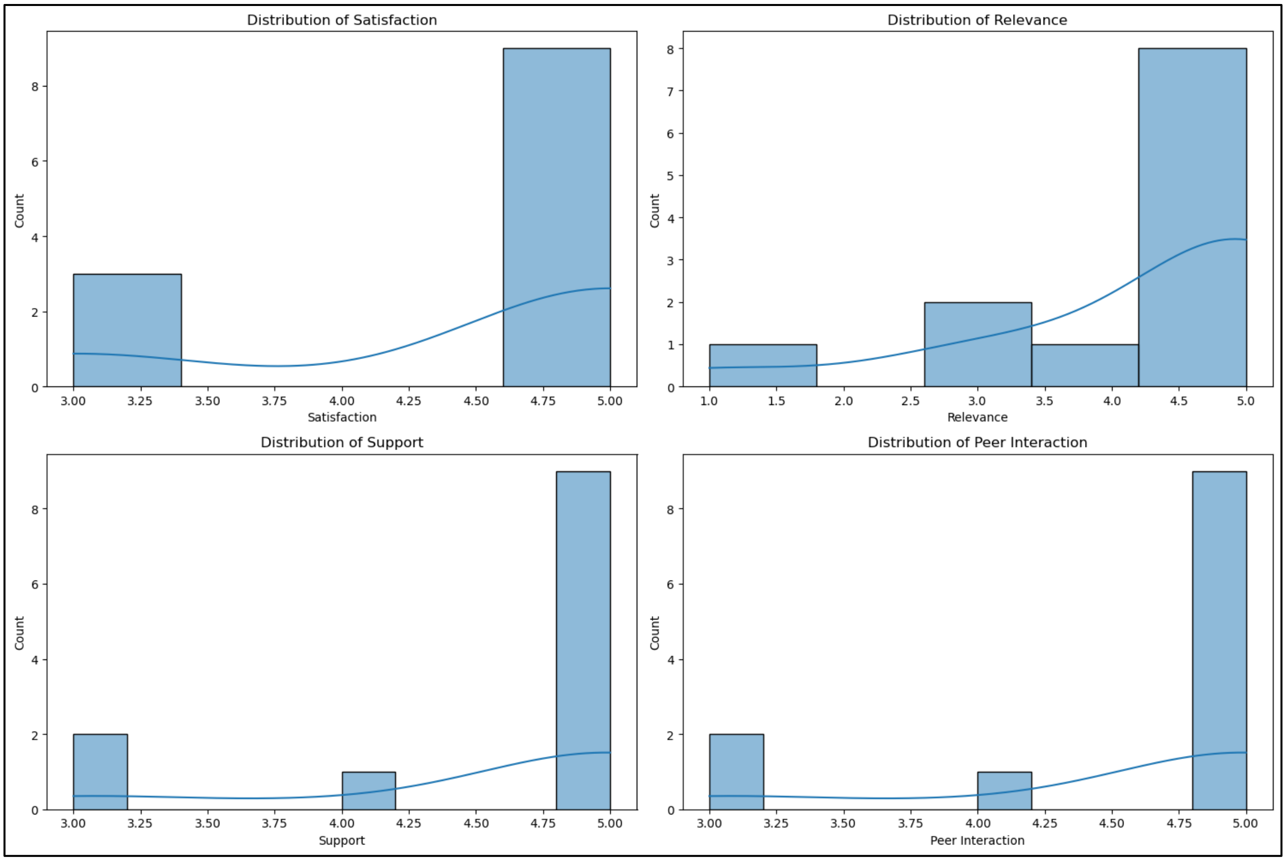

Figure 16: Learning experience

The correlation heatmap shown in Figure 17 visually summarizes the strong positive relationships between satisfaction, relevance, support, and peer interaction, with correlation coefficients ranging from 0.73 to 1.00. These high correlations are in line with the study's findings that PCB integration positively influences student engagement and comprehension of core concepts, leading to a proactive and collaborative learning environment. Hence, the sentiment analysis results are consistent with the study's implications that PCB-based learning significantly improves learning outcomes in digital electronics. The data supports the assertion that PCB integration, compared to traditional methods, is paramount in elevating learning efficacy and student engagement, highlighting the importance of hands-on, experiential learning in the contemporary engineering education framework.

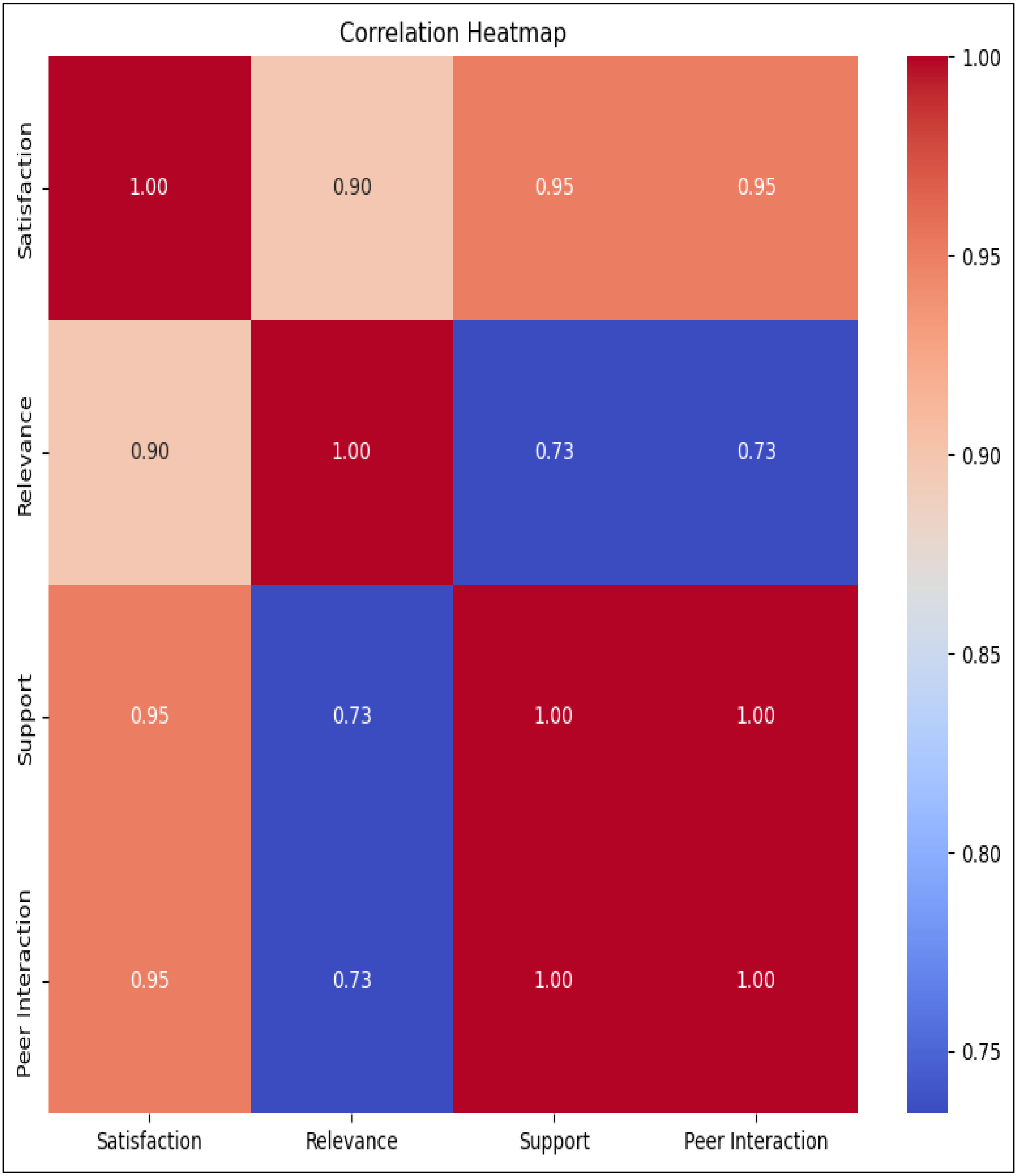

Figure 17: Heat map

Conclusion

The study conclusively demonstrated that integrating Printed Circuit Board (PCB) tools in digital electronics education significantly outperforms traditional teaching methods within an Experiment-Centered Pedagogy (ECP) approach for engineering students. Notably, the PCB method led to an 83% average score on the signature assignment in the pre-test phase, a clear 23% increase over the traditional method. Post-test evaluations further established the effectiveness of PCB integration, with students achieving an 80% average marginally higher than the 76% observed with traditional methods, indicating improved initial comprehension and enhanced retention and understanding. The Motivated Strategy Learning Questionnaire (MSLQ) results positively impacted metacognition and peer learning collaboration. PCB method scores exceeded those of traditional methods by 0.7 and 0.7 points respectively, on a scale of 1 to 7. These improvements underscore the PCB method's capacity to enhance reflective learning practices and student collaborative engagement. Classroom Observation Protocol for Undergraduates in STEM (COPUS) data indicated a significant shift in classroom dynamics with the PCB method, where 'Other assigned group activity, such as hands-on activities with ECP device' (OG) marked a 100% engagement in active, hands-on learning, in stark contrast to the traditional method, which showed no such engagement. This shift towards active learning is critical in STEM education for fostering deeper understanding and skills application. Sentiment analysis using the BERT model further confirmed the positive reception of PCB integration among students, with a 75% positive sentiment toward teaching methods and learning experience. This notable improvement in student perception aligns with the study's goal to enhance engagement and conceptual understanding in digital electronics education. The study's findings advocate for the broader implementation of PCB-integrated learning methods, suggesting a significant potential to elevate engineering education through hands-on, experiment-centered pedagogies. Future works may explore the scalability and applicability of PCB methods across various engineering and educational contexts to further validate and extend these promising results.

Acknowledgement

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