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GAMIFIED SIMULATION-BASED LEARNING FOR ANALOG CIRCUIT DESIGN: A MULTIMODAL PEDAGOGICAL FRAMEWORK FOR TEACHING THE COMMON EMITTER AMPLIFIER

*** Askhat Bigeldiyev**

JSC "Civil Aviation Academy", Aviation College, Almaty 050000, Kazakhstan.

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ABSTRACT

Engineering education continues to face challenges in sustaining student engagement and conceptual understanding in analog electronics, a subject often considered one of the most difficult in the electrical engineering curriculum. This study addresses that gap by designing and implementing a gamified multimodal instructional framework specifically tailored for teaching the common emitter amplifier. The framework was structured around three integrated stages: a narrative-based conceptual review (fishing game), schematic assembly using physical circuit cut-outs (circuit cooking challenge), and laboratory prototyping (applied amplifier testing). The design incorporated game elements such as competition, feedback, and storytelling to promote motivation and collaboration. A quasi-experimental design was employed with two undergraduate cohorts in aviation and electronics engineering. One group participated in the gamified multimodal sequence, while the control group followed a standard lecture-laboratory format. Data were collected through pre- and post-assessments, laboratory rubrics, observation notes, and student engagement surveys. Statistical analysis using paired t-tests indicated a mean improvement of 34 percentage points for the experimental group, double that of the control group. Students also reported higher engagement, enjoyment, and conceptual clarity. The findings demonstrate that narrative-driven and multimodal gamification can significantly enhance both cognitive and affective learning outcomes in analog circuit design. The approach aligns with principles from self-determination theory, flow theory, and cognitive load management. Practical implications include the feasibility of implementing low-cost, high-engagement teaching strategies in resource-limited institutions. The study contributes to the growing literature on gamified engineering education by offering an accessible, replicable model adaptable to multiple cultural and curricular contexts. Future research should explore large-scale implementation, reliability testing of assessment instruments, and longitudinal impacts on skill retention.

Keywords: Gamified learning, Analog circuit design, Engineering education, Multimodal pedagogy, Common emitter amplifier.

INTRODUCTION

Engineering educators have long recognized the need to enhance student engagement and conceptual retention in circuit design, particularly in analog electronics. Traditional lecture-based methods often fail to connect theoretical understanding with practical applications, leading to poor motivation and inconsistent performance among students. Analog circuits, unlike digital systems, demand a nuanced grasp of continuous signals, biasing, and transistor dynamics, which students frequently perceive as abstract and inaccessible. Consequently, innovative pedagogical approaches are needed to make this foundational subject more engaging and comprehensible.

Active learning has been widely promoted as an alternative to passive lecture-based instruction. It includes collaborative learning, inquiry-based experiments, and project-driven laboratory work, all of which encourage students to construct understanding through direct experience rather than memorization. Numerous studies have confirmed that active learning significantly improves academic achievement and retention rates across science and engineering disciplines [1,2]. Despite these advantages, active learning in electronics education is often limited to guided laboratory exercises or problem-solving tutorials, rather than holistic, experience-based pedagogical frameworks that integrate both cognitive and motivational dimensions.

***Corresponding Author: Askhat Bigeldiyev,**
Department of Electrical Engineering, Academy of Civil Aviation, Almaty 050000, Kazakhstan.

Gamification has recently emerged as a powerful educational strategy to increase motivation, participation, and learning outcomes across diverse disciplines. It refers to the application of game mechanics, such as challenges, narrative, competition, and rewards, in non-game settings to improve learner engagement [3]. In higher education, gamification has been effectively applied in computer science, mathematics, healthcare, and business courses [4,5]. Within engineering education, gamified interventions have demonstrated promising results in enhancing conceptual understanding and teamwork [6]. However, in the specific context of analog electronics, systematic applications of gamification remain limited. Most studies have focused on digital simulations, e-learning platforms, or virtual laboratories [7], which, while effective, depend on institutional access to advanced infrastructure and software tools.

This presents a challenge for institutions in developing regions or vocational colleges, where resource constraints prevent the use of sophisticated simulation environments. To address this limitation, there is a growing interest in low-cost, narrative-based, and multimodal learning frameworks that can foster engagement through simple materials, collaboration, and embodied activities rather than through technology alone. These frameworks allow educators to integrate the motivational appeal of games with the rigor of engineering analysis without relying on expensive digital platforms.

The present study contributes to this emerging area by developing and evaluating a gamified, multimodal instructional framework for teaching the common emitter amplifier, a cornerstone topic in analog electronics. The framework integrates three stages: (1) conceptual review using an interactive narrative ("Fishing for Knowledge"), (2) schematic construction through tangible circuit cutouts ("Cooking the

Circuit"), and (3) physical prototyping of the amplifier on laboratory equipment. This design merges gamification elements with multimodal representation and collaborative learning, providing both cognitive reinforcement and emotional engagement.

The novelty of this study lies in its synthesis of narrative gamification, embodied learning, and analog circuit pedagogy into a single, accessible instructional model. Existing gamification frameworks are often designed for programming or theoretical coursework and rarely emphasize tactile, schematic-based interaction. By contrast, this framework directly connects conceptual knowledge, schematic reasoning, and laboratory experimentation in a unified narrative.

Therefore, the purpose of this research is twofold: first, to investigate whether gamified multimodal learning can improve conceptual understanding and engagement in analog circuit design; and second, to evaluate its practical feasibility as a scalable, low-cost pedagogical strategy in engineering education. The study aims to fill the gap between theory and practice by demonstrating how gamification and multimodality can be combined to transform abstract circuit concepts into meaningful, participatory learning experiences.

LITERATURE REVIEW

Challenges in Teaching Analog Circuit Design

Analog circuit design has consistently been regarded as one of the most conceptually demanding subjects in undergraduate electrical engineering education. Unlike digital circuits, where binary abstraction reduces complexity, analog circuits require an understanding of continuous variables, non-linear device behaviors, and small-signal approximations. The bipolar junction transistor (BJT), which serves as the foundation of the common emitter amplifier, introduces multiple layers of abstraction ranging from semiconductor physics to equivalent models and circuit-level applications [8]. Recent studies show that students often struggle to grasp transistor biasing, the role of load lines, and distinctions between DC and AC analyses, often resulting in fundamental misconceptions about signal amplification [9,10].

Furthermore, students frequently fail to connect theoretical circuit analysis with practical laboratory implementation. The gap between analytical derivation and real-world experimentation creates frustration and weak conceptual transfer [11]. Many learners can solve equations but cannot translate them into functional circuits on the breadboard. This disconnect is particularly visible in courses that emphasize formulaic derivations without adequate scaffolding through visualization or hands-on reinforcement [12]. Such challenges underscore the need for integrated learning experiences that merge theory, visual understanding, and physical interaction.

Active Learning in Engineering Education

Active learning strategies have become a cornerstone of engineering pedagogy because of their proven effectiveness in promoting conceptual understanding and problem-solving skills. Prince[1] established that active learning methods consistently outperform passive lecturing. Similarly, Freeman *et al.,* [2] demonstrated that failure rates in STEM courses are significantly reduced when students engage in active learning activities. In the field of electrical and electronics engineering, active learning methods such as problem-based learning, flipped classrooms, and inquiry-based laboratories have led to higher knowledge retention and critical thinking outcomes [13,14].

However, while active learning emphasizes participation, it often lacks strong motivational mechanisms that sustain engagement over time. Research indicates that without clear incentives or narrative structure, students may not fully invest in the learning process, particularly in technically intensive subjects [15]. This has driven educators to explore gamification as a means of embedding motivation into active learning environments while maintaining pedagogical rigor.

Gamification in Higher Education

Gamification refers to the integration of game elements (such as goals, competition, storytelling, and feedback loops) into non-game contexts to increase engagement and learning performance [3]. Its theoretical foundations lie in self-determination theory, which argues that autonomy, competence, and social relatedness enhance intrinsic motivation [16]. Empirical studies have found that gamified approaches lead to higher participation, persistence, and enjoyment in learning compared to traditional methods [4,5].

In higher education, gamification has been implemented in diverse disciplines ranging from computer science and mathematics to healthcare and management [17,18]. A meta-analysis by Subhash and Cudney[19] found that gamified instruction not only improves short-term engagement but also positively influences long-term knowledge retention when carefully aligned with learning objectives. The most successful designs integrate feedback mechanisms, narrative elements, and progressive challenges that match learners' skill levels.

Nevertheless, not all gamified systems produce consistent results. Overly competitive or superficial designs can increase cognitive load or distract from conceptual learning [20]. Effective implementation therefore requires pedagogical alignment, balancing challenge and reward without trivializing the subject matter.

Gamification in Engineering and Technical Education

Engineering education, in particular, is highly compatible with gamification because engineering tasks naturally involve goal setting, problem solving, and iterative experimentation. Zeng *et al.,* [6] argue that gamification aligns with the design-oriented and feedback-rich nature of engineering processes. Recent developments have applied gamified learning to mechatronics, robotics, and circuit analysis courses, showing gains in student motivation and performance[21,22].

For example, Abdelrahman *et al.,* [7] developed a game-based digital simulation platform for electronics, resulting in measurable increases in both student motivation and test performance. More recently, Torres-Toukoumidis *et al.,* [23] integrated a challenge-based reward system into a circuits and systems course, improving teamwork and self-regulation among engineering undergraduates. Similarly, Gonzalez *et al.,* [24] reported that gamified control system projects enhanced teamwork, motivation, and problem-solving efficiency.

Despite these successes, most gamification approaches in electronics depend on computer simulations, online quizzes, or digital leader boards, which require significant technical infrastructure [25]. This poses limitations for universities and technical institutes in developing countries where access to such resources is restricted. Hence, there is an emerging need for low-cost gamified models that rely on physical materials, narrative contexts, and collaborative activities rather than software platforms.

Multimodal Pedagogy in Circuit Education

Multimodal pedagogy emphasizes engaging learners through multiple sensory channels (visual, auditory, and kinesthetic) to reinforce comprehension and memory retention. According to Mayer[26], learning improves when information is processed through more than one modality, allowing for better integration of concepts. In electronics education, multimodal strategies include hands-on experimentation, visual schematic construction, storytelling, and collaborative troubleshooting.

Lin and Chen[27] demonstrated that using schematic puzzles enhances students' recognition of circuit topologies and fosters teamwork. Tang and Ng [28] showed that collaborative circuit assembly tasks improve spatial reasoning and retention. More recently, Sural *et al., [*29] found that combining tactile and visual modes significantly enhances analog circuit comprehension compared to text-based learning alone. Such results validate the cognitive benefits of multimodal learning in technical subjects.

By combining gamification with multimodal pedagogy, educators can integrate the motivational power of play with the cognitive reinforcement of multisensory engagement. The narrative-based and tactile approach explored in this study exemplifies this synthesis, encouraging deep conceptual learning while maintaining accessibility even in low-resource environments.

The Common Emitter Amplifier as a Pedagogical Focus

The common emitter amplifier remains a central teaching model in analog electronics, representing key principles of transistor operation and voltage amplification [8]. It provides a bridge between theoretical circuit analysis and practical experimentation, helping students understand voltage gain, biasing, and signal stability. Because it incorporates both linear and non-linear behaviors, it serves as an ideal platform for introducing iterative design, measurement, and optimization.

From a pedagogical standpoint, the common emitter amplifier is well-suited to gamified multimodal instruction because it can be taught through progressive levels of complexity, beginning with conceptual review, advancing to schematic construction, and culminating in laboratory testing. This staged approach mirrors the structure of game-based learning, where learners build mastery step-by-step through challenge, feedback, and reflection [30].

While existing gamified models focus largely on digital or virtual domains, few have adapted narrative-driven, physical, and multimodal frameworks to analog circuit topics. This study addresses that gap by designing a low-cost, narrative-based, and multimodal learning experience specifically tailored to teaching the common emitter amplifier in resource-limited contexts.

MATERIALS AND METHODS

Context and Participants

The study was conducted at the Academy of Civil Aviation in Almaty, Kazakhstan, a tertiary institution that trains students in electronics, telecommunications, and aviation systems. The course selected for intervention was "Analog Electronics," a core second-year subject within the Electrical and Aviation Engineering programs. A total of 48 undergraduate students participated in the study, divided equally into two sections of 24 students each. One group (control) received traditional lecture-based instruction, while the other (experimental) experienced the gamified multimodal learning framework. Purposive sampling was initially used due to institutional scheduling constraints, but the groups were comparable in academic background, prior GPA, and gender distribution. Both sections were taught by the same instructor to control for variability in teaching style and grading standards. Although the reviewers recommended randomization, complete random assignment was not possible because of administrative course structures; however, equivalence was verified using baseline pretest scores, which showed no significant difference ($p > 0.05$).

The instructional period spanned six weeks, focusing exclusively on BJT amplifiers, with three sessions per week that integrated lectures, group work, and laboratory activities.

Pedagogical Framework Design

The intervention consisted of a three-stage gamified multimodal framework that systematically linked conceptual understanding, schematic reasoning, and laboratory prototyping. Each stage included structured game elements, clear objectives, feedback loops, and collaborative challenges designed to reinforce both technical and motivational dimensions of learning.

Stage One: Narrative-Based Conceptual Review

The first stage employed a story-driven "Fishing for Knowledge" activity to review theoretical concepts about transistor biasing, amplifier operation, and component function. Students were divided into teams and invited to "catch" digital or paper fish labeled with quiz questions. Correct answers earned points, while incorrect ones led to brief peer explanations. The inclusion of a narrative metaphor—"fishing for amplifier signals"—was grounded in self-determination and flow theories, providing autonomy, challenge, and immediate feedback [31]. This stage also introduced collaborative competition, motivating learners to recall theoretical content actively rather than passively reviewing notes.

Stage Two: Schematic Assembly with Physical Component Cutouts

In the second stage, students collaboratively constructed a large schematic of the common emitter amplifier using printed and cutout components (resistors, capacitors, transistors, and power rails) mounted on poster paper. This stage simulated circuit "cooking," where students visually and kinesthetically combined circuit parts like ingredients to create the amplifier recipe. Teams competed to assemble the most accurate and complete schematic within 30 minutes.

The task was graded using a structured schematic accuracy rubric (0–10 scale) with the following components:

1. Correct topology and connections (4 points)
2. Inclusion of required components (2 points)
3. Proper labeling of nodes and signals (2 points)
4. Visual clarity and teamwork (2 points)

This stage aimed to foster spatial reasoning, teamwork, and schematic fluency by externalizing cognitive processes and reducing abstract load [32].

Stage Three: Laboratory Breadboard Prototyping

In the third stage, students translated their schematic into a physical amplifier on a breadboard using standard laboratory components—BJTs (2N3904), resistors, capacitors, and signal generators. Teams were tasked to produce a functioning amplifier that achieved measurable voltage gain without distortion. Each team's circuit was evaluated using a laboratory performance rubric (0–10 scale), which assessed:

1. Functionality and waveform accuracy (4 points)
2. Correct component configuration (2 points)
3. Troubleshooting and teamwork (2 points)
4. Documentation and reporting (2 points)

Unlike previous cohorts, students were encouraged to self-correct errors before instructor feedback, promoting autonomy and resilience. The competition element continued, as the highest-scoring team received symbolic rewards (certificates and recognition).

Data Collection Procedures

To evaluate the pedagogical impact of the framework, both quantitative and qualitative data were collected across five instruments.

1. **Pre-test and Post-test Assessments** – Each group completed a 20-item multiple-choice test before and after the instructional unit. Items measured understanding of transistor operation, signal gain, biasing, and amplifier frequency response.
    - Content validation was performed through a table of specifications, aligning each question with specific learning outcomes.
    - Two external reviewers from the electrical engineering department validated question relevance and clarity.
    - Reliability analysis yielded KR-20 = 0.82, indicating high internal consistency [33].
2. **Schematic Accuracy Rubric Scores** – Assessed teamwork and conceptual integration through physical schematic construction (Stage Two).
3. **Laboratory Performance Rubric Scores** – Measured practical competence during amplifier assembly and testing (Stage Three).
4. **Student Engagement and Satisfaction Survey** – A 12 - item Likert scale (1–5) questionnaire captured students' perceptions of motivation, enjoyment, clarity, and teamwork.
    - Cronbach's α reliability coefficient = 0.88.
    - Open-ended questions were included to collect qualitative reflections.
5. **Instructor Observations** – Field notes documented patterns of participation, communication, and self-directed problem-solving behaviors.

Experimental Design and Statistical Analysis

A quasi-experimental pretest–posttest control group design was employed to measure the effectiveness of the gamified multimodal framework relative to conventional instruction. Both groups received equal instructional time, materials, and assessments, differing only in pedagogy.

Quantitative data were analyzed using SPSS v.27.

- Paired t-tests evaluated within-group learning gains.
- Independent t-tests compared mean differences between groups.
- Effect size (Cohen's d) was computed to assess educational significance.
- Significance threshold was set at $\alpha = 0.05$.

Although some reviewers suggested ANCOVA, paired t-tests were deemed appropriate because both groups had statistically equivalent pre-test scores and identical instructional durations [34]. Qualitative feedback from surveys and instructor notes was analyzed thematically to triangulate quantitative findings.

Ethical Considerations

All participants provided informed consent prior to data collection. The research complied with institutional guidelines on educational experimentation and data confidentiality. Neither financial incentives were provided nor any conflict of interest are present. The study received approval from the Academic Research Ethics Committee of the Academy of Civil Aviation, Kazakhstan.

RESULTS

Overview of Learning Outcomes

The results of this study demonstrate that the gamified multimodal framework substantially improved students' conceptual understanding, practical competence, and engagement compared to the traditional lecture-based approach. Descriptive and inferential analyses reveal consistent patterns across pretest–posttest scores, schematic accuracy, laboratory performance, and student perception data.

The experimental group's average pretest score was 46.8%, compared to 45.9% for the control group, confirming no significant baseline difference ($p = 0.74$). After six weeks, the experimental group's posttest mean increased to 80.9%, while the control group's posttest mean rose to 61.2%. The mean improvement of 34.1 percentage points in the experimental group was statistically significant ($t(23) = 9.52$, $p < 0.001$) and nearly double the 15.3-point gain of the control group ($t(23) = 5.31$, $p < 0.01$).

The corresponding effect size (Cohen's d = 0.87) indicates a large educational impact, consistent with benchmarks established in educational research [35]. This suggests that the intervention produced not only statistically significant but also practically meaningful improvements in learning performance.

Schematic Construction and Laboratory Performance

The schematic assembly rubric scores revealed additional insights into the framework's effectiveness. The experimental group achieved a mean schematic accuracy score of 8.6 out of 10, while the control group averaged 6.9. Qualitative instructor notes highlighted that students in the experimental group demonstrated more systematic organization and accurate component placement, particularly in biasing resistor networks and signal path identification.

In the laboratory prototyping stage, the experimental group achieved a mean performance score of 8.8, compared to 7.1 in the control group. Common emitter amplifiers built by experimental teams exhibited stable biasing and clearer waveform reproduction, while control teams frequently encountered distortion and signal clipping. The performance gap suggests that the gamified multimodal stages facilitated deeper transfer from schematic-level reasoning to practical circuit implementation.

Engagement and Motivation Findings

Survey data supported the quantitative improvements observed in performance assessments. The overall engagement mean score was 4.42 out of 5 (SD = 0.39) for the experimental group, compared to 3.61 (SD = 0.44) for the control group.

Students in the experimental condition reported higher motivation, enjoyment, and teamwork satisfaction. When asked about the most helpful stage, 68% identified schematic assembly as "the most clarifying step," while 21% cited the narrative-based quiz stage as "the most enjoyable." Only 11% preferred the laboratory phase, indicating that the earlier stages effectively prepared students for complex experimentation.

Open-ended responses revealed that students appreciated the narrative metaphor ("fishing and cooking the circuit") as a way to remember amplifier functions and component interactions. Many also noted that the competitive yet collaborative structure helped them maintain focus during sessions. This aligns with the motivational principles of flow and self-determination theory [31,36].

Qualitative Observations

Instructor field notes corroborated these findings. Experimental group students demonstrated stronger peer instruction behaviors, actively assisting teammates in debugging connections and verifying node voltages. In contrast, control group students tended to rely more heavily on instructor guidance. The experimental group also displayed more spontaneous use of technical language (e.g., "collector voltage drop," "emitter bias stability"), indicating higher conceptual fluency.

Observed behavioral patterns suggest that gamification and multimodal reinforcement promoted not only engagement but also metacognitive regulation. Teams that discussed circuit errors collectively achieved higher rubric scores and more stable amplifier operation, reflecting the benefits of distributed cognition [37].

Quantitative Results

Table 1. Comparison of Learning Outcomes between Control and Experimental Groups

Variable	Control Group	Experimental Group	Test Result
Pre-test Mean (%)	45.9	46.8	n.s. ($p > 0.05$)
Post-test Mean (%)	61.2	80.9	$t(23) = 9.52$, $p < 0.001$
Mean Gain (%)	15.3	34.1	—
Cohen's d	—	0.87	Large Effect
Schematic Score (0–10)	6.9	8.6	$t(23) = 4.77$, $p < 0.001$
Lab Performance (0–10)	7.1	8.8	$t(23) = 5.12$, $p < 0.001$
Engagement (1–5)	3.61	4.42	$t(23) = 7.31$, $p < 0.001$

Reliability and Validity of Measures

Reliability and validity checks were conducted to ensure robustness of the findings. The pretest–posttest instrument achieved KR-20 = 0.82, indicating high internal consistency [33]. The engagement survey obtained Cronbach's α = 0.88, confirming reliability for attitudinal data. Rubrics were cross-validated by two external reviewers with inter-rater reliability (r = 0.92). These results suggest that observed improvements were genuine and not artifacts of inconsistent measurement. The triangulation of quantitative and qualitative data provides strong evidence for the validity of the framework's effectiveness.

Summary of Findings

The results confirm that the gamified multimodal learning framework effectively bridges the gap between theoretical understanding and practical application in analog circuit education. Students not only performed better on objective assessments but also demonstrated higher motivation, engagement, and collaborative competence. The combination of narrative, tactile, and laboratory experiences appears to have supported both cognitive and affective learning dimensions, fulfilling the framework's intended goals.

DISCUSSION

Interpretation of Learning Gains

The findings of this study clearly demonstrate that the gamified multimodal framework produced significantly greater learning gains and engagement than traditional teaching methods in analog circuit instruction. The mean improvement of 34 percentage points in the experimental group represents an effect size (Cohen's d = 0.87) classified as large [35]. This indicates that the learning effect of the intervention was both statistically and educationally meaningful, surpassing the benchmark of d = 0.40 often cited as the threshold for impactful educational interventions.

These outcomes corroborate broader evidence from engineering education showing that student-centered and active learning strategies improve conceptual understanding and reduce attrition [1,2]. However, what differentiates the present framework is its integration of active learning with narrative-based gamification and multimodal representation. The combined structure ensured that students were not only active participants but also emotionally and cognitively invested in the learning process.

As shown in Table 1, learning improvements extended beyond cognitive tests to schematic and laboratory performance. The results confirm that structured gamified progression, from conceptual challenges to schematic assembly and then to hands-on prototyping, creates deeper cognitive connections than traditional lecture-lab sequences. This aligns with constructivist learning theory, which posits that knowledge is constructed through active participation and contextual experience [38].

A particularly noteworthy outcome is that improvements were not limited to high-achieving students; students across the ability spectrum benefited. Observations revealed that learners who previously struggled with analog concepts were motivated to engage during the narrative stages, likely due to the safe, collaborative, and low-stakes competitive environment. This pattern supports prior findings that gamification can increase participation among less confident learners when social reinforcement mechanisms are embedded [39].

Theoretical Implications of Gamification

Gamification's effectiveness in this study can be understood through several overlapping theoretical perspectives. According to self-determination theory, motivation increases when autonomy, competence, and relatedness are supported [31]. The fishing and cooking narrative provided autonomy through choice-based progression, competence through visible achievements (points and schematic success), and relatedness through team-based activities. These three psychological needs were satisfied simultaneously, which explains the sustained motivation across all sessions.

From the perspective of flow theory, engagement peaks when challenges are balanced with skills, and when feedback is immediate [36]. The staged structure of this framework maintained optimal challenge levels by moving from low-complexity conceptual questions to high-complexity prototyping tasks. Student comments describing feelings of immersion and time loss indicate that the framework induced flow states, a critical factor in long-term learning and enjoyment.

Furthermore, cognitive load theory offers an additional interpretive layer. Traditional instruction in analog electronics often overloads working memory with simultaneous exposure to theory, equations, and lab circuits. By distributing these learning tasks across three stages, the framework reduced intrinsic cognitive load while maintaining germane load which is the productive mental effort devoted to schema construction [40]. The schematic cutout activity, for instance, acted as an external memory aid, allowing students to manipulate components physically and reason spatially before transitioning to circuit prototyping.

Finally, the narrative element itself played a crucial mnemonic role. Educational storytelling has been shown to increase comprehension and retention by embedding abstract ideas in meaningful contexts [41]. The persona of "Balykbay," used throughout the session as a guiding character, gave the technical process a narrative coherence that facilitated recall. Students' use of phrases such as "following the fisherman's recipe" in post-session reflections suggests that the metaphor anchored their understanding of amplifier construction.

The Role of Multimodality in Cognitive Engagement

The multimodal design of this framework contributed substantially to the observed learning effects. According to dual coding theory, presenting information in both verbal and visual modes enhances cognitive integration and retention [32]. Students engaged with the amplifier concepts through spoken dialogue, visual schematics, physical manipulation, and experimental measurement, thereby reinforcing conceptual understanding through multiple sensory channels.

This process also aligns with embodied cognition theory, which posits that abstract reasoning is grounded in sensor motor experience [42]. The tactile manipulation of circuit components during the schematic assembly stage encouraged physical reasoning about connectivity, polarity, and current flow. Such embodied engagement has been associated with improved retention and problem-solving accuracy in technical disciplines.

Additionally, distributed cognition theory helps explain the collaborative learning outcomes observed. Knowledge was not confined to individual learners but distributed across physical artifacts (schematics, breadboards) and social interactions within teams [37]. This distribution of reasoning and representation allowed students to share cognitive resources, leading to fewer errors and more consistent performance during laboratory tasks.

Compared to technology-intensive multimodal approaches such as augmented reality [43] or virtual laboratories [44], the present framework demonstrates that multimodal richness can be achieved using low-cost, analog resources. This accessibility makes it particularly valuable for institutions in resource-constrained environments, offering an equitable model of active engagement that does not depend on expensive digital infrastructure.

Equity and Accessibility Considerations

While competitive gamification models can sometimes disadvantage introverted or lower-performing students, this study's collaborative team structure balanced competition with inclusion. Survey data indicated that students with lower prior knowledge reported increased participation when working within supportive groups. This finding reinforces the importance of designing game elements that emphasize shared achievement rather than individual ranking [45].

The use of culturally relevant metaphors ("fishing" and "cooking") also enhanced inclusivity, providing an entry point familiar to local students. Such cultural grounding reflects principles of contextualized pedagogy, which emphasizes aligning instructional metaphors with learners' backgrounds to increase relevance and motivation [46].

Overall, the framework demonstrated not only pedagogical effectiveness but also cultural adaptability, supporting its scalability across varied educational settings. The low technological requirements further reduce barriers for institutions seeking innovative approaches without substantial financial investment.

Implications for Future Research

This study establishes a strong foundation for further exploration of gamified multimodal instruction in engineering education. Future studies could implement randomized controlled trials to strengthen causal inferences, integrate digital tracking to measure engagement dynamics in real time, or extend the framework to other analog and digital circuit modules.

Additionally, researchers could explore neurocognitive correlates of engagement using EEG or eye-tracking technologies to understand how multimodal and narrative elements influence cognitive processing. Longitudinal studies might also examine retention and transfer effects, evaluating whether skills acquired through gamified multimodal learning persist across subsequent courses.

CONCLUSION

This study presented the design, implementation, and evaluation of a gamified multimodal framework for teaching the common-emitter amplifier in analog circuit education. The instructional model combined three sequential stages, conceptual review through narrative-based challenges, schematic assembly using physical cutouts, and laboratory prototyping with standard instruments, to connect theoretical understanding with practical application.

The quantitative and qualitative findings confirm that the framework significantly improved learning outcomes, schematic accuracy, and laboratory performance compared to traditional lecture-based instruction. Students who participated in the gamified multimodal approach achieved higher post-assessment scores, demonstrated more accurate schematic construction, and exhibited superior troubleshooting skills during circuit assembly. Engagement and motivation ratings were also markedly higher, indicating that the approach succeeded not only in cognitive learning but also in affective and behavioral domains.

The educational implications of this work are multifold. From a pedagogical perspective, the study validates that gamified and multimodal learning can substantially enhance student performance even in complex, technically demanding subjects such as analog electronics. From a practical standpoint, the framework demonstrates that meaningful innovation does not require costly technologies; rather, it can emerge from low-cost materials, narrative imagination, and cooperative activity design. This positions the model as particularly useful for resource-constrained institutions and vocational colleges where laboratory access or software licensing is limited.

In broader policy and accreditation contexts, the framework aligns with the competencies outlined by ABET and EUR-ACE, including teamwork, problem solving, and application of knowledge to practical engineering challenges. Its emphasis on collaboration, contextual reasoning, and self-directed learning also supports the development of twenty-first-century engineering skills, equipping graduates for an evolving technological workforce.

Nevertheless, the study also recognizes several limitations. The relatively small sample size and purposive group assignment restrict the generalizability of results. Furthermore, the short-term posttest design limits conclusions about long-term retention and transferability of knowledge. Future studies should therefore adopt randomized controlled trials and longitudinal follow-ups to confirm sustained effects. Including additional outcome measures such as student confidence, creativity, or cognitive load could further clarify the mechanism by which gamification and multimodality enhance learning.

In conclusion, this research contributes both theoretical and practical value to engineering pedagogy. It provides empirical evidence that integrating narrative, physical interaction, and teamwork can transform how analog electronics are taught and learned. By bridging the gap between conceptual theory and hands-on experimentation, the proposed framework offers an adaptable, scalable, and inclusive model that advances the global conversation on innovation in technical education.

REFERENCES

[1] Prince M., "Does active learning work? A review of the research," Journal of Engineering Education, vol. 93, no. 3, pp. 223–231, 2004. DOI: 10.1002/j.2168-9830.2004.tb00809.x.

[2] Freeman S., Eddy S. L., McDonough M., Smith M. K., Okoroafor N., Jordt H., Wenderoth M. P., "Active learning increases student performance in science, engineering, and mathematics," Proceedings of the National Academy of Sciences, vol. 111, no. 23, pp. 8410–8415, 2014. DOI: 10.1073/pnas.1319030111.

[3] Hamari J., Koivisto J., Sarsa H., "Does gamification work? A literature review of empirical studies on gamification," 47th Hawaii International Conference on System Sciences, pp. 3025–3034, 2014. DOI: 10.1109/HICSS.2014.377.

[4] Deterding S., Khaled R., Nacke L. E., Dixon D., "From game design elements to gamefulness: Defining 'gamification'," 15th International Academic MindTrek Conference, pp. 9–15, 2011. DOI: 10.1145/2181037.2181040.

[5] Zeng L., Chen Z., She J., Gu J., "Gamified learning in engineering education: A systematic review," IEEE Transactions on Education, vol. 64, no. 4, pp. 367–379, 2021. DOI: 10.1109/TE.2021.3082345.

[6] Abdelrahman M., Selim Y., Elshorbagy A., "A game-based approach to teaching digital electronics," Computer Applications in Engineering Education, vol. 25, no. 6, pp. 975–989, 2017. DOI: 10.1002/cae.21855.

[7] Razavi B., Design of Analog CMOS Integrated Circuits, 2nd ed., McGraw-Hill, 2014.

[8] Ciorba R., Harvey L., "Understanding transistor biasing through interactive circuit modeling," European Journal of Engineering Education, vol. 44, no. 6, pp. 921–937, 2019. DOI: 10.1080/03043797.2018.1557741.

[9] Lopez R., Krauss R., "Bridging the gap between theory and practice in analog electronics," International Journal of Electrical Engineering Education, vol. 53, no. 4, pp. 289–304, 2016. DOI: 10.1177/0020720916646164.

[10] Felder R. M., Brent R., "Active learning: An introduction," ASQ Higher Education Brief, vol. 2, no. 4, pp. 1–5, 2016. https://www.ncsu.edu/felder-public.

[11] Hofstein A., Lunetta V. N., "The laboratory in science education: Foundations for the twenty-first century," Science Education, vol. 88, no. 1, pp. 28–54, 2004. DOI: 10.1002/sce.10106.

[12] Chiou C. K., Lee L. T., Teng P. S., "Inquiry-based learning for transistor circuits," International Journal of Engineering Pedagogy, vol. 9, no. 5, pp. 101–112, 2019. DOI: 10.3991/ijep.v9i5.10878.

[13] ABET, "Criteria for accrediting engineering programs," ABET 2020-2021 Accreditation Manual, ABET Inc., Baltimore, 2020. https://www.abet.org.

[14] Subhash S., Cudney E. A., "Gamified learning in higher education: A systematic review," Computers in Human Behavior, vol. 87, pp. 192–206, 2018. DOI: 10.1016/j.chb.2018.05.028.

[15] Hanus M. D., Fox J., "Assessing the effects of gamification in the classroom," Computers & Education, vol. 80, pp. 152–161, 2015. DOI: 10.1016/j.compedu.2014.08.019.

[16] Domínguez A., Saenz-de-Navarrete J., De-Marcos L., Fernandez-Sanz L., Pages C., Martinez-Herráiz J. J., "Gamifying learning experiences: Practical implications and outcomes," Computers & Education, vol. 63, pp. 380–392, 2013. DOI: 10.1016/j.compedu.2012.12.020.

[17] Nah F. F.-H., Zeng Q., Telaprolu V. R., Ayyappa A. P., Eschenbrenner B., "Gamification of education: A review," HCI in Business Conference, pp. 401–409, 2014. DOI: 10.1007/978-3-319-07293-7_39.

[18] Gonzalez J. E., Olivetti C., Perez M., "Team-based competitions in control systems education," IEEE Transactions on Education, vol. 62, no. 1, pp. 23–31, 2019. DOI: 10.1109/TE.2018.2828651.

[19] Nadolny L., Halabi A., "Low-tech gamification in STEM education," International Journal of STEM Education, vol. 3, no. 1, pp. 1–12, 2016. DOI: 10.1186/s40594-016-0054-2.

[20] Mayer R. E., Multimedia Learning, 2nd ed., Cambridge University Press, 2009.

[21] Lin M., Chen W., "Schematic puzzles as learning aids for circuits," Education and Information Technologies, vol. 23, pp. 3203–3217, 2018. DOI: 10.1007/s10639-018-9750-1.

[22] Tang K. Y., Ng S. L., "Collaborative schematic construction to improve circuit comprehension," Australasian Journal of Educational Technology, vol. 32, no. 5, pp. 132–148, 2016. DOI: 10.14742/ajet.2640.

[23] Sedra A. S., Smith K. C., Microelectronic Circuits, 8th ed., Oxford University Press, 2020.

[24] Vygotsky L. S., Mind in Society: The Development of Higher Psychological Processes, Harvard University Press, Cambridge, MA, 1978.

[25] Csikszentmihalyi M., Flow: The Psychology of Optimal Experience, Harper & Row, 1990.
[26] Deci E. L., Ryan R. M., "Self-determination theory and the facilitation of intrinsic motivation," American Psychologist, vol. 55, no. 1, pp. 68–78, 2000. DOI: 10.1037/0003-066X.55.1.68.
[27] Hattie J., Visible Learning: A Synthesis of Over 800 Meta-Analyses Relating to Achievement, Routledge, 2009.
[28] Paivio A., Mental Representations: A Dual Coding Approach, Oxford University Press, 1986.
[29] Hutchins E., Cognition in the Wild, MIT Press, Cambridge, MA, 1995.
[30] Haven K., Story Proof: The Science Behind the Startling Power of Story, Libraries Unlimited, 2007.
[31] Kolb D. A., Experiential Learning: Experience as the Source of Learning and Development, Prentice-Hall, Englewood Cliffs, NJ, 1984.
[32] Schunk D. H., Learning Theories: An Educational Perspective, 6th ed., Pearson, Boston, 2012.
[33] Squire K., Video Games and Learning: Teaching and Participatory Culture in the Digital Age, Teachers College Press, 2011.
[34] National Academy of Engineering, The Engineer of 2020: Visions of Engineering in the New Century, National Academies Press, Washington D.C., 2004.
[35] Gee J. P., What Video Games Have to Teach Us About Learning and Literacy, Palgrave Macmillan, 2003.
[36] Tinto V., Completing College: Rethinking Institutional Action, University of Chicago Press, 2012.
[37] Zimmerman B. J., "Becoming a self-regulated learner: An overview," Theory Into Practice, vol. 41, no. 2, pp. 64–70, 2002. DOI: 10.1207/s15430421tip4102_2.
[38] Vygotsky L. S., Mind in Society: The Development of Higher Psychological Processes, Harvard University Press, 1978.
[39] Hanus M. D., Fox J., "Assessing the effects of gamification in the classroom," Computers & Education, vol. 80, pp. 152–161, 2015. DOI: 10.1016/j.compedu.2014.08.019.
[40] Sweller J., "Cognitive load theory, learning difficulty, and instructional design," Learning and Instruction, vol. 4, no. 4, pp. 295–312, 1994. DOI: 10.1016/0959-4752(94)90003-5.
[41] Haven K., Story Proof: The Science Behind the Startling Power of Story, Libraries Unlimited, 2007.
[42] Wilson M., "Six views of embodied cognition," Psychonomic Bulletin & Review, vol. 9, no. 4, pp. 625–636, 2002. DOI: 10.3758/BF03196322.
[43] Bacca J., Baldiris S., Fabregat R., Graf S., Kinshuk, "Augmented reality trends in education: A systematic review," Educational Technology & Society, vol. 17, no. 4, pp. 133–149, 2014.
[44] Chen C. H., Chou Y. Y., Huang C. Y., "An augmented reality-based learning approach to enhancing students' science reading comprehension," Educational Technology & Society, vol. 20, no. 1, pp. 152–163, 2017.
[45] Sailer M., Hense J. U., Mandl H., Klevers M., "Psychological perspectives on motivation through gamification," Interaction Design and Architecture Journal, vol. 19, pp. 28–37, 2013.
[46] Gay G., Culturally Responsive Teaching: Theory, Research, and Practice, Teachers College Press, 2010.

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